Papers

Allochthonous salt, structure and stratigraphy of the north-eastern Gulf of Mexico. Part I: Stratigraphy

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Major sequence boundaries associated with eustatic sea level changes are correlated to the general stratigraphy of the north-eastern Gulf of Mexico. The details of a Middle Cretaceous Flooding Surface, marking a major break in sedimentation, are documented. The sequence stratigraphic work provides an example of the 'stratigraphic signature of the Neogene'. Three major episodes of sediment accumulation are represented by: (1) Late Jurassic (150.5 Ma) to Middle Cretaceous (94 Ma) aggradation and progradation of sediments with significant sediment accumulation in the present shelf and slope areas; (2) an extended period of starved sedimentation during 94–30 Ma corresponding to Middle Cretaceous flooding events (93.5 and 91.5 Ma) and the lack of sediment supply; and (3) since Late Oligocene time, unusually rapid sedimentation rates that characterize the deep water study area. These patterns of sediment accumulation directly affect the formation of allochthonous salt in the study area.

Keywords: North-eastern Gulf of Mexico; stratigraphy; allochthonous salt

Introduction

The stratigraphy of the northern Gulf of Mexico basin has been recently summarized by Winker (1982), Galloway (1989), Curtis (1987) and Winker and Buffler (1988). The Gulf Coast Correlation Chart (Huddlestun *et al.*, coordinators, 1988) of the American Association of Petroleum Geologists summarizes and correlates the stratigraphy in the northern Gulf Coast region. The Gulf Coast Cenozoic Stratigraphic Chart (PI Exploration Systems, 1989) presents a stratigraphic system that is commonly used in the industry. In this paper, sequence stratigraphic concepts are used to interpret seismic and well information in order to provide a stratigraphic frame of reference for the structural studies in the north-eastern Gulf of Mexico described in Part 2 of this series [(Wu *et al.* (1990)] *Fold-out 1* lists the major formation names used in this area of the Gulf of Mexico. A brief summary of conventional Gulf Coast stratigraphy is first given, followed by more detailed sequence stratigraphic comments.

Summary of conventional Gulf coast stratigraphy

Basement

The landward portion of the Gulf of Mexico Basin is situated on a basement of deformed Palaeozoic rocks which crops out beyond the northern boundary of the basin in the Appalachian and Ouachita orogenic belts (Buffler and Sawyer, 1985; Rodgers, 1987; Curtis, 1987; Bally, 1987; Salvador, 1987, Buffler, 1989; *Figure 1*). Pennsylvanian and Permian interpreted to infill á backarc basin (Milliken 1988) suggest an upper Palaeozoic ancestry of the Gulf of Mexico basin. Thick undeformed Palaeozoic sediments are seen on seismic profiles and have been drilled. Seaward, the Gulf of Mexico basin is underlain by a transitional and oceanic crust (*Figure 1;* Buffler and Sawyer, 1985; Buffler, 1989).

Mesozoic

The oldest Mesozoic strata consist of Upper Triassic–Lower Jurassic red beds and basalts (Eagle Mills) which fill extensional depressions near the northern margin of the basin. There is much speculation about extension in the deeper portions of the basin but conclusive evidence is lacking. Evaporites (Callovian Louann Salt and the underlying Werner anhydrite) deposited during late Middle Jurassic time extend from the rim of the province to the central Gulf, but may be thin or absent under the south Texas coastal plain and continental shelf. In the shallow portion of the basin, evaporites clearly discordantly overlie pre-existing graben systems (Milliken, 1988). Overlying the salt is an Upper Jurassic (Oxfordian) sequence of sandstones (Norphlet) and limestones (Smackover). In parts of the Gulf, these are conformably overlain by Upper Jurassic (Kimmeridgian) evaporites and red beds (Buckner) and followed by deltaic and marine shelf sandstones, shales and carbonates. These are succeeded in turn by a thick sequence of deltaic and non-marine to nearshore marine deposits that extend into earliest Cretaceous (Cotton Valley).

Lower Cretaceous (Hauterivian through Lower Cenomanian) rocks (*Figure 2A;* Huddlestun *et al.*, 1988; Winker and Buffler, 1988) form an onlapping sequence over the pre-Cretaceous unconformity and extend landward to rest on Palaeozoic rocks well

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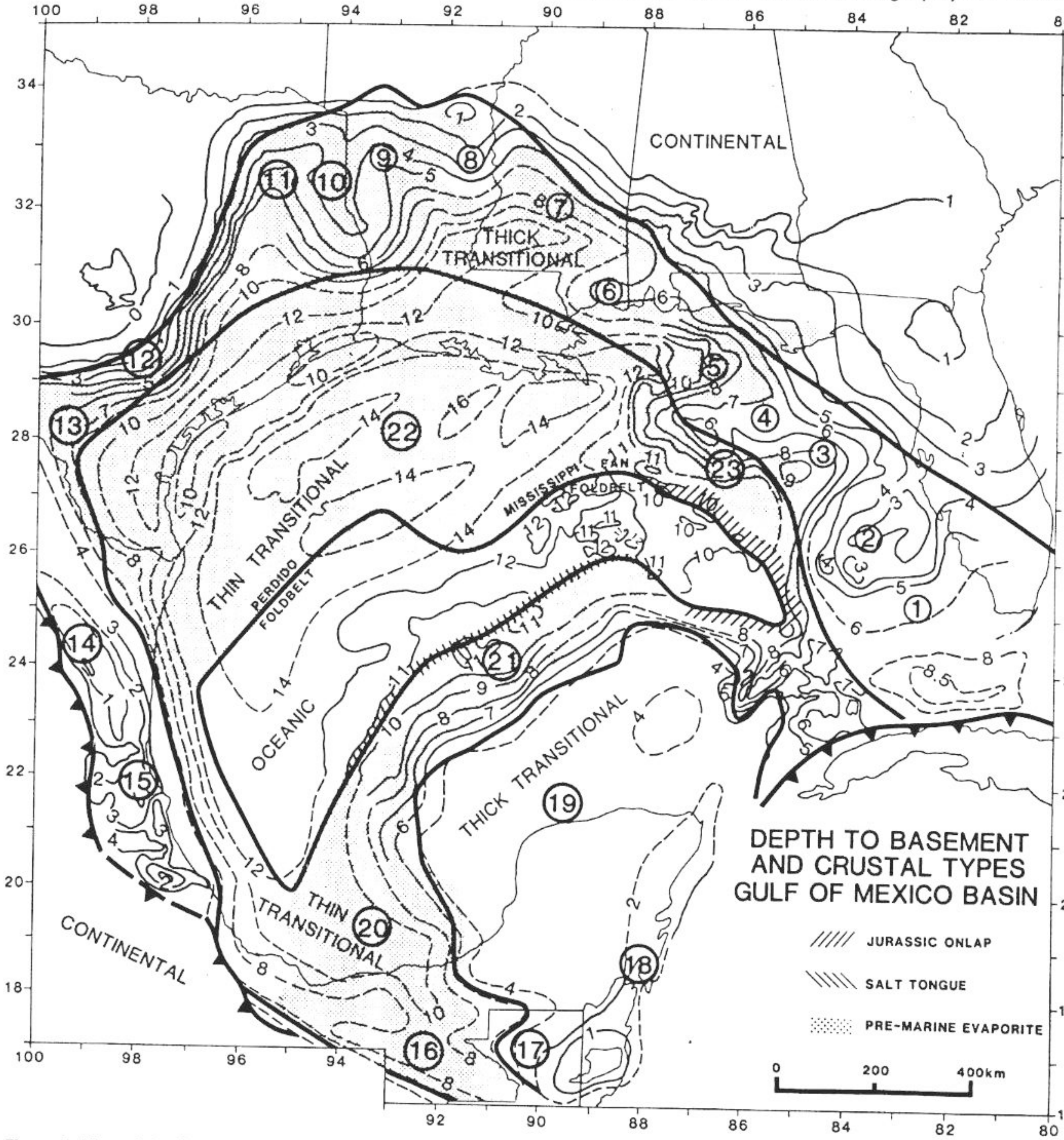


Figure 1 Map of the Gulf of Mexico region showing: (1) generalized depth to basement in kilometers; (2) distribution of four crustal types — continental, thick transitional, thin transitional and oceanic crust; and (3) known distribution of Middle-Jurassic pre-marine evaporites (Louann salt and equivalent rocks) (stippled area). Basement includes oceanic crust plus all rock lying below (older than) pre-marine evaporites. Circled numbers refer to major named basement highs, lows, basins, arches, etc. (from Buffler, 1989)

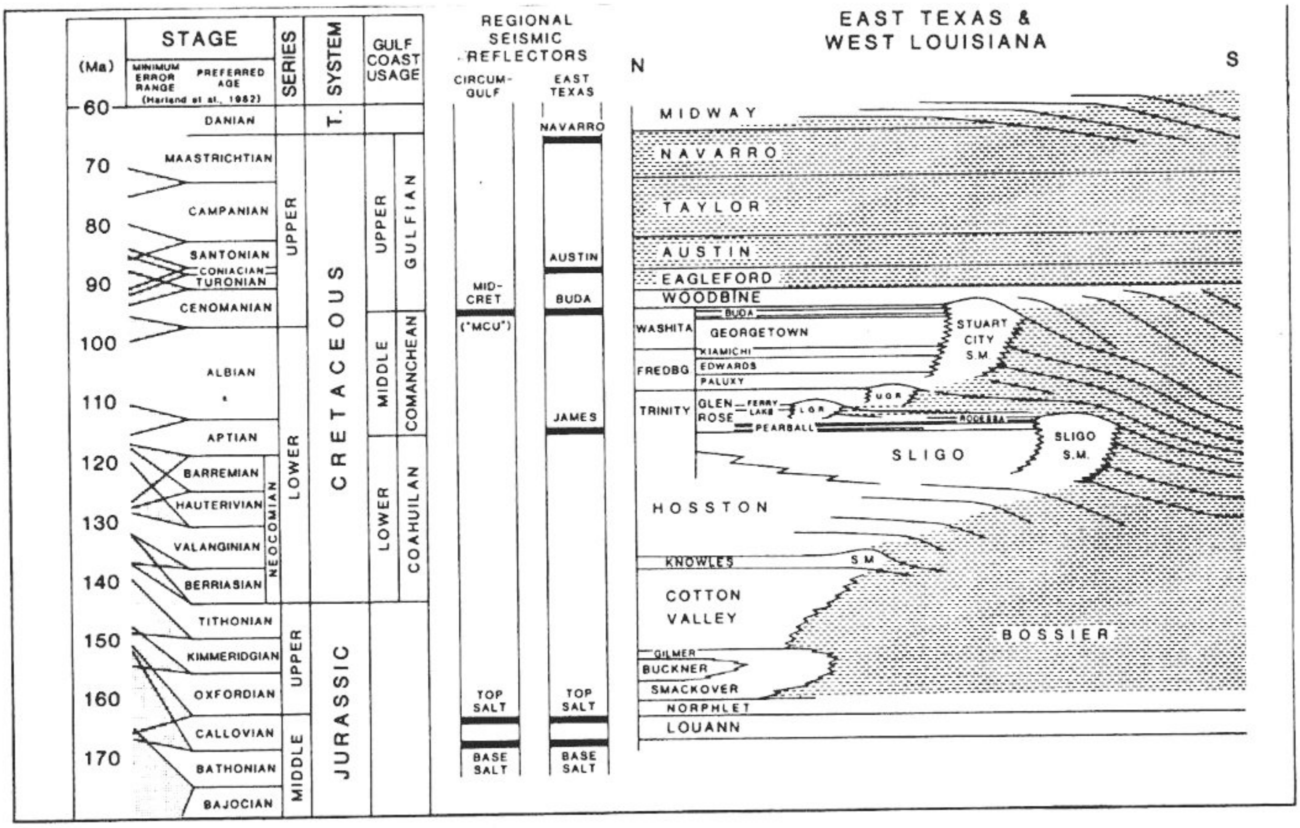
beyond the peripheral faults of the northern coastal province (Cook and Bally, 1975). The oldest Lower Cretaceous rocks throughout the province are terrigenous clastics (Hosston), which are overlain in south and central Texas by carbonates (Sligo, Trinity, Fredericksburg, Washita) of Aptian, Albian and Early Cenomanian age. The section becomes more terrigenous and contains an evaporite section from north-east Texas eastward to Alabama and north-west Florida. In southern Florida, the Lower Cretaceous rocks are almost entirely carbonates (*Figure 2B*).

A composite series of carbonate shelf-margin reef build ups form the lower Cretaceous shelf edge (e.g. Edwards or Stuart City reef trend, *Figure 2A*) from the Rio Grande across Texas and Louisiana, extending as a submarine scarp south-eastward to form the edge of the Florida platform (*Figures 2A,B* and *3a*).

A Mid-Cenomanian unconformity (MCU) (Buffler *et al.*, 1980; Buffler, 1983b; and Buffler and Sawyer, 1985; Winker and Buffler, 1988; *Figure 2A,B*) separates rocks of Lower from those of Upper Cretaceous (Late Cenomanian to Maastrichtian) age. Note that the MCU correlates to the Top Lower Cretaceous (TLC) (94 Ma sequence boundary of Haq *et al.*, 1987) of this study on the Middle Cretaceous shelf (*Foldout 1*, for a detailed discussion see later).

The Late Cretaceous transgression extended up to the Mississippi embayment and into the continental

(A)



(B)

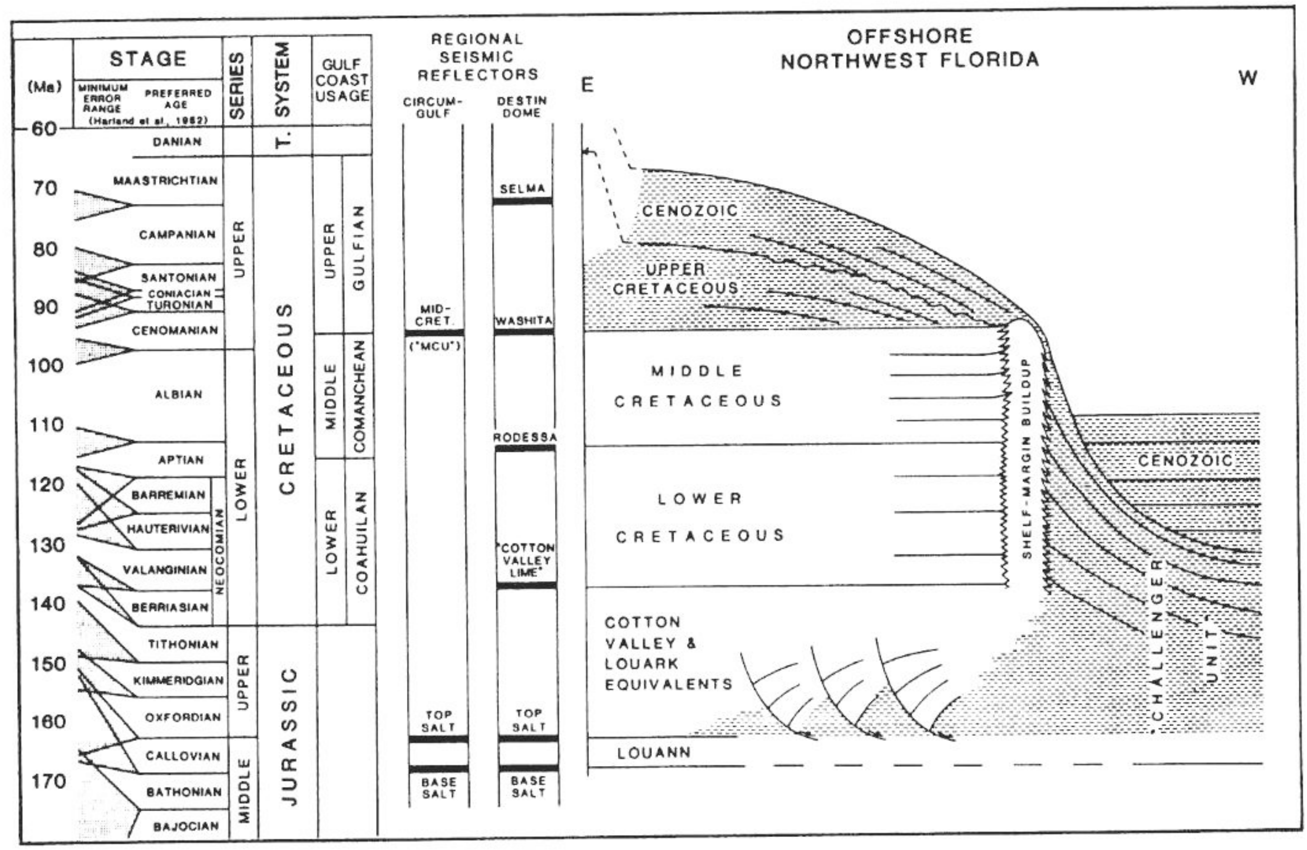


Figure 2(A) Stratigraphic nomenclature and seismic stratigraphy geometry of the Upper Mesozoic platform (unshaded) to basin (shaded) transition for eastern Texas and western Louisiana (from Winker and Buffler, 1988). **(B)** Stratigraphic nomenclature of offshore MAFLA (Mississippi-Alabama-Florida) area. Interpretation of structures in Upper Jurassic is speculative due to lack of deep well control (from Winker and Buffler, 1988)

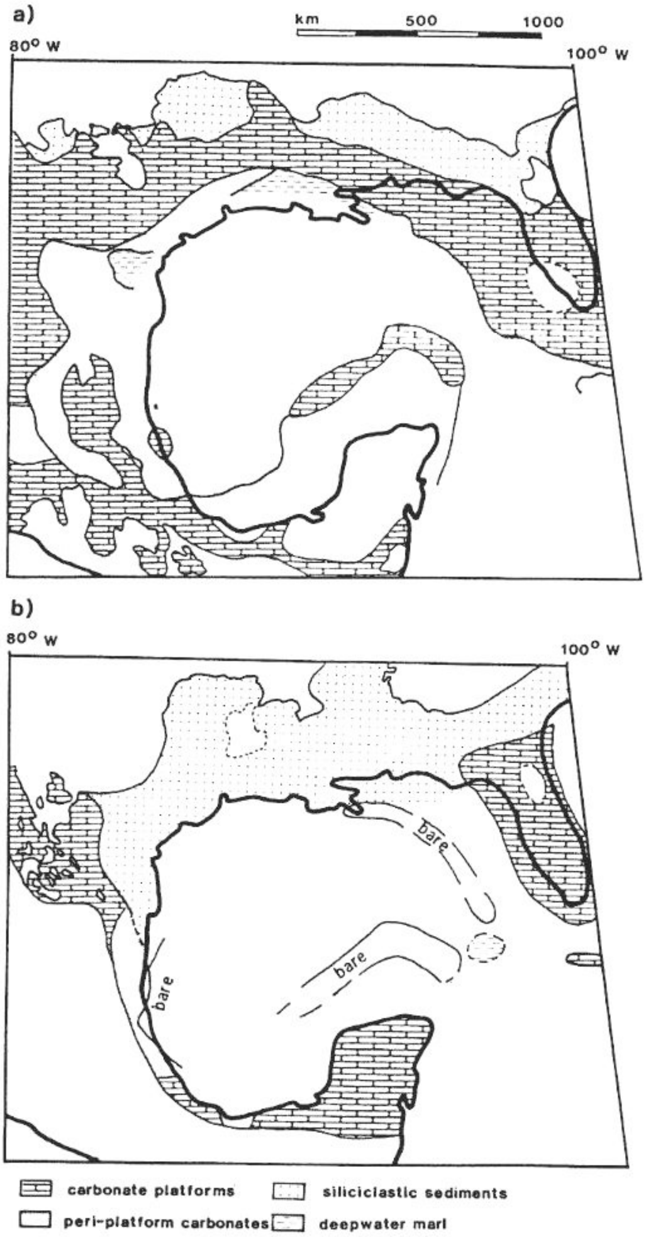


Figure 3 Mid-Cretaceous drowning of carbonate platforms around the Gulf of Mexico. **(a)** Palaeogeography of Mid-Aptian to Mid-Cenomanian: Gulf almost completely surrounded by carbonate platforms. **(b)** Palaeogeography of Mid-Cenomanian to top Turonian: platforms greatly reduced, former platform margins appear as bare submarine outcrops and siliciclastics dominate northern rim. After Cook and Bally (1975, modified) (from Schlager, 1989)

interior to join with the Western Interior seaway (*Figure 3b;* Cook and Bally, 1975; Schlager, 1989). The oldest Upper Cretaceous unit (Woodbine–Eagleford–Tuscaloosa) is a terrigenous clastic fluvio-deltaic and nearshore marine sequence that extends across the Early Cretaceous shelf edge, expanding in thickness across a series of growth faults that are the oldest predecessors of the Tertiary Gulf coast growth faults. Sediments overlying the Austin Group are generally chalky and marly, becoming more sandy eastward, whereas the younger Taylor and Navarro groups are terrigenous clastics that become increasingly calcareous eastward. Downdip from the Lower Cretaceous shelf edge, the Upper Cretaceous rocks are slope shales, except for the Tuscaloosa turbidites and some Woodbine slump blocks. However, the Upper Cretaceous is largely restricted to the Lower Cretaceous shelf in our study area. As will be shown, the Upper Cretaceous is extremely starved beyond the Middle Cretaceous shelf margin in the study area in the north-eastern Gulf of Mexico.

Cenozoic

The Cenozoic sediments are almost entirely terrigenous clastics, which prograded beyond the Early Cretaceous shelf margin to the present continental slope. Overall regressive basin-filling sequences comprise the sedimentary prism. These sequences typically consist of fluvial deposits represented by an inner deltaic massive sand and shale facies, a delta plain composed of delta fringe interbedded sand and shale facies, and a marine pro-delta consisting of outer shelf to continental slope shale facies (Curtis, 1987).

Thick overall regressive sequences were deposited during Late Palaeocene–Early Eocene (Wilcox), Mid to Late Oligocene (Frio), Miocene and Plio-Pleistocene times. The transgressive sequences were deposited during Mid-Eocene (Claiborne), Lower Oligocene (Vicksburg) and Upper Oligocene to Early Lower Miocene (Anahuac). The Cenozoic shelf margins (Martin, 1978; Winker, 1982) indicate the shifting of major depocentres in the northern Gulf of Mexico (*Figure 4*). They show that south-east of the Mississippi Delta there was very little Cenozoic sedimentation until the Miocene. As will be shown in this paper, the sediment accumulation was very slow until after the Middle Oligocene (*Foldout 1,* 30 Ma sequence boundary of Haq *et al.*, 1987).

During the Late Oligocene–Neogene phase of rapid sedimentation, more than 5 km of clastic sediments accumulated in the north-eastern Gulf of Mexico. The well developed sequences in the Gulf of Mexico allow the use of sequence stratigraphic methods to correlate the stratigraphy of the study area.

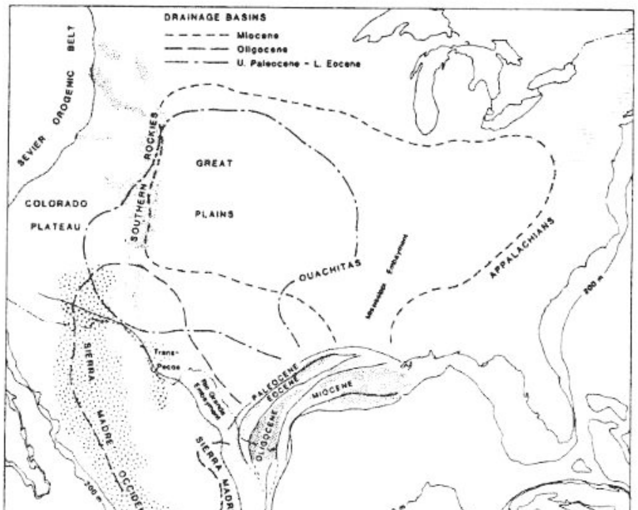


Figure 4 Some postulated Tertiary drainage basins of central North America in relation to major tectonic uplifts, volcanism and deltaic sedimentation. Inferred primarily from the correlation of tectonic and volcanic episodes with shelf-margin deltaic sedimentation and from general sandstone compaction (from Winker, 1982)

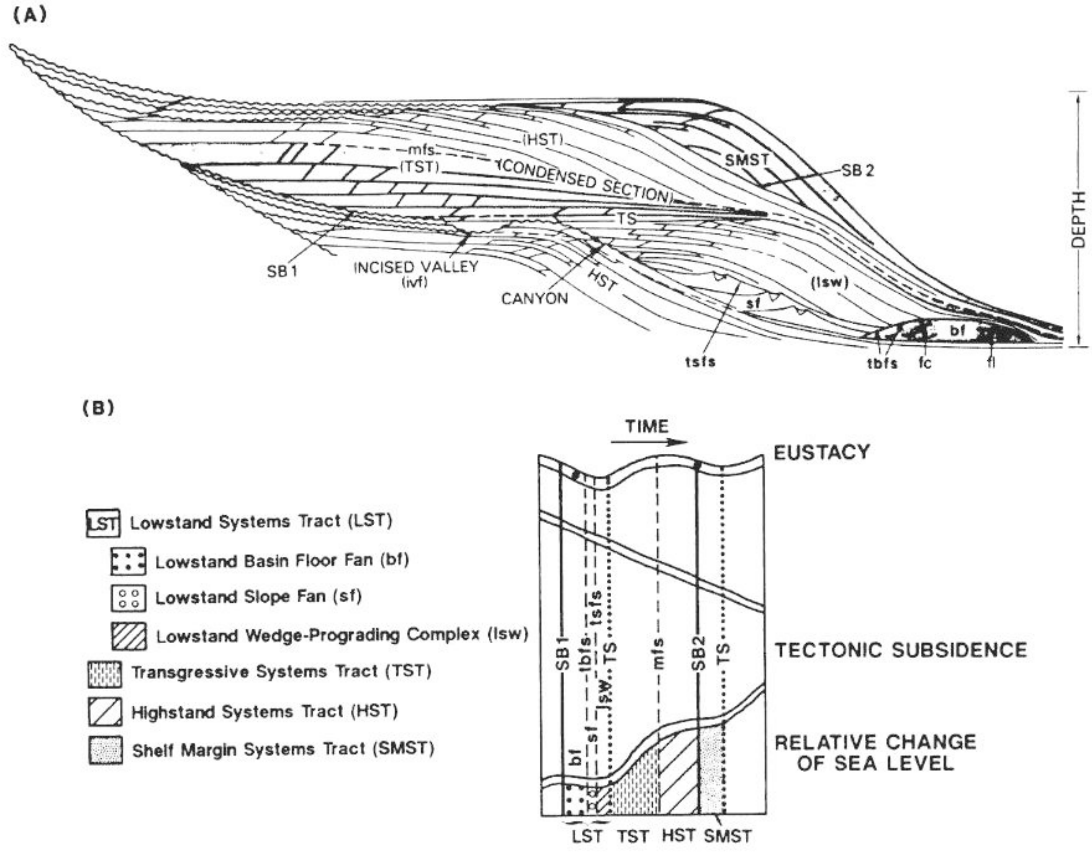
Sequence stratigraphy

Sequence stratigraphy concepts (Vail *et al.*, 1977; Haq *et al.*, 1987; and Vail, 1987) were applied in this study to correlate the geological events on well logs and seismic data. Sequence stratigraphy, along with biostratigraphic control, is the most effective way of correlating the stratigraphy of well logs and seismic profiles. This study does not try to document in detail sea level changes, but it uses sequence stratigraphy concepts to correlate the stratigraphy in the study area.

Basics of sequence stratigraphy

Sequence stratigraphy concepts have evolved mainly from the seismic stratigraphy studies of Vail *et al.* (1977). As defined by Van Wagoner *et al.* (1987): 'Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities. The fundamental unit of sequence stratigraphy is the sequence ... A sequence can be subdivided into systems tracts ...' 'Depositional sequences correlate throughout sedimentary basins and perhaps correlate globally. Particular sets of depositional processes and thus certain depositional environments and lithofacies are associated with particular system tracts' (Vail, 1987).

A sequence is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchum, 1977), which are called sequence boundaries. The sequence boundary is recognized by overlying regional onlap and truncation below. There are two types of sequence boundaries. A Type-1 sequence boundary is 'a regional surface' (SB 1 in *Figure 5A*, Vail, 1987) 'characterized by subaerial exposure and concurrent subaerial erosion associated with stream rejuvenation, a basinward shift of facies, a downward shift in coastal onlap, and onlap of overlying strata' (Van Wagoner *et al.*, 1987). A



LEGEND

SURFACES

(SB) SEQUENCE BOUNDARIES
(SB 1) = TYPE 1
(SB 2) = TYPE 2
(DLS) DOWNLAP SURFACES
(mfs) = maximum flooding surface
(tbfs) = top basin floor fan surface
(tsfs) = top slope fan surface
(TS) TRANSGRESSIVE SURFACE
(First flooding surface above maximum progradation)

SYSTEMS TRACTS

HST = HIGHSTAND SYSTEMS TRACT
TST = TRANSGRESSIVE SYSTEMS TRACT
ivf = incised valley fill
LST = LOWSTAND SYSTEMS TRACT
ivf = incised valley fill
lsw = lowstand wedge-prograding complex
sf = lowstand slope fan
bf = lowstand basin floor fan
fc = fan channels
fl = fan lobes
SMST = SHELF MARGIN SYSTEMS TRACT

Figure 5(A) Sequence stratigraphic cross-section and terminology. **(B)** Relationships of sequences and system tracts to relative sea level changes (from Vail, 1987)

Type-2 sequence boundary is 'a regional surface' (SB 2 in *Figure 5A*) 'marked by subaerial exposure and a downward shift in coastal onlap landward of the depositional-shoreline break' (Van Wagoner *et al.*, 1987). A sequence bounded below by a Type-1 sequence boundary and above by either a Type-1 or Type-2 sequence boundary is a Type-1 sequence. A sequence bounded below by a Type-2 sequence boundary and above by either a Type-1 or Type-2 sequence boundary is a Type-2 sequence.

A system tract is 'a linkage of contemporaneous depositional systems' (Brown and Fisher, 1977). System tracts are correlative chronostratigraphic units. A Type-1 sequence (*Figure 5A*) is composed of lowstand, transgressive and highstand systems tracts. A Type-2 sequence is composed of shelf-margin, transgressive and highstand systems tracts (*Figure 5A*). A lowstand system tract (*Figure 5A*) in a deep water setting consists of basin floor fan, slope fan and lowstand prograding wedge. A lowstand system tract is bounded below by a sequence boundary and above by a transgressive surface. A transgressive surface is the first flooding surface above the lowstand prograding wedge (*Figure 5A*). Top of slope fan and top of basin floor fan are usually downlap surfaces below the lowstand wedge and highstand system tract (*Figure 5A*). A shelf margin wedge system tract in a Type-2 sequence is bounded by a sequence boundary below and a transgressive surface above. A transgressive system tract is underlain by a transgressive surface or sequence boundary and above by a maximum flooding surface. A highstand system tract is bounded below by a maximum flooding surface or a sequence boundary and above by a sequence boundary. The depositional systems which comprise systems tracts are composed of fan-delta, carbonate-shelf, shelf-edge and slope systems (Brown and Fisher, 1977).

Sequences and systems tracts (*Figure 5A*) are due to the interaction of tectonic subsidence, sediment supply and eustatic sea level changes (Vail, 1987). Tectonic

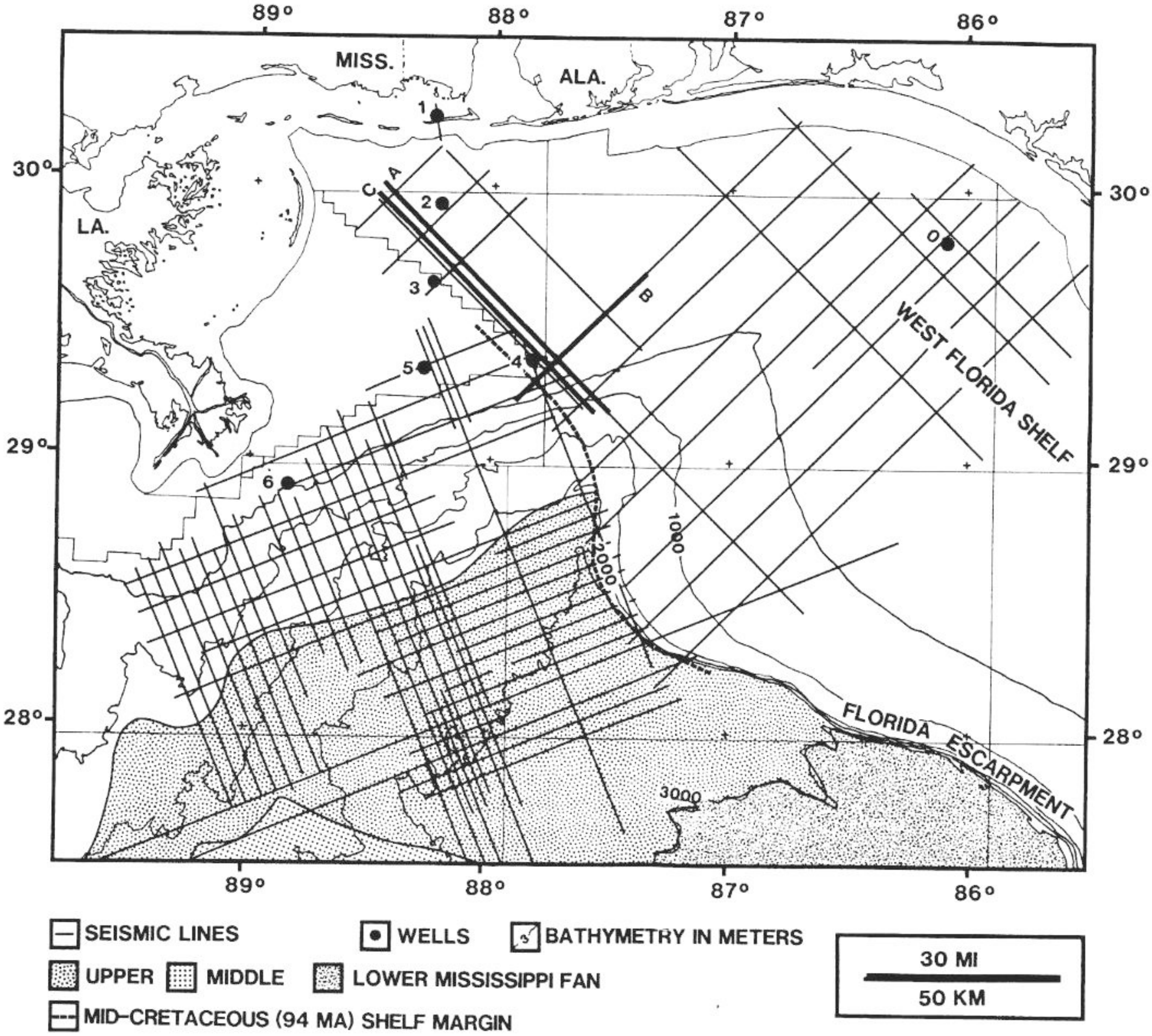


Figure 6 The index map of seismic lines and key well information used in this study. Locations of Line A-*Foldout 3;* Line B-*Foldout 4;* Line C-*Foldout 5.* The bathymetry is from the Regional Map of Eastern Gulf of Mexico of NOAA, U.S. Department of Commerce, 1986. The Mississippi Fan is from Moore *et al.* (1978). The wells on the map are: 0-Sun No. 1, Destin Dome block 166; 1-Mobil No. 1, Mississippi Sound block 72; 2-Chevron No. 1, Viosca Knoll block 30; 3-Shell No. 1, Main Pass block 154; 4-Shell No. 1, Main Pass block 253; 5-Chevron No. 2, Main Pass block 264; and 6-Exxon No. 1, Main Pass block 67

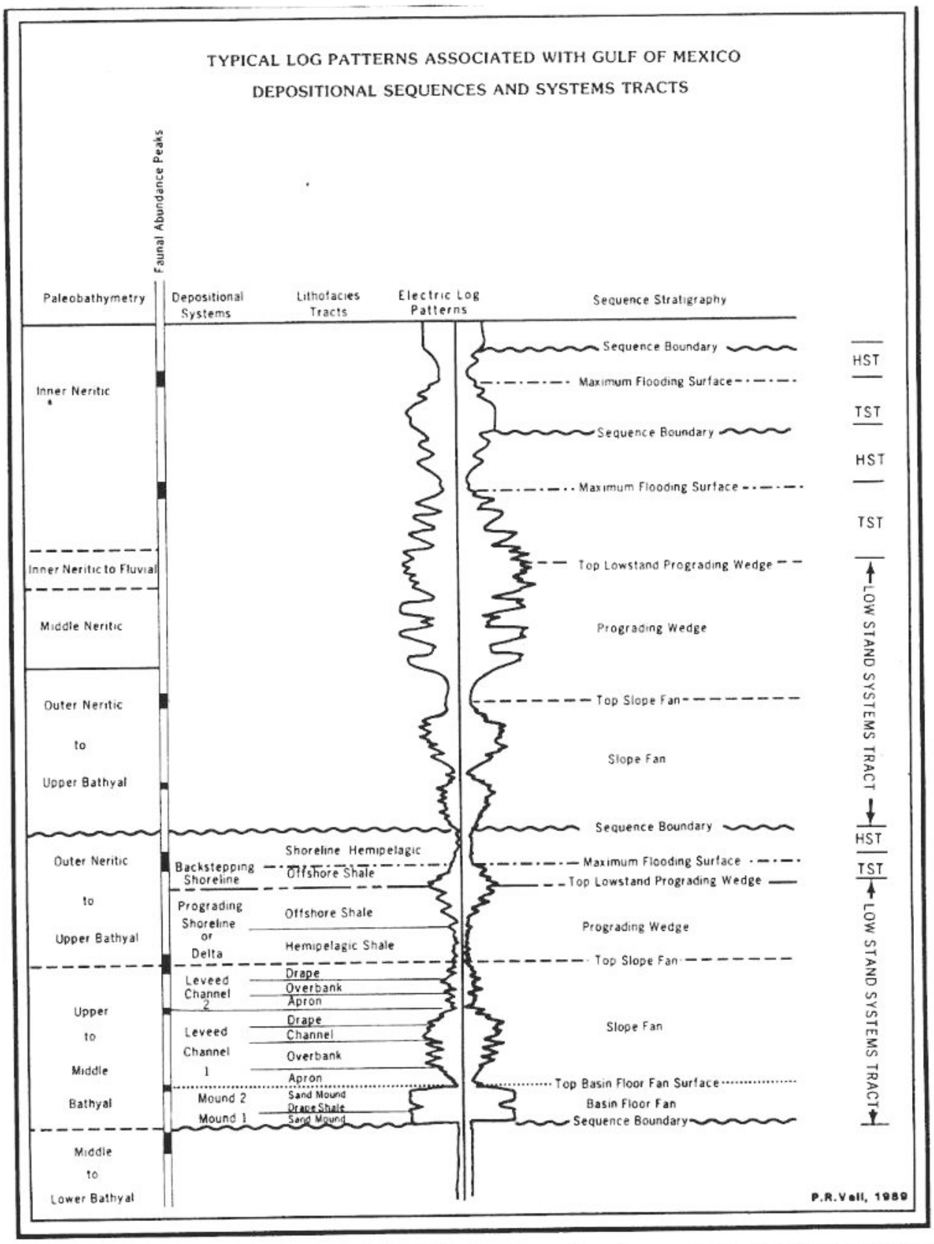


Figure 7 Typical electric log patterns associated with Gulf of Mexico depositional sequences and system tracts (Vail, 1989)

subsidence and eustacy provide the space for the sediments. Tectonic subsidence in any particular basin creates the accommodation for the sediments and amplifies the major transgressive and regressive cycles of lithofacies in the basin. Eustacy dominates the formation of sequences and systems tracts. Sequence and system tract boundaries bound chronostratigraphic intervals caused by changes of eustatic sea level (*Figure 5B*). A sequence boundary corresponds to the start of a relative fall of sea level. When relative sea level starts to rise rapidly following the fall and lowstand, a transgressive surface is formed. The maximum flooding surface represents the time of maximum landward extent of marine sediments. The intervals between these surfaces are the systems tracts (*Figure 5B*).

Sequence stratigraphy offers an objective criterion for chronostratigraphic correlation by relating stratal geometries, vertical facies and log patterns observable on seismic and well log sections to physically definable chronostratigraphic events. Physically definable sequence stratigraphic units calibrated by biostratigraphy provide the best stratigraphic correlation of well logs and seismic profiles. The integrated sequence stratigraphic analysis using well logs, biostratigraphic information, lithostratigraphic information and seismic data can be used to date structural history and to predict lothology. The Mesozoic–Cenozoic Cycle Chart of Haq *et al.* (1987) is the main sequence stratigraphic reference for this study.

Sequence stratigraphic correlations

Sequence stratigraphic correlations in this paper are based on seismic data, well logs, biostratigraphic information and published sources. *Figure 6* shows the seismic profiles and the key wells used in this study. A tentative correlation of general stratigraphy of the north-eastern Gulf of Mexico with sequence stratigraphy in the study area is shown in *Foldout 1*. The correlation is based on the Mesozoic–Cenozoic Cycle Chart (Haq *et al.*, 1987), the Gulf Coast Regional Correlation Chart (Huddlestun *et al.*, 1988), the Gulf

Coast Cenozoic Stratigraphic Chart (PI Exploration Systems, 1989) and the data base of this study.

The standard chronostratigraphy of each of the above-mentioned charts differs from the accepted chronology of worldwide nannofossil and planktonic foram biostratigraphic zones. Even greater differences are found in the numerical age scale in millions of years on each chart, indicating some fundamental problems in stratigraphic precision which are beyond the scope of this study. The Mesozoic–Cenozoic Cycle Chart of Haq *et al.* (1987) is taken as standard for all the correlations in this study. The standard chronostratigraphy, planktonic and nannofossil biostratigraphic zonation, sequence chronostratigraphy and eustatic curves in *Foldout 1* are adopted directly from the Mesozoic–Cenozoic Cycle Chart (Haq *et al.*, 1987). The North American chronostratigraphy from the Gulf Coast Region Correlation Chart (Huddlestun *et al.*, 1988) is correlated to the Mesozoic–Cenozoic Cycle Chart using the biostratigraphic zonation and standard chronostratigraphy with some adjustments (see *Foldout 1* for details). The position of Gulf Coast/Gulf of Mexico benthic foraminifera zones are adopted from the Gulf Coast Cenozoic Correlation Chart (PI Exploration Systems, 1989).

Sequence stratigraphic interpretations on well logs

Sequence boundaries and flooding surfaces (*Foldout 1*) corresponding to major sea level fluctuations are interpreted and correlated on both well logs and seismic data. *Figure 7* (Vail, 1989) shows the relationship of electric log patterns and the boundaries of sequences and system tracts in different environments for the northern Gulf of Mexico.

The principal well log reference section (*Foldout 2*) across the shallow water study area is correlated using sequence stratigraphy concepts and the correlation standard shown in *Foldout 1*. Only sequence boundaries and a few major Maximum Flooding Surfaces are shown on this cross-section. The biostratigraphic information and lithologic tops used in the correlation and their relationship to the correlated sequences for each well are summarized in *Tables 1A* and *B*. Check shot velocities and/or synthetic seismograms were available for the wells shown on the cross-section in *Foldout 2*. The correlation is based on the best fit of all the available information.

Sequence stratigraphic interpretation on seismic profiles

The sequence stratigraphic interpretation on our

(A)

Correlated Sequence Boundaries (Ma)	Viosca Knoll Block 30 Chevron #1 (A)	Main Pass Block 253 Shell #1 (A)	Main Pass Block 264 Chevron #2	Mississippi Canyon Block 67 Exxon #1 (A)
				• T.A.
0.8				• A.B.
1.6			• In L.1 (B)	• L.1
2.4				• B. N.
3.0			• B.1 (B)	
3.8			• In B.1 (B)	• B.1
4.2			• T.X. (?) (B)	• T.X
5.5	• B.A.			
6.3	• D.12		• T.6 D.12 (B)	
8.2	• T.L.		• B.2 (B)	
10.5	• G.F.F.	• G.F.F		
13.8	• G.F.B.	• G.F.B	• C.I. • G.F.B. (A)	
15.5			• C.D. (A)	
21				
22	• HET.			
25.5		• G.O.O.	• G.S. (A)	
30	• Jackson	• Vicksburg Claiborne • G.L.	G.B.(Claiborne) • (A)	
39.5	In Basal Claiborne •	• Wilcox	• Wilcox (A)	
49.5	• Midway	Midway •	• G.C. (A)	
58.5	• Taylor	• G.P.B. Basal • Navarro	• Midway •Navarro (A)	
68				

Abbreviations

- A.B.-Angulogerina B
- B.A.-Bigenerina A
- B.N.-Basal Nebraskan
- B.1-Buliminella 1
- B.2-Bigenerina 2
- C.D.-Catapsydrax dissimilis
- C.I.-Cristellaria K
- D.12-Discorbis 12
- G.B.-Globorotalia barisanensis
- G.C.-Globorotalia chapmani
- G.F.B.-Globorotalia foshi brisanensis
- G.F.F.-Globorotalia foshi foshi
- G.L.-Globorotalia lehneri
- G.O.O.-Globorotalia opima opima
- G.P.B.-Globorotalia pseudobulloides
- G.S.-Globorotalia sellii
- HET-Heterostegina SP
- L.1-Lenticulina 1
- T.A.-Trimosina A
- T.L.-Textularia L
- T.X.-Textularia X
- T.6-Textularia 6

Note:

Biostratigraphy from
A-Paleo-Data, Inc.
B-MMS,U.S. Dept. of the Interior

Table 1(A) See overleaf for caption

(B)

Correlated Sequence Boundaries (Ma)	Destin Dome Block 166 Sun #1 B	Mississippi Sound Block 72 Mobile #1 C	Viosca Knoll Block 30 Chevron #1 A	Main Pass Block 253 Shell #1 A	Main Pass Block 264 Chevron #2 A
	• B. Navarro				
68					
	• Selma (Taylor) G.E.				
80	• U. Eutaw (Austin) G.C.		• Austin		• Austin M.C.
	L. Eutaw • (Eagleford) (?)		Eagleford •		
90					
	• Tuscaloosa • R. C.		• M.H.		• Eagleford M.H. • Woodbine R.T.
93				• In Washita (?)	
94					
	• Washita (?) • Fredericksburg • Paluxy	• In Washita • Fredericksburg	• Washita		
98		• Paluxy			
	• Trinity (?) In Trinity • O.T.	• Ferry Lake			
108.5	• Sligo				
	• In Jurassic (?) E.M.				
112		• Hosston			
		Cotton Valley •			
128.5					
	(Anhydrite & greenshale) •				
144	• (Oolitic Ls.)	• Smackover			
150.5	• Top Salt	• Norphlet			

Abbreviations

E.M.-Epistomina Mosquensis
G.C.-Globotruncana carinata
G.E.-Globotruncana elevata
M.C.-Marginotruncana concavata
M.H.-Marginotruncana helvetica
O.T.-Orbitolina Texana
R.C.-Rotalipora cushmani
R.G.-Rotalipora greenhornensis

Note:
Biostratigraphy from
A-Paleo Data, Inc.
B-MMS,U.S. Dept. of the Interior
C- Total Minatome Corp.

Table 1(A) Biostratigraphic information for Cenozoic sequences. Dots (·) represent approximate relative position of palaeo horizons and formation tops from the well logs with respect to the proposed sequence boundaries. For example, the relative positions of the top of Midway varies from well to well with respect to sequence boundary 58.5 Ma. **(B)** Biostratigraphic information for Mesozoic sequences. Dots (·) represent approximate relative position of palaeo horizons and formation tops from the well logs with respect to the proposed sequence boundaries

seismic profiles is based on the procedures described by Vail (1987). The physical geometrical relationships of seismic reflections shown in *Figure 5A* are the criteria used to interpret the sequence and systems tracts on seismic data. The seismic reflectors are tied through velocities and/or synthetic seismograms to the sequences interpreted on the well logs. Adjustments are made iteratively to interpretations on well logs and seismic profiles until all the available information and interpretations are fitted to a coherent interpretation.

Sequence boundaries (*Foldout 1*) are interpreted and correlated on seismic profiles used for this study and tied to well information. Major flooding events are correlated on some of the seismic profiles which are represented as line drawings in *Foldouts 3–5*. Sequences as well as systems tracts (Vail, 1987) are interpreted only on the seismic example in *Foldout 5*. In this seismic example, ages of sequences younger than 5.5 Ma are based solely on a speculative correlation of stratal geometries seen on the seismic profiles with the Mesozoic–Cenozoic Cycle Chart of Haq *et al.* (1987), as for this interval there was not enough biostratigraphic information.

The sequence boundaries at the base (155.0 Ma or BS) and top (150.0 Ma or TS) of Jurassic autochthonous salt, Middle Cretaceous (94 Ma or TLC), Middle Oligocene (30.0 Ma or TMO), top Lower Miocene (15.5 Ma or TLM), top Upper Miocene (5.5 Ma or TUM) and top Pliocene (1.6 Ma or TP) and Middle Cretaceous Flooding Surface (91.5 Ma, MCFS) are correlated throughout the entire study area to serve as key horizons for the structural interpretations discussed in the following paper of this issue. The remaining sequence boundaries in *Foldout 1* are only correlated across the shelf areas.

Middle and Late Jurassic sequences

The oldest sequence boundary correlated in this study is the base of the Werner anhydrite formation. It is correlated with the 158.5 Ma sequence boundary

(*Foldout 1*). This regional surface is underlain by angular unconformities observed on some of the seismic data in Destin Dome area. The base of Werner formation, given our relatively poor seismic resolution, is a relatively smooth surface without striking changes in topography except at the north-eastern edge of the Middle-Jurassic salt basin (see Wu *et al.* (1990) for seismic examples). Note that elsewhere in the Gulf the Werner Anhydrite fills a topographically irregular surface (Milliken, 1988). The base Werner is a correlative surface (*Foldout 3*) with overlying evaporite deposits uniquely recognizable on seismic profiles in most of the area. In our study there is no direct biostratigraphic information that would help to date this surface. On our seismic profiles the base of Louann Salt (155.5 Ma, *Foldout 1*) is indistinguishable from the Werner (158.5 Ma; *Foldouts 1, 3* and *4*).

The next sequence boundary correlated is the top of Louann Salt. It is correlated with the 150.5 Ma sequence boundary (*Foldout 1*). This surface is encountered by wells drilled into the Louann Salt. Mobil No. 1 in Mississippi Sound Block 72 and Sun No. 1 in Destin Dome Block 166 provide the control for the top of the Louann Salt. The top of Louann Salt in the study area is often overlain by the Norphlet sand. The base of the Norphlet is correlated to be a sequence boundary formed at 150.5 Ma. This surface appears to be affected by syndepositional salt tectonism and is a faulted and an undulating surface with varying reflection strength on seismic profiles.

Both the base of Werner (158.5 Ma or BS surface on interpreted seismic lines) and the top of Louann Salt or base of Norphlet [150.5 or Top Salt (TS) on interpreted seismic lines] are correlated throughout the entire area. In between these two sequence boundaries, seismic data show a zone of random reflections with occasional internal reflections. This is particularly typical for the deep water area where the salt is relatively thick. Reflections within the salt suggest some layering within the evaporites.

The top of Smackover formation is correlated to the 144 Ma sequence boundary (*Foldout 1*). It is an erosive surface with onlap often broken by normal faults associated with salt rollers (*Foldouts 3* and *4*). Evidence for downlap on to this surface presumably represents the flooding event following the 144 Ma sea level fall. This sequence boundary is penetrated by Mobile No. 1 and Sun No. 1 wells. The Smackover thins rapidly basinward from approximately 0.7–0.15 s in two way reflection time or about 1600–350 m (*Foldout 4*). A number of salt rollers formed during this interval in the study area on the shelf (*Foldouts 3* and *4*).

The Jurassic ended with a major sea level fall at 128.5 Ma (*Foldout 1*). The top of the Cotton Valley group is correlated to this 128.5 Ma sequence boundary. According to Todd and Mitchum (1977) there is an approximately 7 × 10^6 year hiatus between this sequence boundary and the base of Hosston formation (Hauterivian). This sequence boundary is penetrated by the Mobil No. 1 and Sun No. 1 wells (*Foldout 2*). On seismic profiles, it is a distinct reflector underlying the Middle Cretaceous shelf with coastal onlap on to the shelf margin (*Foldouts 3* and *4*). A downdip wedge at the Late Jurassic shelf margin is interpreted to be formed during the lowstand of sea level and is recognizable in *Foldouts 3* and *4*.

Lower Cretaceous sequences

The sequence boundary of 112 Ma is correlated to the top of Hosston in the study area. Regional onlaps are observed on this boundary in the study area (*Foldout 4*). The sea level fall at 108.5 Ma is interpreted to have formed a sequence boundary in the upper Rodessa formation. Regional onlaps are associated with this surface at the 108.5 Ma shelf margin (*Foldout 4*). The sequence boundary of 98 Ma is correlated to the top of Paluxy formation in the study area. It is also a surface with regional onlap at the shelf margin.

The Fredericksburg and Washita groups are usually not differentiated in the available wells from this study area. The top of the Washita group is correlated to the 94 Ma sequence boundary on the Middle Cretaceous shelf (*Foldouts 1, 3* and *4*). In some places along the Florida Escarpment this surface is sometimes not covered by succeeding sediments due to the steep carbonate platform margins (*Figures 2B* and *3b*).

Middle Cretaceous Flooding Surfaces

According to Haq *et al.* (1987) the Lower Cretaceous is terminated by a rapid sea level fall at 94 Ma (*Foldout 1*) followed by two major rises of sea level culminating at 93.5 and 91.5 Ma. These maximum flooding surfaces are correlated throughout our study area and may be observed on seismic profiles in shallow and deep water areas. The sediments associated with the two flooding events coalesce into a major condensed section in the deep Gulf of Mexico. This condensed section may be followed throughout the Gulf of Mexico as a strong band of reflectors (top of Challenger unit of Shaub *et al.*, 1984). The Cenomanian flooding event culminated at 93.5 Ma and is correlated to the 'marine Tuscaloosa' formation (*Foldout 1*). The base of the Eagleford formation is correlated to the 91.5 Ma maximum flooding surface. Six wells used in this study penetrated the 93.5 and 91.5 Ma maximum flooding surfaces (*Foldout 2*). On seismic profiles the 93.5 Ma maximum flooding surface is not particularly clear as a downlap surface because the interval of marine Tuscaloosa is very thin in our area. However, the maximum flooding surface is clearly associated with a shaly section on the well log cross-section above the 94 Ma sequence boundary (*Foldout 2*). The 91.5 Ma maximum flooding surface is easily recognized on seismic profiles (*Foldouts 3* and *4*) as a downlap surface over the Middle Cenomanian carbonate platform. It is also recognized along parts of the Florida Escarpment and the deep water Gulf of Mexico as a surface which is apparently onlapped by Tertiary deep water siliciclastic turbidites. The onlapping Tertiary and Quaternary corresponds to the toes of the Tertiary slopes and basinal sediments that are derived from the north (south-east Louisiana, Alabama, Mississippi) as shown by Martin (1978), Winker (1982; and *Figure 4*) and Shaub *et al.* (1984 and *Figure 8*).

Addy and Buffler (1984) also correlate the top of Washita of the Middle Cenomanian carbonate platform to the 94 Ma sea level fall (the 97 Ma sequence boundary in Vail *et al.*, 1977 was subsequently changed to 94 Ma on Haq *et al.*, 1987). However, the Middle Cenomanian Unconformity (MCU of Buffler *et al.*, 1980; Buffler, 1983) beyond the Middle Cenomanian platform margin does not correlate with the 94 Ma sea level fall but with the Turonian 91.5 Ma (MCFS)

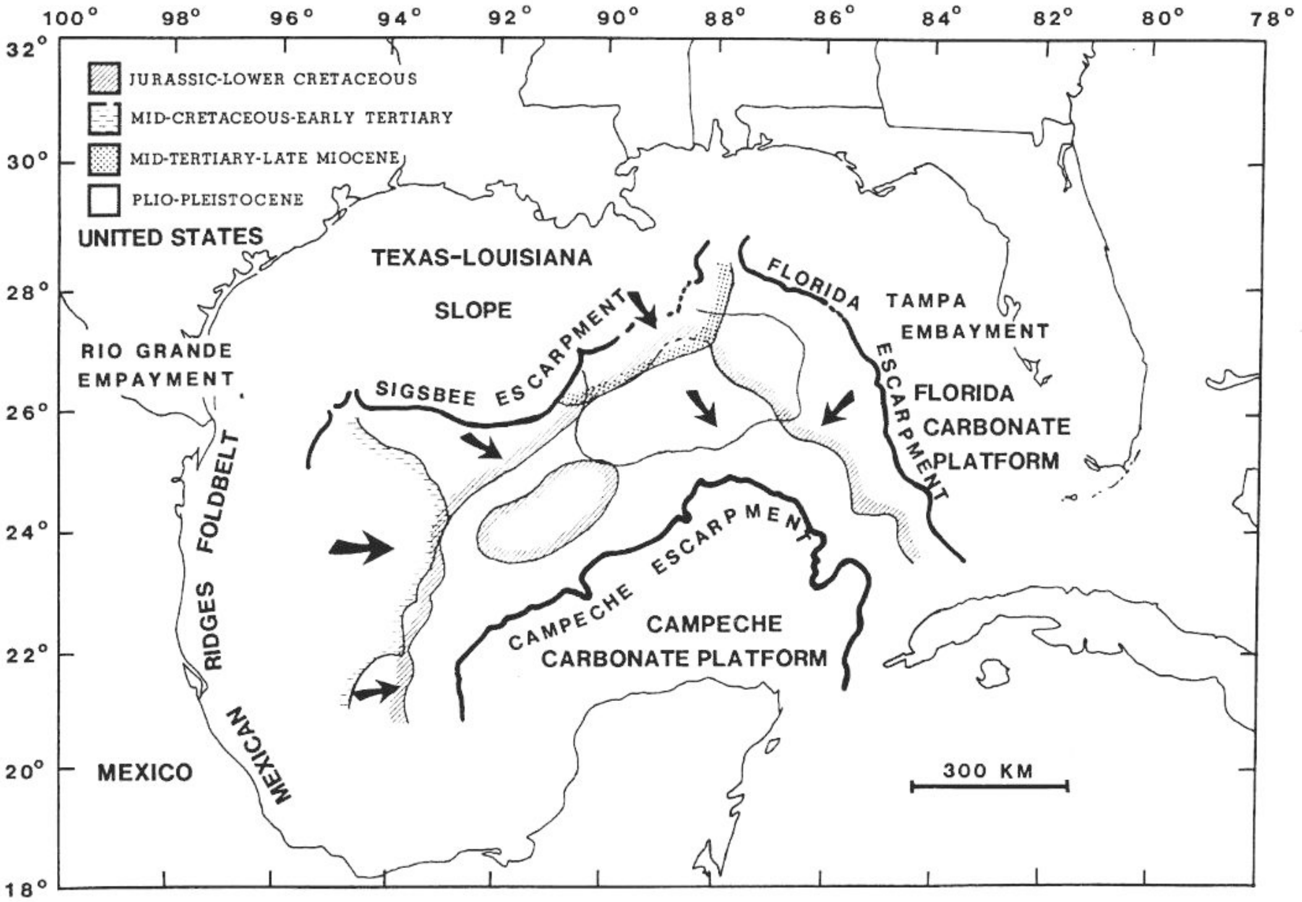


Figure 8 Deep Gulf of Mexico depocentres and inferred directions of sediment supplies, adapted from Shaub *et al.* (1984). The shaded boundaries enclose the areas that have isopachs greater than 2 km. Sediments came from carbonate platforms during the Jurassic–Lower Cretaceous; from the west (Cordilleras) during Middle Cretaceous–Early Tertiary; from north (Mississippi) during Middle Tertiary to Late Miocene; and from north (Mississippi) during Plio-Pleistocene

maximum flooding surface according to this study. Schlager (1989) interprets the Middle Cretaceous platform margin as a submarine onlap surface separating Middle Cretaceous carbonates from onlapping Late Cretaceous and Tertiary sediments. Schlager (1989) calls this surface a 'drowning unconformity' and states that 'the drowning unconformity is a sequence boundary formed by a change in sediment source' and states that 'These drowning unconformities are related to a rise or a highstand of sea level, yet they resemble the classic lowstand unconformity in geometry'. In the case of eastern Gulf of Mexico, Schlager's drowning unconformity is interpreted in this study as coeval to the maximum flooding surface (91.5 Ma, Haq *et al.*, 1987) and does not correspond to the Middle Cretaceous 94 Ma sequence boundary (or the MCU of Buffler *et al.*, 1980). Thus we prefer to refer to the Middle Cretaceous Flooding Surface instead of the Middle Cenomanian Unconformity of Buffler *et al.* (1980). *Figure 9* summarizes the seismic and well information associated with the major Middle to Upper Cretaceous sequence boundaries and maximum flooding surfaces of Haq *et al.* (1987; *Foldout 1*). *Figure 10* schematically shows the evolution of the geometries associated with the Middle Cretaceous Flooding Surface along the Florida Escarpment.

The apparent onlap along the Florida Escarpment (*Figure 10*) is the termination geometry formed by 'sidelapping' of the basinward end of various lowstand and highstand deposits to a drowned platform margin. The isopach maps made by Shaub *et al.* (1984; and *Figure 8*) clearly show the terminations of sediments against the Florida Escarpment. The source of sediment supply was from the Florida carbonate platform only before the MCFS (*Figure 8*). The postulated sequence boundaries (93 and 94 Ma) associated with the Cenomanian sea level fall are below the flooding surface (MCFS, 91.5 Ma, Haq *et al.*, 1987) as shown clearly on the well log cross section (*Foldout 2*).

Upper Cretaceous sequences

The 94 Ma sequence boundary separates Lower Cretaceous carbonates from increasingly more siliciclastic Upper Cretaceous sediments. The regional unconformity (Huddlestun *et al.*, 1988) at the top of Eagleford (or Tuscaloosa, eastern Gulf time equivalent of Eagleford) is correlated to the 90 Ma sequence boundary of Haq *et al.* (1987; *Foldout 1*). *Foldout 2* shows six wells drilled through this surface. Only the basinward continuation of this sequence boundary occurs in our study area and it is therefore relatively conformable on seismic sections. The 90 Ma sequence boundary merges on to and becomes conformable with the 91.5 Ma MCFS on the Middle Cretaceous platform (*Foldout 3*). In the deep water study area, it is believed that condensed pelagic sediments were deposited during this interval.

The top of Austin group (or Eutaw formation of the

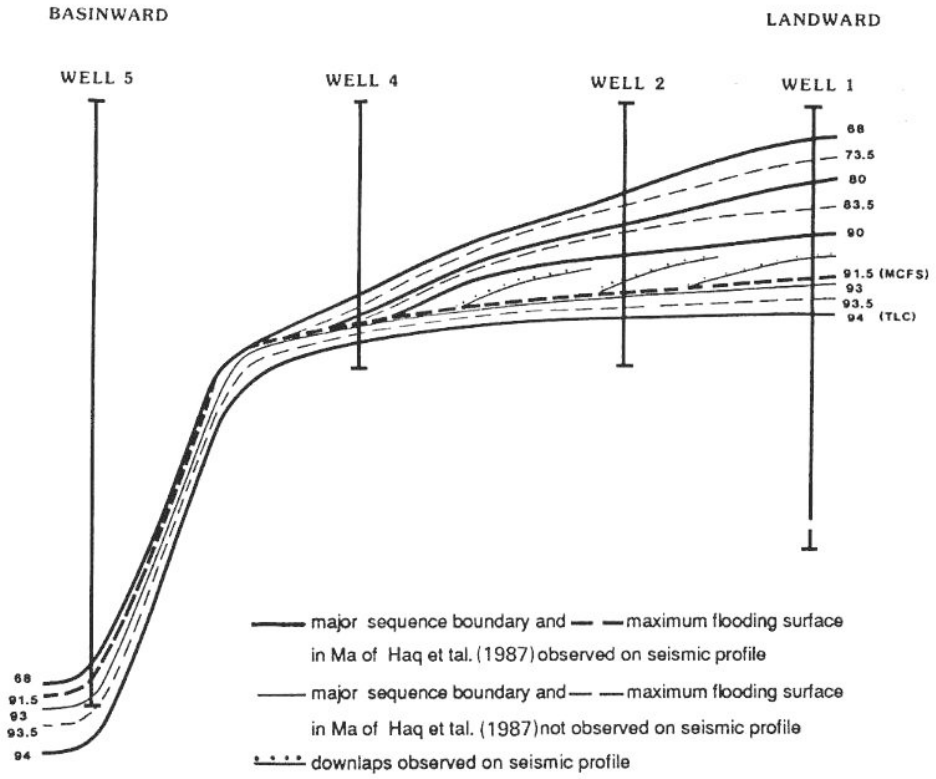


Figure 9 Summary of seismic and well information associated with Middle–Upper Cretaceous sequence boundaries and maximum flooding surfaces at the Middle Cretaceous shelf margin. Schematic well locations are shown on the section. See *Figure 6* for location of the wells

eastern Gulf) is correlated to the 80 Ma sequence boundary (Haq *et al.*, 1987; *Foldout 1*). It merges on to the MCFS near the Mid-Cretaceous shelf margin (*Foldout 3* and *Figure 9*). Six wells used in this study penetrated this surface (*Foldout 2*). Chalk and shale dominate in the Eutaw formation. The 68 Ma sequence boundary is correlated to the regional unconformity near the top of Selma group (or the top of Navarro group, *Foldout 1*). This surface is shown as a regional unconformity by Huddlestun *et al.* (1988). Six wells in the study area provide good control on the age of the sequence boundary (*Foldout 2*). On seismic profiles, the unconformity is displayed as an erosional surface. There was a major flooding event at 66 Ma above the 68 and 67 Ma (not correlated) sequence boundaries as shown on the well log cross-section (*Foldout 2*). However, in the study area and within the resolution of the available seismic data, the top of Selma group or top of Cretaceous is more easily recognized in most of the study area as a downlap surface representing the 66 Ma flooding event (*Foldout 3*). The Upper Cretaceous sediments thin out in the basinward direction and become starved in the deep water area (*Foldouts 2–4* and *Figure 9*).

Palaeogene sequences

The Palaeogene sequences are palaeontologically controlled by the wells shown on *Foldout 2*. Typically, the Palaeogene sequences are thin as the major depocentres were located far away in the western Gulf of Mexico (e.g., Martin, 1978; Winker, 1982). The 58.5 Ma sequence boundary is correlated to the top of the Midway group (*Foldouts 1–3*). There are five wells that provide control of this surface in our study area. Regional onlaps are developed on this sequence boundary as shown in *Foldout 3*. Basinward shifts of the Palaeogene sequences are observed. The Midway group downlaps on to and becomes conformable with the 66 Ma flooding surface in the basinward direction of the study area. The downlaps are clearly visible on examples in *Foldouts 3* and *5*.

The top of the Wilcox group is correlated to the 49.5 Ma sequence boundary (Haq *et al.*, 1987). The Wilcox group is thin in the study area as the depocentre was far from the study area in the western Gulf of Mexico (e.g., Martin, 1978; Winker, 1982). The top Claiborne is correlated to the 39.5 Ma sequence boundary on which regional onlaps are observed on seismic data. The Jackson group is thin in the study area and so it has not been correlated on seismic profiles. However, the top of Jackson is a regional unconformity (Huddlestun *et al.*, 1988) and correlates to the 36 Ma sequence boundary. The regional base of the Vicksburg shale is correlated to the 35 Ma maximum flooding surface.

Beginning with the 91.5 Ma Mid-Cretaceous flooding event of Haq *et al.* (1987), typically thin and condensed Upper Cretaceous and Palaeogene sediments were deposited in the deep water areas beyond the Middle Cretaceous shelf margin (*Foldouts 2–4*). Following the major sea level fall at 30 Ma and the subsequent shifting of depocentres towards the study area (Winker, 1982), the rate of sedimentation changed significantly in the study area. Six wells used in this study penetrated the 30 Ma sequence boundary (*Foldout 2*). The 30 Ma sequence boundary is a regional erosional surface that cuts into older sediments, particularly so at the shelf margin (*Foldouts 2* and *3*). Regionally, the surface can be correlated on both seismic profiles and well logs. The 30 Ma sea level fall caused a major Middle Oligocene basinward shift of 30–25.5 Ma lowstand wedges throughout the area (*Foldout 5*).

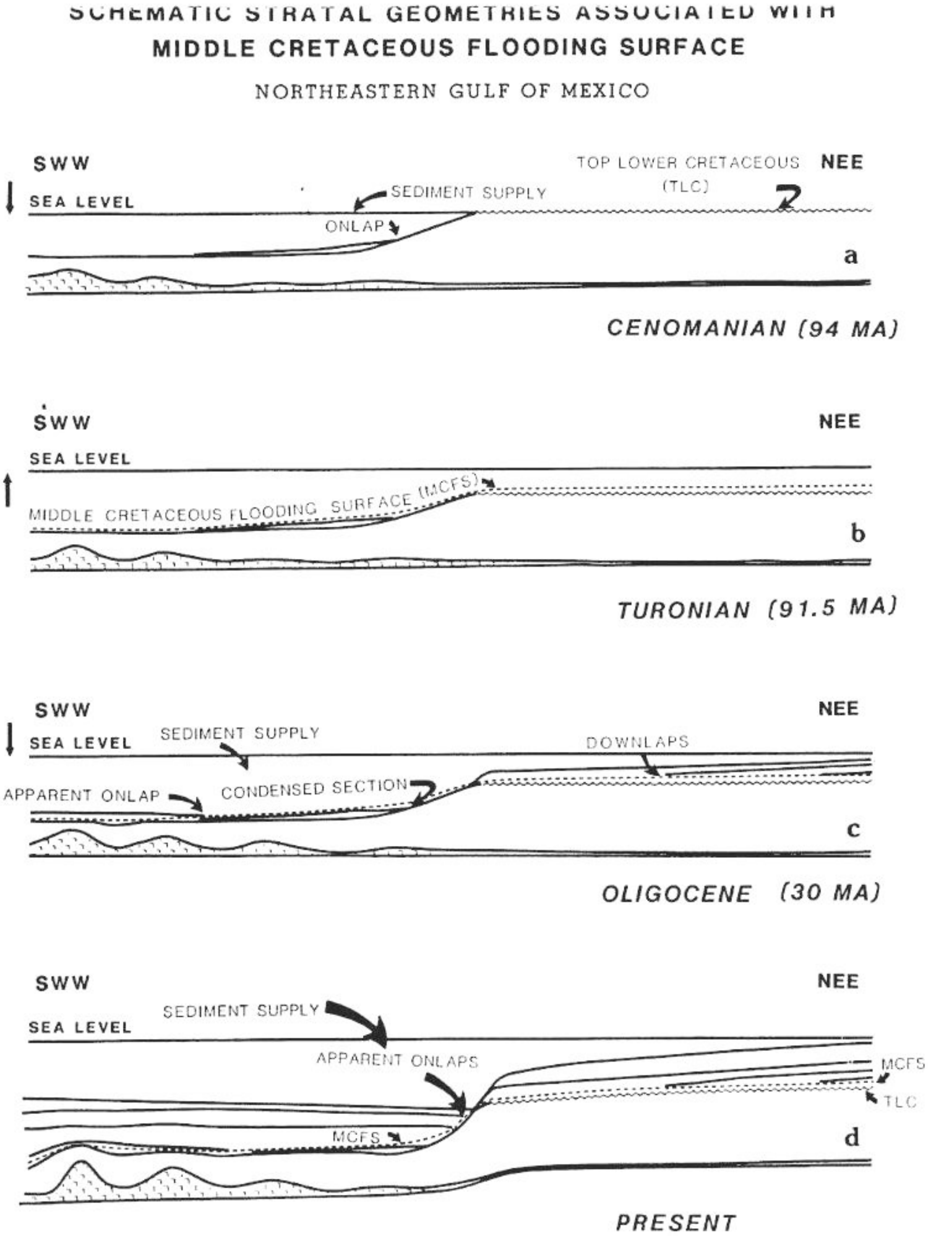


Figure 10 Schematic stratal geometries associated with Middle Cretaceous Flooding Surface along the Florida Escarpment. **(A)** 94 Ma sea level fall and widespread development of unconformity and lowstand deposit. **(B)** Middle Cretaceous Flooding events culminated at 93.5 and 91.5 Ma and formed widespread Middle Cretaceous Flooding Surface (MCFS, 91 Ma). **(C)** Progradation and aggradation of sediments on pre-MCFS shelf and carbonate platform and condensed sedimentation in the deep water study area. (D) Late Oligocene–Holocene sediment fill deposited in the deep water study area. Apparent onlaps formed by terminating the toe of prograding slope and Mississippi Fan against the MCFS

Neogene–Holocene sequences

Most of the Neogene–Holocene sequences (Haq *et al.*, 1987) are calibrated by wells and can be correlated over much of the Gulf of Mexico using good biostratigraphy (*Foldouts 1* and *2*). The Neogene–Holocene sequences are also well documented on seismic profiles (e.g. *Foldouts 3–5*).

The study area is an example of the global 'stratigraphic signature of the Neogene' (*Figure 11*; Vail *et al.*, 1989; Bartek *et al.*, in press) during this time interval. The correlation between the stratal geometries on *Foldout 5* and *Figure 11* can be readily seen. The lack of well developed Lower and Middle Miocene sequences (25.5–10.5 Ma) on the Alabama shelf is attributed to a relative highstand during this interval (Haq *et al.*, 1987) and insufficient sediment supply to the region. Depocentres were located to the west and landward of the shallow water study area during Lower and Middle Miocene time (Martin, 1978; Winker, 1982; Greenlee, 1988). Typically a general aggradational stratal geometry is observed from 25.5 to 21 Ma. The flooding event at 24.8 Ma is represented by the deposition of a shale section (Anahuac) in Lowest Miocene. During 21–13.8 Ma, there was a period of flooding and sediment starvation on the Alabama shelf. Another significant flooding event culminated at 16 Ma. Basinward thickening by progradation is shown during 13.8–10.5 Ma interval. A progradational pattern can be seen between the 15.5 and 10.5 Ma sequence boundaries. Upper Miocene and Plio-Pleistocene sequences are very well developed due to the increased sediment supply (e.g. Martin, 1978 and Winker, 1982)

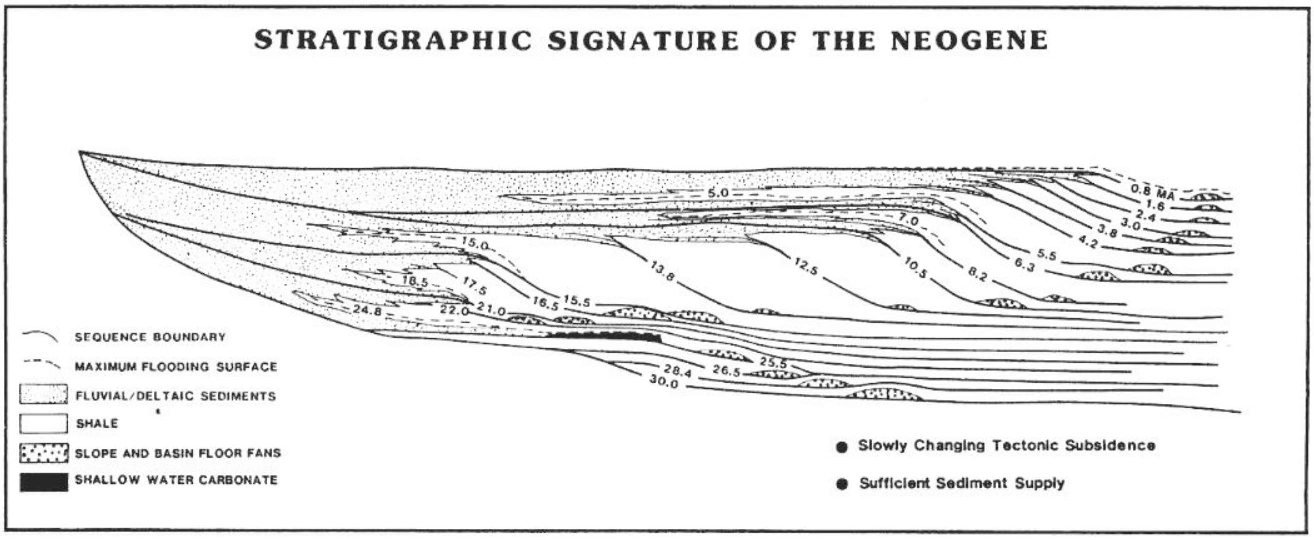


Figure 11 Stratigraphic signature of the Neogene: (1) Lower Oligocene landward thickening; (2) Upper Oligocene wedge, which laps out at or near the shelf margin and thickens basinward; (3) basal Lower Miocene flooding; (4) Lower Miocene (Aquitanian) aggradation, commonly ending with lowstand deposits; (5) Lower Miocene (Burdigalian) aggradation, commonly ending with major lowstand deposits; (6) Middle Miocene (Langhian and lower most Serravallian) flooding; (7) Middle Miocene (Serravallian) major progradation; (8) end of Middle Miocene major downward shift of onlap and lowstand deposits; (9) Upper Miocene aggradation commonly ending with lowstand deposits; (10) lowermost Pliocene flooding; (11) Pliocene–Lower Pleistocene aggradation with multiple lowstand deposits; (12) Upper Pleistocene high frequency sequences (from Bartek *et al.*, in press)

and increased subsidence caused by the Tertiary sediment loading as documented by the study of Greenlee and Moore (1988). The Upper Miocene aggradation with lowstand deposits is well documented in *Foldout 5*. The seismic example also shows a lowermost Pliocene flooding followed by Pliocene–Lower Pleistocene aggradation with multiple lowstand deposits. Upper Pleistocene high frequency sequences as summarized in *Figure 11* are seen on the seismic example in *Foldout 5*.

In this study we differ from Greenlee (1988) and Greenlee and Moore (1988) because of the difference in the correlation of the biostratigraphic information to sequence stratigraphy. Thus for the Miocene, the major difference is in the position of the 10.5 Ma sequence boundary which is considerably deeper according to our data. This in turn leads to a different distribution of the sequences between 13.8 and 6.3 Ma. On the Plio-Pleistocene interpretations, Greenlee (1988) and Greenlee and Moore (1988) reported two additional sequence boundaries (i.e., 5.1 and 4.7 Ma) which are not documented on the Meso–Cenozoic Cycle Chart (Haq *et al.*, 1987). Based on the published palaeo-tops of Chevron 6 Main Pass 253 well (Feeley *et al.*, 1990) and some proprietory data of the same well, we have not found the two sequences reported by Greenlee (1988). These two sequences have not been reported anywhere else. A further investigation of the differences in the Plio–Pleistocene interpretations will be conducted based on the work of Greenlee (1988), Greenlee and Moore (1988), Feeley *et al.* (1990) and this study. However, the general stratal patterns of Neogene are still very similar despite the differences in the interpretations.

The stratal geometry of the Neogene shown in *Foldout 5* can be greatly modified in the areas beyond the Middle Cretaceous shelf margin due to varying sediment supply combined with active growth faulting and salt and shale tectonism. Such modifications often lead to structural enhancement or obscuration of sequence boundaries.

Patterns of sediment accumulation

The proposed sequence stratigraphic framework provides an understanding of general sediment accumulation patterns through time in our study area. In turn these sediment accumulation patterns directly influence salt deformation in the Gulf of Mexico. Patterns of sediment accumulation through time in our study area are best summarized as follows:

(1) The Werner anhydrite and much of the Louann Salt were deposited in a widespread area during an extended period of about 8×10^6 years (158.5–150.5 Ma).

(2) The Norphlet sand unit in the northern part of the study area deposited directly on top of Louann Salt in a short period of time (150.5–150 Ma).

(3) The Smackover carbonate unit (top 144 Ma, *Foldouts 3* and *4*) was deposited on the Norphlet and Louann Salt during 150–144 Ma. Syndepositional deformation of the carbonate unit and basinward salt movement was initiated. The Smackover appears to rapidly thin basinward near a presumed Jurassic shelf margin (*Foldout 4*).

(4) The Late Jurassic progradational Cotton Valley group (top 128.5 Ma, *Foldouts 3* and *4*) accumulated a great amount of clastic sediments in the study area during a 12×10^6 year period. It thickens towards the Late Jurassic shelf margin and thins across the shelf margin (*Foldout 4*). In some areas the generally progradational Cotton Valley group further displaced the Louann Salt downdip towards the deep Gulf.

(5) A generally aggradational and progradational Hosston and Sligo (121.5–112 Ma) sequences built the Lower Cretaceous shelf margin toward the basin and beyond the Jurassic shelf margin (*Foldout 4*). The accumulated sediments moved salt further into the deep water area. A major progradation is shown in the western Gulf of Mexico by Winker and Buffler (1988) during this period (*Figure 2A*).

(6) In another Lower Cretaceous aggradational and progradational period (112–94 Ma), the Upper Trinity,

the study area. Carbonate platform margins developed over a large area (*Figure 3;* e.g. Cook and Bally, 1975; Schlager, 1989). The deposition during this period continued to push salt downdip into the deep water Gulf. The second major cycle of carbonate production and progradation is summarized by Winker and Buffler (1988) for the western Gulf of Mexico (*Figure 2A*).

(7) In the deep water area starved sedimentation persisted during a very long period (91.5–30 Ma) following the 93.5 and 91.5 Ma flooding events. Over the shallow water Lower Cretaceous shelf margin the Upper Cretaceous and Palaeogene sediments prograded basinward (*Foldouts 3* and *4*). Only thin lowstand deposits and highstand pelagic sediments were deposited in the study area south of the Lower Cretaceous shelf margin (*Foldouts 2–4*). This extended period of condensed sedimentation in the deep water area allowed the salt structures to stabilize.

(8) Major episodic influxes of Late Palaeogene (after 30 Ma) to Holocene resulted in rapidly accumulating of sediments in the deep water Gulf of Mexico (*Foldouts 2–4*). Generally prograding Neogene and Holocene sediments are punctuated by transgressive events. As discussed by Wu *et al.* (1990), the rapid aggradation and progradation of enormous amounts of clastic sediments in the deep water area since 30 Ma has led to the formation of the allochthonous salt structures in the study area.

Summary

A sequence stratigraphic framework is established for our study area, based on seismic data, well information and with biostratigraphic control. Major depositional events are correlated to eustatic sea level changes. A basinwide Middle Cretaceous Flooding Surface formed as a consequence of the Late Cenomanian (93.5 Ma) and Early Turonian (91.5 Ma) flooding events. Patterns of sediment accumulation in the study area are recognized. Pre-MCFS sedimentation is aggradational and progradational and, as shown by Wu *et al.* (1990) initiated the lateral salt movements towards deep Gulf basin. The MCFS was followed by an extended period (91.5–30 Ma) of starved sedimentation in the deep water study area. During this period, the major depocentres were located far away in the north-western Gulf of Mexico. With the shift in depocentre to the eastern Gulf area in the Late Oligocene to Holocene, siliciclastic sediments prograded into and rapidly filled the eastern deep Gulf of Mexico. Allochthonous salt structures formed in the study area during the Neogene as a consequence of increased sediment loading and gravity spreading of salt in the downslope direction. The integrated sequence stratigraphic analysis provided a stratigraphic framework for a structural analysis described by Wu *et al.* (1990).

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