Sequence-stratigraphic analysis of Jurassic and Cretaceous strata and petroleum exploration in the central and eastern Gulf coastal plain, United States

Ernest A. Mancini, Jamal Obid, Marcello Badali, Kaiyu Liu, and William C. Parcell

ABSTRACT

The formulation of an integrated sequence-stratigraphic and biostratigraphic framework is fundamental in the design of an effective strategy for petroleum exploration in a sedimentary basin. For the interior salt basins of the Gulf coastal plain of the United States that are filled primarily with Mesozoic post-rift nonmarine to marine siliciclastic and carbonate deposits, a sequence-stratigraphic approach using transgressive-regressive (T-R) sequences and integrated with biostratigraphic information has utility as a method for establishing such a framework. The sequence stratigraphy established for Upper Jurassic and Cretaceous strata is used to categorize petroleum reservoirs in the central and eastern Gulf coastal plain. Transgressive aggrading eolian, fluvial, and coastal sandstone facies of the T-R sequences include highly productive hydrocarbon reservoirs in the eastern Gulf coastal plain. Productive reservoirs in the central and eastern Gulf coastal plain include regressive infilling fluvial to nearshore marine sandstone facies, and nearshore marine, shelf, ramp, and reef carbonate facies. Transgressive backstepping nearshore marine facies include highly productive reservoirs in the central Gulf coastal plain. These transgressive and regressive facies are recognized by their wireline log patterns and seismic reflection configurations.

Manuscript received April 3, 2008; provisional acceptance June 4, 2008; revised manuscript received August 13, 2008; final acceptance August 13, 2008.
DOI:10.1306/08130808046

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ACKNOWLEDGEMENTS

We thank Lee Hooper with WesternGeco for permission to publish the 2-D seismic profiles and the grid of the seismic data included in this article. We are most appreciative of the assistance of Jim Donahoe in preparing the graphics for this article. We thank the president of the Gulf Coast Association of Geological Societies for the permission to modify our outcrop figures from the 2003 and 2006 *Gulf Coast of Association of Geological Societies Transactions* volumes for inclusion in this article. The manuscript reviews by Ashton Embry, Robert W. Scott, and Berry (Nick) H. Tew improved the quality of this article. This research was funded by the U.S. Department of Energy (DOE), Office of Fossil Energy through the National Technology Laboratory, and the U.S. Minerals Management Service (MMS). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of DOE or MMS.

Knowledge of the diagnostic wireline log signatures and seismic reflection characteristics assists in the detection of exploration targets.

INTRODUCTION

The formulation of an integrated sequence-stratigraphic and biostratigraphic framework is fundamental to the development of an effective petroleum exploration strategy for a sedimentary basin. Third-order (1 to 10 m.y. in duration), unconformity-bounded depositional sequences as recognized in seismic reflection sections and as defined by Mitchum et al. (1977), Vail et al. (1977), Posamentier et al. (1988), and Van Wagoner et al. (1988) are generally used to provide the sequence-stratigraphic component in establishing such a framework. These depositional sequences, bounded by unconformities or correlative conformities, and the systems tracts of these sequences have provided a reliable means to perform stratigraphic analysis and to correlate marine facies deposited in shelf environments (transgressive and highstand systems tract deposits) with those that accumulated in slope and abyssal plain environments (lowstand systems tract deposits). In the study of Paleogene strata in the eastern Gulf coastal plain, Mancini and Tew (1991, 1995) and Tew and Mancini (1995) performed facies analysis and constructed paleogeographic maps for interpreting the geohistory of this area using an integrated approach of biostratigraphic (planktonic foraminifera and calcareous nannoplankton) and sequence-stratigraphic (depositional sequences) criteria. In studying Upper Jurassic and Cretaceous strata of the Gulf coastal plain that are characterized by nonmarine to marine siliciclastic and carbonate deposition and in which stratal patterns are driven by low-frequency, tectonic-eustatic events associated with postrift, passive margin conditions, Mancini and Puckett (2002a, b; 2003a) and Mancini et al. (2004b) found that sequence-stratigraphic analysis, based on the transgressive-regressive (T-R) sequences of Embry (1993, 2002) and integrated with biostratigraphy, is a useful method for establishing a stratigraphic framework for petroleum exploration in the interior salt basins of the Gulf coastal plain. In addition, Donovan (2004) concluded that stratal surfaces used to divide the depositional sequences of Vail et al. (1977) and the T-R sequences of Embry (1993, 2002) are the keys to stratigraphic analysis.

The objectives of this article are (1) to build on the existing body of knowledge on the sequence stratigraphy of Mesozoic strata in the Gulf coastal plain; (2) to demonstrate the merits of using an integrated sequence-stratigraphic method, based on

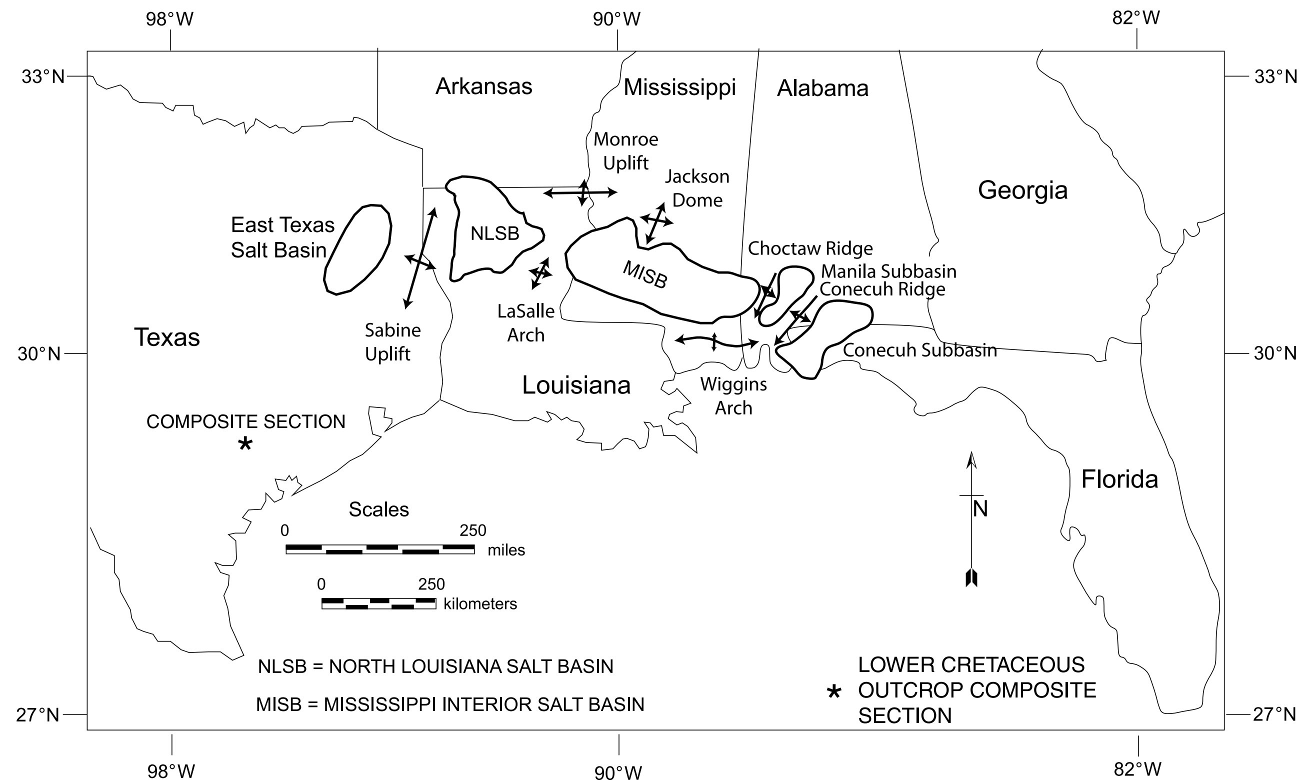


Figure 1. Interior Salt basins and subbasins and structural highs in the Gulf coastal plain and location of the Lower Cretaceous outcrop composite section in south-central Texas studied (modified from Mancini et al., 2008b).

T-R sequences and biostratigraphic information, in establishing a stratigraphic framework for the interior salt basins and subbasins of the Gulf coastal plain (Figure 1); and (3) to show the utility of employing an integrated stratigraphic method in facilitating the design of strategies for petroleum exploration in the interior salt basins of the Gulf coastal plain. The usefulness of this approach to petroleum geologists is demonstrated through case studies involving Upper Jurassic, Lower Cretaceous, and Upper Cretaceous strata, mainly from the eastern Gulf coastal plain and the offshore northeastern Gulf of Mexico region (Figure 2). These examples are drawn from studies of the Gulf coastal plain strata by the senior author; from the dissertation research of Badali (2002), Liu (2005), and Obid (2006); and from a 3-yr research project funded by the U.S. Department of Energy on T-R sequence characterization and methodology (Mancini et al., 2006c). Although the examples in this article are from the northeastern Gulf of Mexico, the authors have also studied Mesozoic strata in the central and western Gulf coastal plain both in outcrop (Mancini, 1977, 1979; Mancini and Scott, 2006) and the subsurface (Mancini et al., 2006a, b; 2008a, b).

GULF COASTAL PLAIN GEOLOGIC SETTING

The northern Gulf of Mexico rim is a passive continental margin dominated by Triassic to Early Jurassic extension and wrench faulting (Pilger, 1981; Miller, 1982; Salvador, 1987; Winker and Buffler, 1988). Accumulation of Gulf coastal plain deposits was associated with rifted margin tectonics and was a result of basement cooling and subsidence that produced accommodation space for sediment accumulation (Nunn, 1984; Sawyer et al., 1991). The resulting Mesozoic and Cenozoic stratigraphic section of the Gulf coastal plain accumulated as part of a seaward-dipping wedge of sediment that was deposited in differentially subsiding basins in the developing Gulf of Mexico (Martin, 1978). The interior extensional salt basins, which were major negative structural features that served as

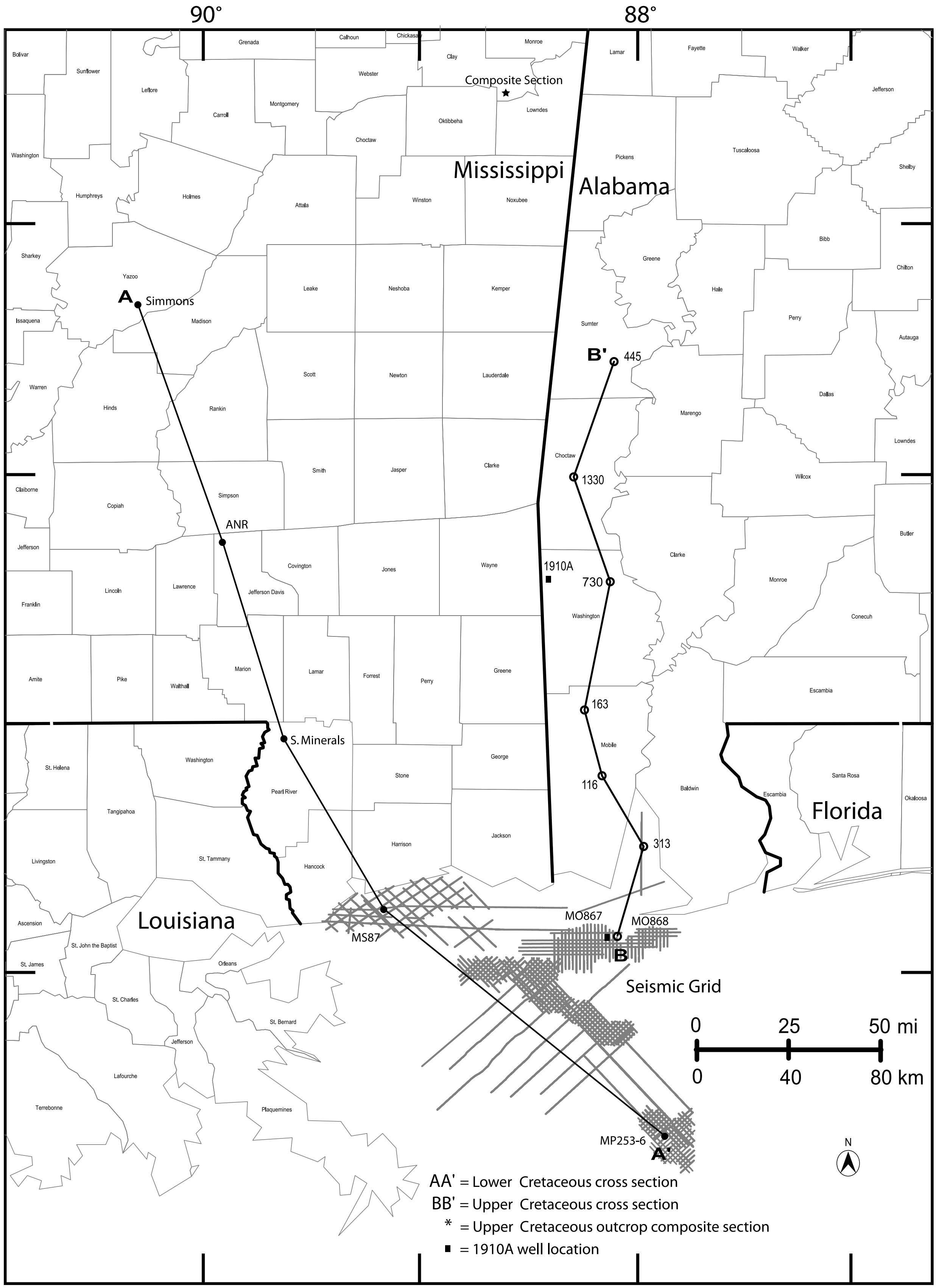


Figure 2. Map showing the location of the Upper Cretaceous outcrop composite section, wells, grid of seismic sections studied, and lines of prepared cross sections.

depocenters, include the east Texas, north Louisiana, and Mississippi Interior Salt basins and the Manila and Conecuh subbasins (Figure 1). Structural elements that affected the general orientation of the strata include basement highs associated with plate movement and features formed because of halokinesis of the Jurassic Louann Salt. The major basement paleohighs that influenced the distribution and thickness of Mesozoic deposits onshore were the Sabine uplift, Monroe uplift, Wiggins arch, Jackson dome, Choctaw ridge, and Conecuh ridge. The movement of the Louann Salt produced an array of structural features (Martin, 1978). Salt-related structures include pillows, diapirs, extensional faults, and half-graben systems (Hughes, 1968; Lobao and Pilger, 1985).

INTEGRATED SEQUENCE-STRATIGRAPHIC FRAMEWORK

The integrated sequence-stratigraphic framework established in this study is based on combining sequence stratigraphy (T-R sequences) and biostratigraphy (Figure 3). This integrated sequence-stratigraphic framework builds on the work of many Gulf Coast geoscientists.

Previous workers have published sequence-stratigraphic classifications at various scales for the Mesozoic strata of the Gulf coastal plain. For example, Todd and Mitchum (1977), Mancini et al. (1990, 2004b), Prather (1992), and Wade and Moore (1993) studied the sequence stratigraphy of Jurassic strata. Obid (2006) compared these sequence-stratigraphic classifications for Jurassic strata in the northeastern Gulf of Mexico. Tyrrell and Scott (1989), Scott (1993), Yurewicz et al. (1993), Immenhauser and Scott (1999), Scott et al. (2000, 2003), Scott and Kerans (2004), and Scott and Filkorn (2007) published on the sequence stratigraphy of Lower Cretaceous strata, and Mancini et al. (1996), Puckett and Mancini (1998, 2000) and Mancini and Puckett (2003a) reported on the sequence stratigraphy of Upper Cretaceous strata. Most of the above sequence-stratigraphic classifications for the Lower Cretaceous are discussed by Mancini and Puckett (2002a), and Liu (2005) evaluated the Upper Cretaceous sequence-stratigraphic classifications. Haq et al. (1988) and Hardenbol et al. (1998) provided global sequence-stratigraphic frameworks for Mesozoic strata.

Biostratigraphic Component

Ammonite, calcareous microfossil, and palynomorph stratigraphic distributions are used to establish Jurassic and Cretaceous biochronozones in this study. The Jurassic chronostratigraphy is based on the stratigraphic ranges of ammonites as reported by Imlay and Herman (1984) and Young and Oloriz (1993), calcareous nannofossil ranges as discussed by Cooper and Shaffer (1976), and palynomorph data from Kirkland and Gerhard (1971) and Rogers (1987). The Lower Cretaceous chronostratigraphy is based on ammonite biochronozones after Young (1966, 1967, 1986) and Hancock et al. (1993) and calcareous microfossil data from Cooper and Shaffer (1976), Scott (1984), Petty et al. (1995), and Scott et al. (2003). The Upper Cretaceous chronostratigraphy is based on planktonic foraminiferal biochronozones after Pessagno (1969), Smith and Pessagno (1973), Mancini (1979), and Caron (1985) (Figure 3). The geologic time scale of Gradstein et al. (2004) is used for the Jurassic–Cretaceous section.

Sequence-Stratigraphic Component

The T-R sequences used in this article follow the definition of these sequences as published by Embry (1993, 2002). That is, a T-R sequence consists of a transgressive systems tract below and a regressive systems tract above (Figure 4), which are separated by a maximum flooding surface. The maximum flooding surface is the downlap surface as viewed in seismic reflection data (Van Wagoner et al., 1988, 1990) and the surface of maximum sediment starvation as observed in wireline log data and surface exposures (Baum and Vail, 1988). Embry (2002) used a subaerial unconformity or shoreface ravinement unconformable surface to recognize the unconformable part of a T-R sequence boundary and a maximum regressive surface to identify the conformable part of a T-R sequence boundary.

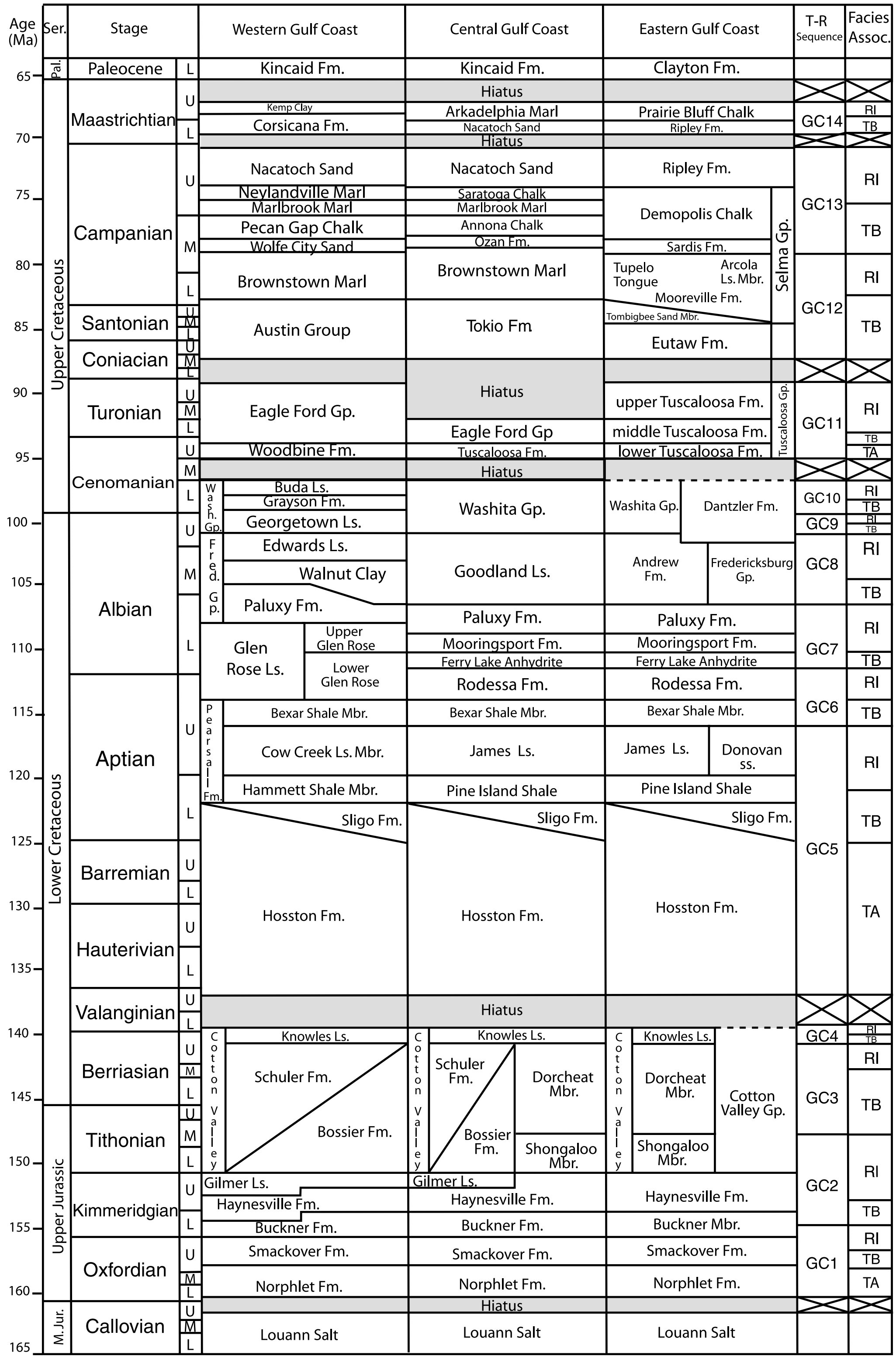


Figure 3. Chronostratigraphy, sequence stratigraphy, and lithostratigraphy for Jurassic and Cretaceous strata in the Gulf coastal plain. T-R = transgressive-regressive sequence; GC = Gulf Coast; TA = transgressive aggrading facies association; TB = transgressive backstepping facies association; and RI = regressive facies association.

The following physical surfaces are used in this study to define the boundaries of the T-R sequences, systems tracts, and facies association intervals: subaerial unconformity, shoreface ravinement surface, transgressive surface, maximum regressive surface, and maximum flooding surface. The subaerial unconformity, shoreface ravinement surface, and transgressive surface are unconformable and

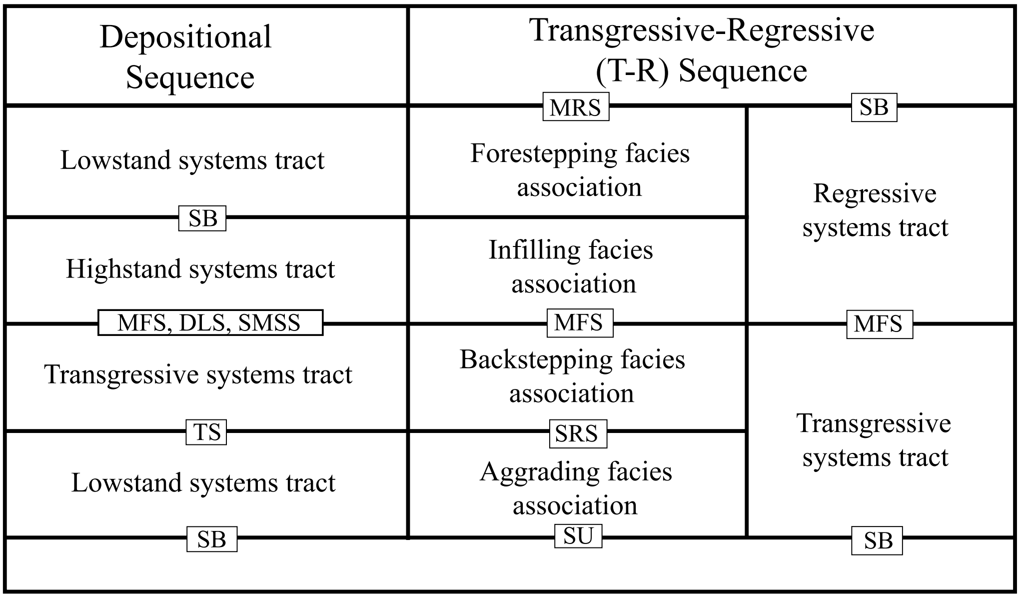


Figure 4. Comparison of systems tracts described for depositional sequences and transgressive-regressive sequences. SB = sequence boundary; SU = subaerial unconformity; TS = transgressive surface; SRS = shoreface ravinement surface; MFS = maximum flooding surface; DLS = downlap surface; SMSS = surface of maximum sediment starvation; MRS = maximum regressive surface.

are associated with a significant hiatus. A subaerial unconformity is an irregular erosional surface overlain by nonmarine or coastal deposits (Figure 5A). A soil horizon can be associated with this surface. In carbonate systems, the subaerial unconformity (Figure 5B) can be associated with a mineralized and/or diagenetic zone (hardground or karst surface), or it can be represented by an exposed surface characterized by mudcracks in supratidal deposits associated with sabkha evaporites. A shoreface ravinement surface is an irregular erosional surface overlain by transgressive nearshore marine deposits (Figure 6B). The basal marine beds of the overlying transgressive deposits commonly contain reworked clasts, fossils, and/or plant material from the underlying nonmarine to coastal beds. A transgressive surface or first transgressive surface of Van Wagoner et al. (1988) and Loutit et al. (1988) is recognized in this study as an irregular erosional surface typically overlain by shelf (Figure 5C) or ramp beds. The basal marine beds of the overlying transgressive deposits commonly contain reworked marine fossils and clasts from the underlying beds. Burrowing can be intense across this surface.

A maximum regressive surface represents the conformable part of the subaerial unconformity, shoreface ravinement surface, or transgressive surface that defines the boundary between T-R sequences. The maximum regressive surface occurs within a marine shelf (Figure 6A) or ramp section and marks a change from a shallowing (decreasing)-upward trend in water depths in an underlying marine interval to a deepening (increasing)-upward trend in water depths in an overlying marine interval (Embry, 2002). This surface signals the initiation of transgression, and its recognition requires the interpretation of the water depths that the sediments were deposited through studies, such as facies analysis (Embry, 2002) and/or paleontologic studies.

A surface of maximum sediment starvation is a surface of erosion or nondeposition (omission) in marine shelf (Figure 5D) and ramp strata. This surface represents the maximum landward extent of marine flooding (maximum flooding of Van Wagoner et al., 1988, 1990) and is characterized in middle to outer shelf settings by sediment yields of low rates and volumes (Baum and Vail, 1988; Loutit et al., 1988). A surface of maximum sediment starvation is generally associated with condensed section deposits and corresponds to a downlap surface and a surface of maximum flooding (Baum and Vail, 1988; Loutit et al., 1988; Van Wagoner et al., 1988, 1990). According to Embry (2002), the maximum flooding surface marks a change from a deepening (increasing)-upward trend in water depths in an underlying stratigraphic interval to a shallowing (decreasing)-upward trend in water depths in an overlying stratigraphic interval.

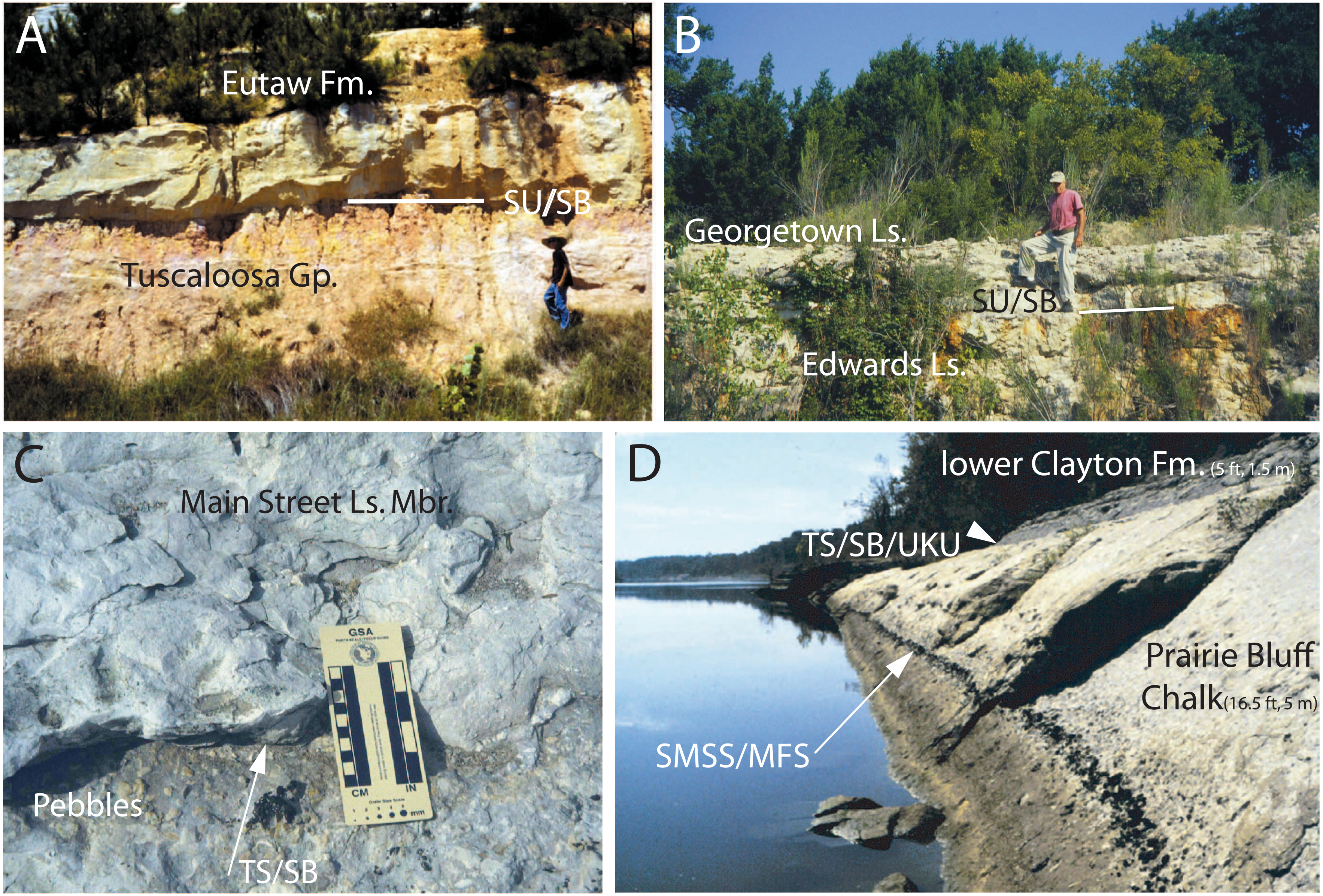

A
Eutaw Fm.
SU/SB
Tuscaloosa Gp.
B
Georgetown Ls.
SU/SB
Edwards Ls.
C
Main Street Ls. Mbr.
GSA
CM
IN
Pebbles
TS/SB
D
lower Clayton Fm. (5 ft, 1.5 m)
TS/SB/UKU
Prairie Bluff
Chalk (16.5 ft, 5 m)
SMSS/MFS

Figure 5. Outcrop photographs of Cretaceous strata: (A) T-R GC12 sequence boundary and subaerial unconformity in siliciclastics associated with the Tuscaloosa Group and Eutaw Formation, in Phenix City, Russell County, Alabama (modified from Mancini and Puckett, 2003a); (B) T-R GC9 sequence boundary and subaerial unconformity in carbonates associated with the Edwards Limestone and Georgetown Limestone, Belton Quarry, Highway 36, Bell County, east-central Texas (modified from Mancini and Scott, 2006), as interpreted by Scott et al. (2003) and supported by isotope data; (C) T-R GC10 sequence boundary and unconformable transgressive surface in carbonates marked by the pebble bed in the Main Street Member of the Georgetown Limestone, near Aquilla, White Rock Creek, Hill County, northeast Texas; and (D) T-R GC14 upper sequence boundary and unconformable transgressive surface associated with the Upper Cretaceous Prairie Bluff Chalk and Paleocene Clayton Formation (Cretaceous-Paleogene boundary) and surface of maximum sediment starvation and maximum flooding surface of the T-R GC14 sequence, at Moscow Landing on the Tombigbee River, southwest of Demopolis, Sumter County, Alabama (modified from Mancini and Puckett, 2003a). SB = sequence boundary; SU = subaerial unconformity; TS = transgressive surface; SMSS = surface of maximum sediment starvation; MFS = maximum flooding surface; UKU = Upper Cretaceous unconformity as described by Mancini et al. (1989).

Loutit et al. (1988) reported that water depth is a function of relative sea level and sediment yield, and therefore, the maximum water depth in a stratigraphic section can occur at a level above the surface of maximum sediment starvation and maximum flooding surface because of differing rates and amounts of sediment accumulation and depositional conditions (Naish and Kamp, 1997; Catuneanu et al., 1998; Loutit et al., 1988; Liu, 2005). The surface of maximum sediment starvation and the maximum flooding surface are commonly marked by a concentration of microfossils, authigenic glauconite, phosphatic and sideritic fossil molds (steinkern), and encrusted and bored fossils (Baum and Vail, 1988; Loutit et al., 1988). Burrowing can be common across these surfaces, and in carbonates, a bored hardground can develop.

Because knowledge of the stratigraphic position of potential reservoir facies in the systems tracts is critical in the formulation of an effective exploration strategy, the systems tracts of the T-R sequences were divided into intervals of facies associations based on the classification of Jacquin and de Graciansky (1998). Jacquin and de Graciansky (1998) recognized T-R facies cycles in strata in basins of western Europe. They interpreted these facies cycles to represent second-order events and further concluded that the cycles were composed of third-order depositional sequences that could be grouped into early transgressive or an aggrading sequence, late transgressive or a backstepping sequence, early regressive or an infilling sequence, and late regressive or a forestepping sequence.

For this work, the transgressive systems tract is divided into an aggrading facies association interval of nonmarine and coastal deposits and a backstepping facies association interval of marine deposits (Figure 4). The aggrading facies association overlies a subaerial unconformity and is separated from the overlying backstepping facies association by a shoreface ravinement surface. The aggrading facies association is not recognized in all of the T-R sequences described in this study because of a lack of preservation or nondeposition because of environmental and tectonic conditions. The regressive systems tract is divided into an infilling facies association interval of marine to

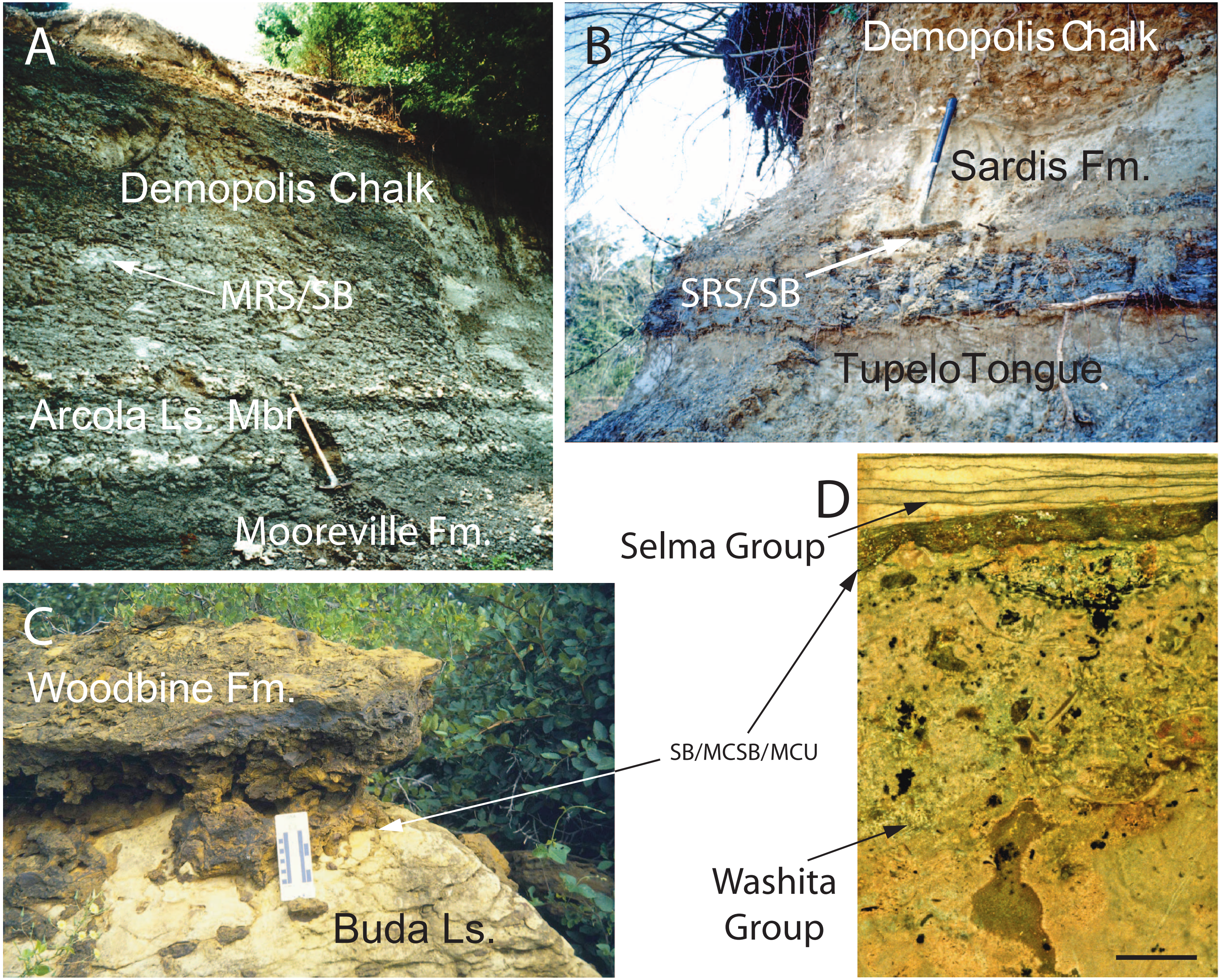

A
Demopolis Chalk
MRS/SB
Arcola Ls. Mbr
Mooreville Fm.
B
Demopolis Chalk
Sardis Fm.
SRS/SB
TupeloTongue
C
Woodbine Fm.
Buda Ls.
SB/MCSB/MCU
D
Selma Group
Washita
Group

Figure 6. Outcrop photographs of Upper Cretaceous strata: (A) T-R GC13 sequence boundary and conformable maximum regressive surface associated with the Arcola Limestone Member of the Mooreville Formation and the Tibbee Creek member of the Demopolis Chalk, near Tibbee, Tibbee Creek, Clay County, east-central Mississippi, eastern Gulf coastal plain; (B) T-R GC13 sequence boundary and unconformable shoreface ravinement surface associated with the Tupelo Tongue of the Coffee Sand and the Sardis Formation, near Frankstown, Prentiss County, northern Mississippi, eastern Gulf coastal plain (modified from Mancini and Puckett, 2003a); (C) T-R GC11 sequence boundary and unconformable contact between the Lower Cenomanian Buda Limestone and the middle Cenomanian Woodbine Formation, Bolo Point, Denton County, northeast Texas, western Gulf coastal plain (modified from Mancini and Scott, 2006); and (D) T-R GC11 sequence boundary and unconformable contact (MCSB and MCU on seismic sections) between the lower Cenomanian Washita Group and Campanian deposits in the Chevron 253-6 Main Pass well, offshore northeastern Gulf of Mexico (modified from Badali, 2002). SB = sequence boundary; MRS = maximum regressive surface; SRS = shoreface ravinement surface; MCSB = middle Cretaceous sequence boundary as described by Buffler (1991), which is the informal MCU or middle Cretaceous unconformity of Buffler and Sawyer (1985) (middle Cenomanian unconformity).

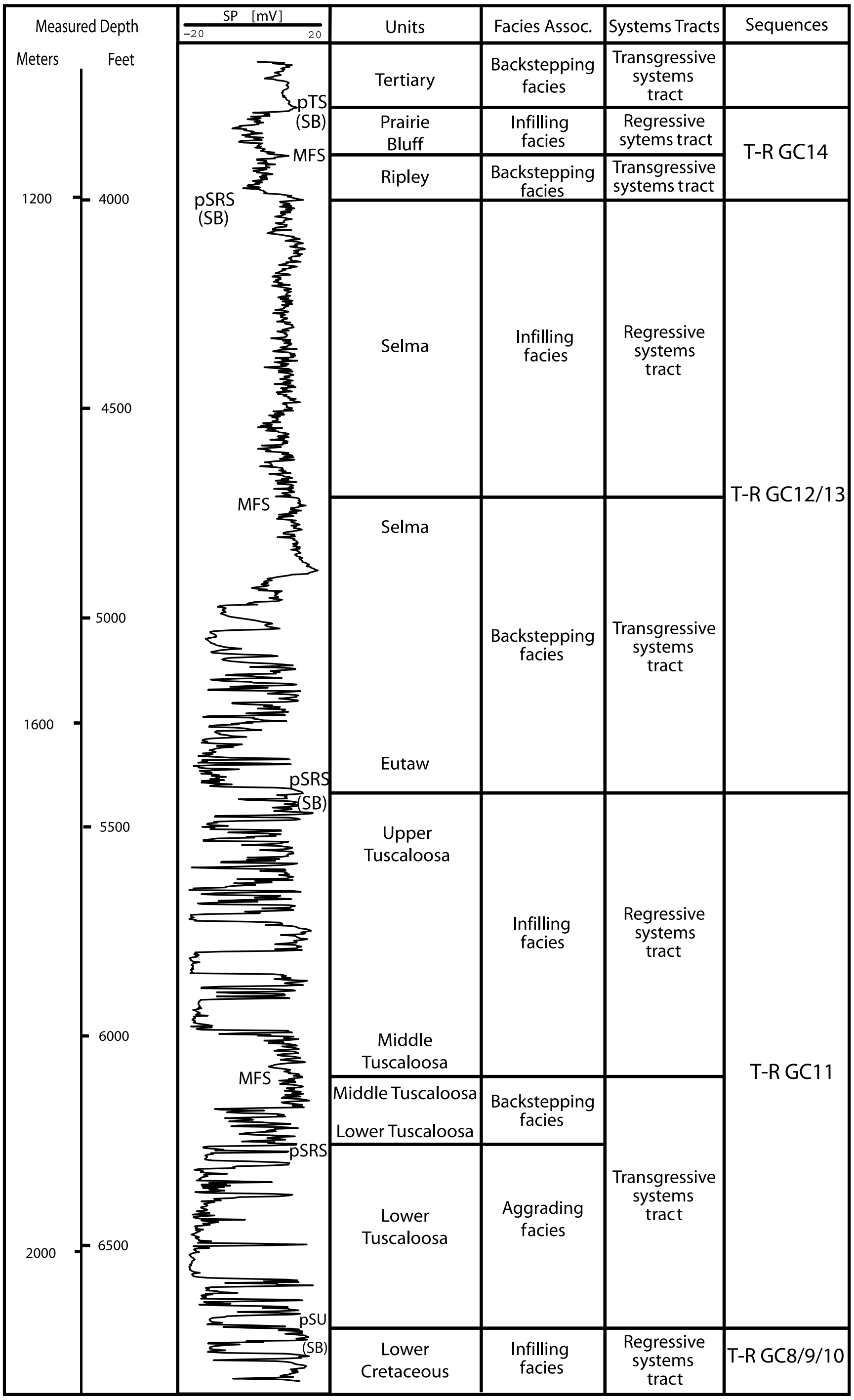
nonmarine deposits and a forestepping facies association interval of primarily deep-water deposits (Jacquin and de Graciansky, 1998). The transgressive backstepping facies association interval is separated from the regressive infilling facies association interval by a maximum flooding surface. The deep-water facies of the forestepping facies association interval are not recognized in the Mesozoic shelf and ramp deposits studied in this work. The prograding fluvial facies of the regressive systems tract observed in this study are included in the infilling facies association. In the eastern Gulf coastal plain, sequences in which a regressive systems tract includes carbonate facies in the lower part of the sequence and siliciclastic facies in the upper part of the sequence, typically the infilling carbonate strata exhibit an aggradational pattern in wireline log signatures and the siliciclastic strata exhibit a progradational signature in wireline log patterns.

UPPER JURASSIC AND CRETACEOUS CASE STUDIES

Fourteen T-R sequences are recognized in Upper Jurassic and Cretaceous strata of the Gulf coastal plain in this study. This total expands on the 11 T-R sequences reported by Mancini and Puckett (2005) for Mesozoic strata in the northern Gulf of Mexico. In this study, T-R sequences were identified by a combination of factors, including the nature of the sequence boundaries, stratal geometries, facies stacking patterns and associations within sequences, and large-scale shifts in major facies association boundaries. These sequences were recognized based on seismic reflection, wireline log, well core, paleontologic, and outcrop data.

Mancini and Puckett (2005) used the following discontinuities and trends in wireline log patterns to recognize the components and boundaries of a T-R sequence (Figure 7). A change from increasing to decreasing gamma ray or from more to less positive spontaneous potential (SP) log signature was used to identify the discontinuity inferred to be a maximum flooding surface. An increase in gamma ray or a change to a more positive SP log response (bell shaped or fining-upward trend) from

Figure 7. Wireline log patterns for the Plymouth 1 Hunter-Benn well (permit 730), Mobile County, Alabama, showing characteristic spontaneous potential (SP) log signatures for transgressive aggrading and backstepping and regressive infilling sections of transgressive-regressive (T-R) sequences for Upper Cretaceous strata in the eastern Gulf coastal plain. See Figure 2 for the location of the well. GC = Gulf Coast; SB = sequence boundary; pSU = possible subaerial unconformity; pSRS = possible shoreface ravinement surface; pTS = possible transgressive surface; MFS = maximum flooding surface. Sequence boundaries, maximum flooding surfaces, and other inferred surfaces are recognized based on observed discontinuities or changes in trend in the signature of wireline log records in combination with facies analysis, core and well cutting sample study, and outcrop analog data.



the top of a discontinuity in the log pattern recognized as a lower sequence boundary to the base of the maximum flooding surface was used to delineate the backstepping marine facies association interval of the transgressive systems tract. An overall decrease in gamma ray or a change to a more negative SP log response (funnel-shaped or coarsening upward trend) from the top of the maximum flooding surface to the base of a discontinuity in the log pattern recognized as an upper sequence boundary was used to identify the regressive infilling marine to nonmarine facies association interval of the regressive systems tract. The regressive systems tract commonly consists of a series of coarsening-upward stacking patterns. A static gamma ray or SP log signature (box shaped related to approximately uniform grain size vertically) is typically characteristic of the aggrading nonmarine and coastal facies association interval of the transgressive systems tract. The transgressive aggrading facies association interval, where present, directly overlies the lower sequence boundary and is separated from the transgressive backstepping facies association interval by a discontinuity inferred to be a shoreface ravinement surface.

Mancini and Puckett (2005) identified and used seismic reflection terminations, such as toplap (Figure 8A), onlap (Figure 8B), and downlap (Figure 8C), to recognize horizons in the seismic data that had the potential to be T-R sequence boundaries and downlap surfaces after Mitchum et al. (1977). They used seismic reflection configurations, as reported by Van Wagoner et al. (1988) and Yurewicz et al. (1993), to characterize the seismic intervals (potential T-R systems tracts) defined by the recognized horizons. Thick (several seismic cycles) intervals of seismic reflectors exhibiting aggradational reflection configurations were interpreted as characteristic of strata of the aggrading nonmarine and coastal facies association interval of the transgressive systems tract. Thin (commonly one or two seismic cycles), continuous, parallel, retrogradational seismic reflection configurations with onlap reflection terminations were interpreted as characteristic of strata of the backstepping marine facies association interval of the transgressive systems tract (Figure 8B, D). Thick (several seismic cycles), oblique, progradational seismic reflection configurations showing downlap were interpreted as prograding clinoforms characteristic of the infilling marine to nonmarine facies association interval of the regressive systems tract (Figure 8C).

Upper Jurassic to Lower Cretaceous Example

The T-R sequences recognized in the Gulf coastal plain for the Late Jurassic to Early Cretaceous reflect the postrift tectonic and depositional conditions during this period. This series of sequences is bracketed at the base by the Louann Salt-Norphlet Formation contact (Callovian–Oxfordian as reported by Salvador, 1987) and at the top by the Cotton Valley Group-Hosston Formation contact (Valanginian as reported by McFarlan and Menes, 1991).

Deposition in the Gulf coastal plain during this time was characterized by high tectonic subsidence rates, high sediment supply, and arid conditions (Salvador, 1991; Sawyer et al., 1991). Paleotopography affected the distribution of sediment, particularly in the eastern Gulf coastal plain, because of the presence of numerous pre-Jurassic basement paleohighs (Mancini et al., 1985). During the Late Jurassic, sediment accumulated in a ramp setting (Ahr, 1973; Mancini and Benson, 1980). The thickness of the Norphlet and Cotton Valley siliciclastic nonmarine to marginal marine sections reflects high sediment supply (Mancini et al., 1999). Carbonate sedimentation, including microbial buildups, characterized Smackover deposition (Salvador, 1991; Mancini et al., 2004a). Haynesville deposition was primarily a function of arid and evaporitic conditions (Mann, 1988; Mann and Kopaska-Merkel, 1992).

Four Upper Jurassic (Oxfordian) to Lower Cretaceous (Valanginian) T-R sequences are identified across the Gulf Coast (GC) and the offshore northeastern Gulf of Mexico region based on wireline log, core, and seismic data (Figure 3). These sequences include an upper transgressive interval of backstepping limestone, interbedded limestone and shale, interbedded limestone and anhydrite, sandstone, and interbedded sandstone and shale facies and a regressive interval of infilling limestone, interbedded shale and limestone, interbedded limestone and anhydrite, and interbedded shale and sandstone facies. The Oxfordian to Kimmeridgian T-R GC1 sequence also includes a lower transgressive interval of aggrading fluvial and eolian sandstone facies. The Berriasian–Valanginian T-R GC4 is not recognized in wireline log signatures from the Mississippi Interior Salt Basin and the Manila and Conecuh subbasins north of the Wiggins arch. This sequence is not preserved or not deposited because of tectonic and environmental conditions in these areas, or it is not recognized because of a lack of diverse lithologies and an absence of distinctive stratal surfaces in this interval in this area

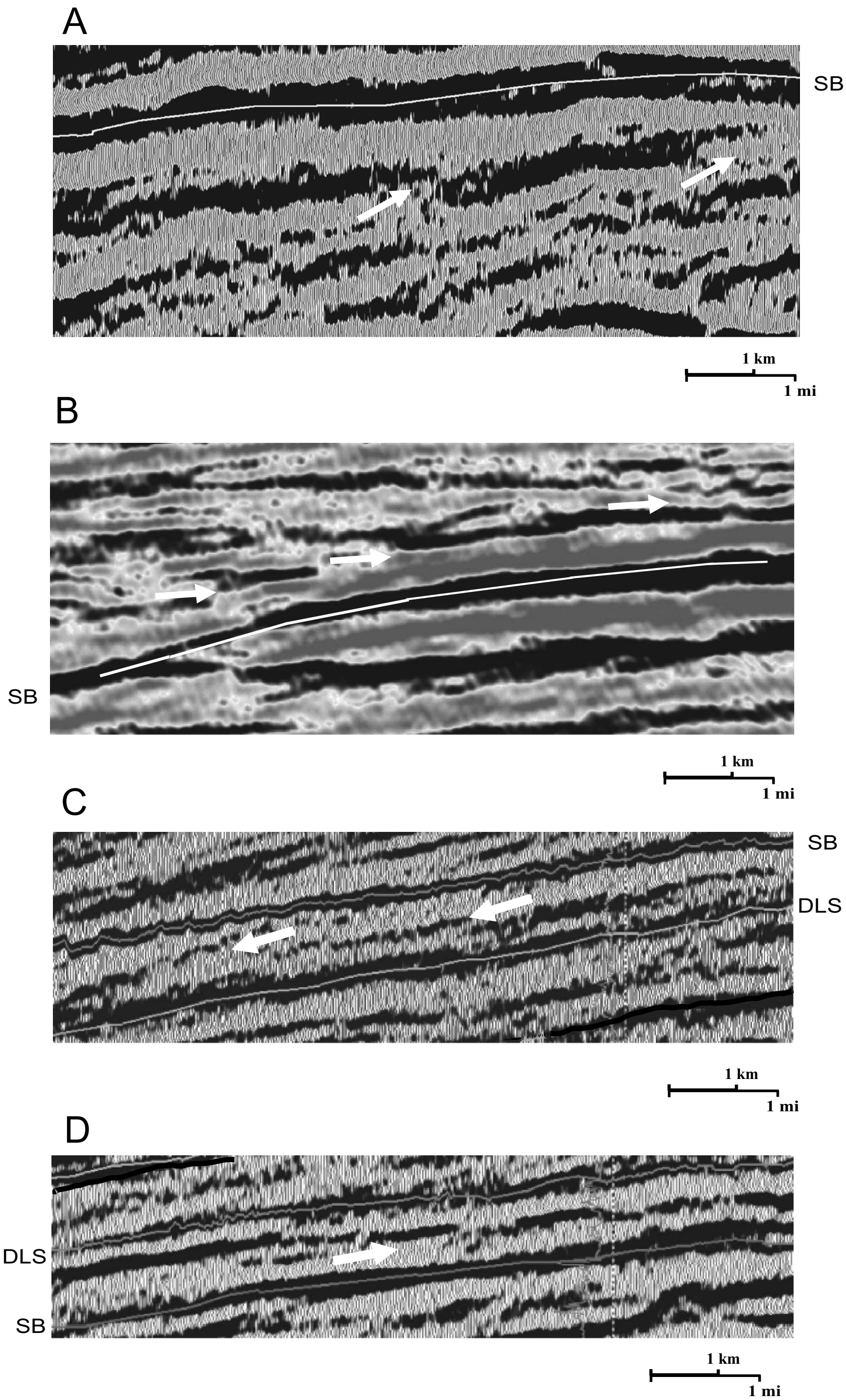


Figure 8. Seismic reflection profiles from the offshore northeastern Gulf of Mexico area showing characteristic seismic reflection terminations and configurations for Jurassic and Cretaceous strata associated with T-R sequences: (A) Toplap (truncation of topset beds) reflection termination indicating an unconformable sequence boundary of a T-R sequence in Upper Jurassic strata; (B) onlap reflection termination indicating an unconformable sequence boundary and retrogradational reflection configuration typical of a transgressive backstepping section of a T-R sequence in Upper Jurassic strata; (C) downlap reflection surface indicating a surface of maximum transgression and oblique, clinoform progradational reflection configuration typical of the regressive infilling section of a T-R sequence in Upper Cretaceous strata; and (D) continuous, parallel retrogradational reflection configuration typical of the transgressive backstepping section of a T-R sequence in Upper Cretaceous strata. SB = sequence boundary; DLS = downlap surface.

to provide for its recognition (Figure 9). South of the Wiggins arch, the Kimmeridgian–Tithonian T-R GC2 sequence is difficult to distinguish from the T-R GC1 sequence in wireline log data chiefly because of a similarity in lithologies (Figure 10). In the offshore northeastern Gulf of Mexico, the Tithonian–Berrasian T-R3 sequence is difficult to recognize in seismic data mainly because of an absence of distinctive stratal surfaces in these intervals to provide for their recognition (Figure 11A).

This case study demonstrates the use of an integrated sequence-stratigraphic and biostratigraphic framework for the correlation of postrift nonmarine to marine strata. In the eastern Gulf coastal

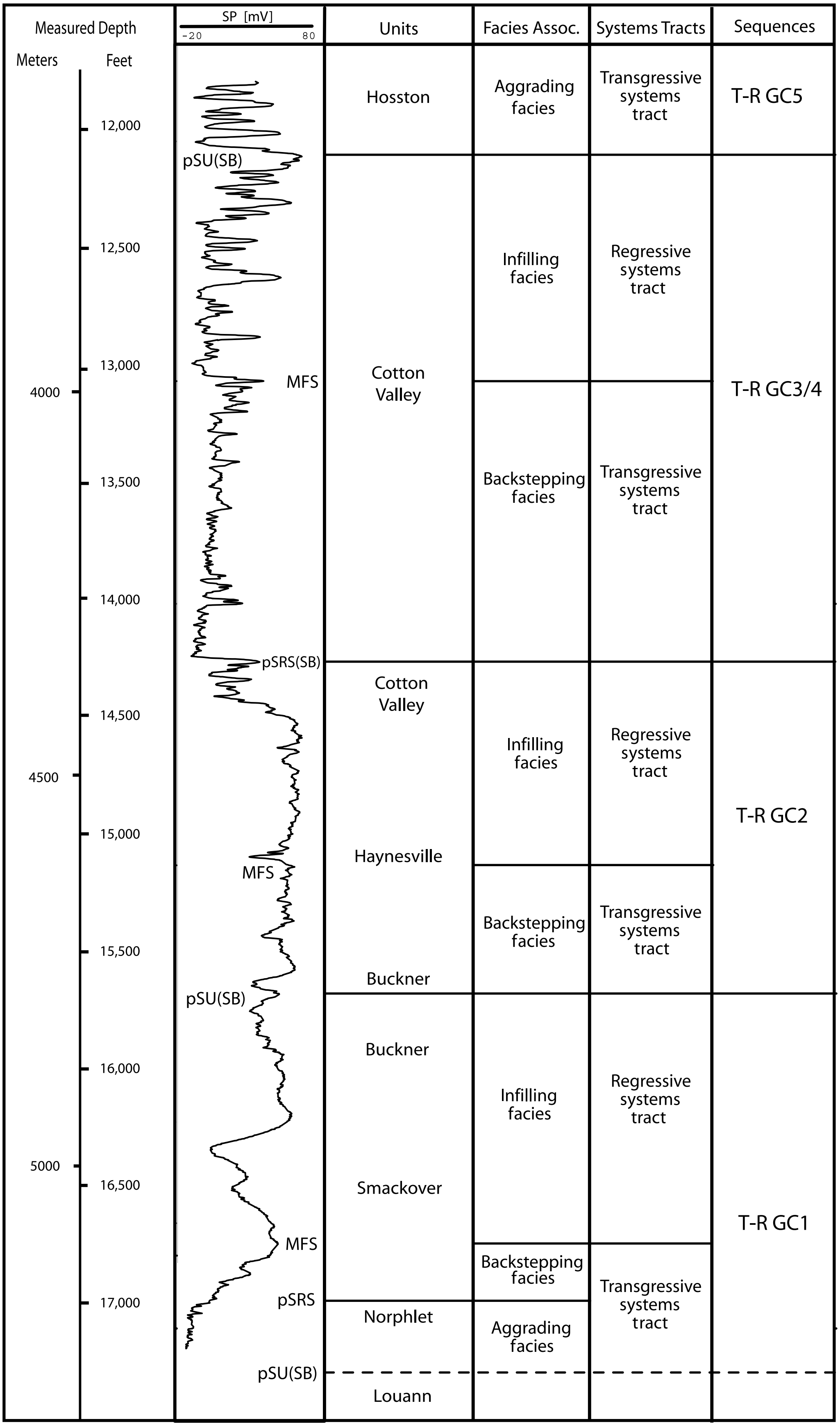


Figure 9. Wireline log patterns for the Tenneco 1A Hopkins well (permit 1910A), Washington County, Alabama, located in an inner ramp setting north of the Wiggins arch, showing the spontaneous potential (SP) log signature for the Upper Jurassic transgressive-regressive (T-R) sequences in the subsurface of the onshore eastern Gulf coastal plain. See Figure 2 for the location of the well. GC = Gulf Coast; SB = sequence boundary; pSU = possible subaerial unconformity; pSRS = possible shoreface ravinement surface; MFS = maximum flooding surface. Sequence boundaries, maximum flooding surfaces, and other inferred surfaces are recognized based on observed discontinuities or changes in trend in the signature of wireline log records in combination with facies analysis and core and well cutting sample study.

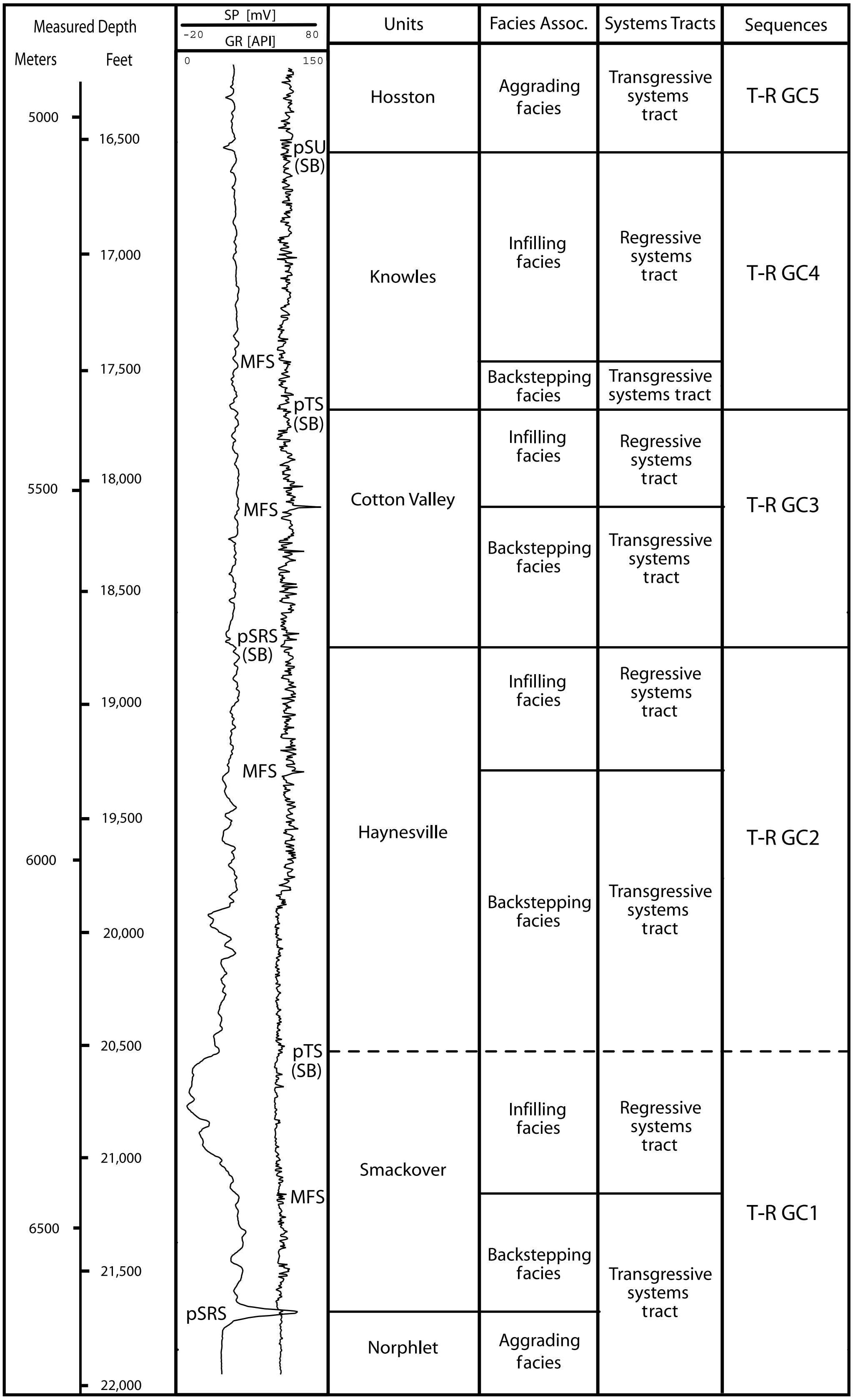


Figure 10. Wireline log patterns for the Exxon 1 OCS-G-5066 well (MO-867), Mobile area, located in an outer ramp setting south of the Wiggins arch, showing the spontaneous potential (SP) and gamma ray (GR) log signatures for the Upper Jurassic transgressive-regressive (T-R) sequences in the subsurface of the offshore northeastern Gulf of Mexico. See Figure 2 for the location of the well. GC = Gulf Coast; SB = sequence boundary; pSU = possible subaerial unconformity; pSRS = possible shoreface ravinement surface; MFS = maximum flooding surface. Sequence boundaries, maximum flooding surfaces, and other inferred surfaces are recognized based on observed discontinuities or changes in trend in the signature of wireline log records in combination with facies analysis and core and well cutting sample study.

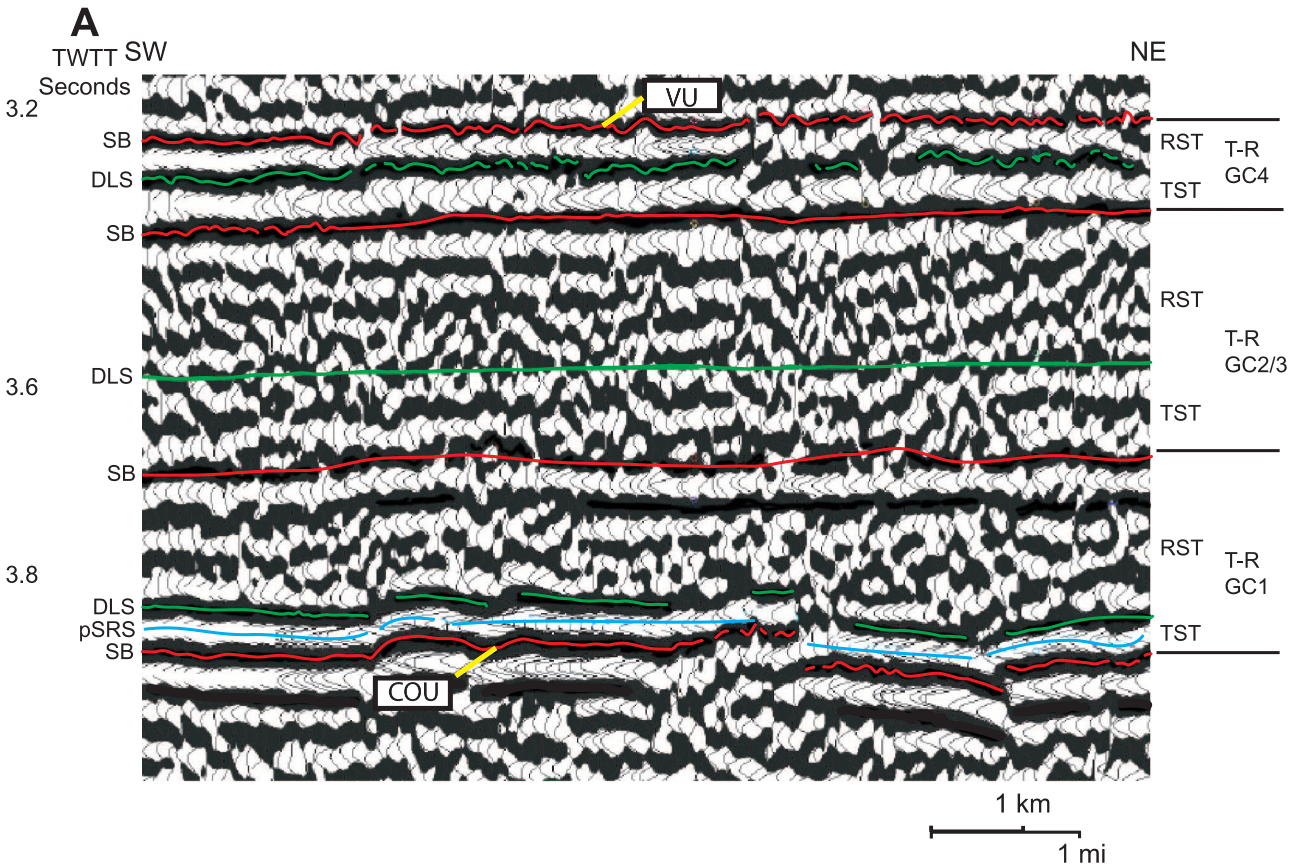
plain, these deposits were affected primarily by tectonics and high sediment supply, and in the western Gulf coastal plain, these strata were affected chiefly by tectonics and relative sea level changes (Figure 3). Strata in an updip fluvial to marginal marine and marine, inner ramp setting (Figure 9) can be correlated with strata in a downdip eolian to marine, outer ramp setting (Figure 10). This case study also shows that the identification of stratigraphic sequences and associated stratal surfaces is dependent on the contrast in sedimentary and lithologic characteristics of the rocks, the presence of distinctive stratal surfaces, and in the resolution of the tools used for sequence-stratigraphic analysis. The ability to discern the T-R GC2 sequence in the wireline log patterns and cores in the Mississippi Interior Salt Basin and Manila and Conecuh subbasins north of the Wiggins arch and the difficulty in recognizing this sequence in wireline log data south of the Wiggins arch illustrate this point. This difference in being able to recognize this sequence is attributed to inner to outer ramp facies and lithologic changes in the Smackover-Haynesville interval associated with the Wiggins arch. The Smackover carbonate beds north of the Wiggins arch in the eastern Gulf coastal plain are overlain by a thick section of sabkha and subaqueous anhydrite of the Buckner Member of the Haynesville Formation, whereas south of the Wiggins arch and in the offshore northeastern Gulf of Mexico region, the Smackover carbonate beds are overlain by a thick section of carbonate rocks of the lower part of the Haynesville Formation (Obid, 2006). The study of core and well cutting samples in conjunction with the records of wireline logs is required to recognize this sequence in this area.

Lower to Upper Cretaceous Example

The T-R sequences recognized in the Gulf coastal plain for the Early Cretaceous (Valanginian) to the earliest Late Cretaceous (middle Cenomanian) record the paleoenvironmental conditions during this period. This series of sequences is bracketed at the base by the contact between the Cotton Valley Group and the Hosston Formation (Valanginian) and at the top by the contact between the Dantzler Formation or Washita Group and the Tuscaloosa Group and the Washita Group and the Woodbine Formation. The upper contact is the middle Cenomanian or middle Cretaceous sequence boundary (MCSB) of Buffler (1991) and the informal middle Cretaceous unconformity (MCU) of Buffler and Sawyer (1985).

Sediment accumulation in the Gulf coastal plain at this time was dominantly mixed carbonate and siliciclastic deposition in a continental shelf to slope setting (Mancini and Puckett, 2002a, b). Siliciclastic deposition in fluvial to shelf paleoenvironments in proximity to terrigenous source terranes typified the eastern Gulf coastal plain, and carbonate sediment accumulation in shelf to slope paleoenvironments in association with coral-sponge-algal and rudist reefs characterized the western Gulf coastal plain (Scott, 1993; Mancini and Puckett, 2002a).

Six Lower Cretaceous (Valanginian) to lower Upper Cretaceous (Cenomanian) T-R sequences are identified across the Gulf Coast and the offshore northeastern Gulf of Mexico based on outcrop, paleontologic, wireline log, core, and seismic data (Figure 3). These sequences include an upper transgressive interval of backstepping limestone, anhydrite, calcareous shale, and shale facies and a regressive interval of infilling limestone, calcareous shale, sandy shale, interbedded sandstone and shale, interbedded sandstone and siltstone, and sandstone facies. The Valanginian to upper Aptian T-R GC5 sequence also includes a lower transgressive interval of aggrading fluvial and coastal sandstone facies. In much of the Mississippi Interior Salt Basin and the Manila and Conecuh subbasins, the T-R GC5, T-R GC7, and T-R GC8 sequences are capped by prograding fluvial facies of the infilling marine to nonmarine facies association. The upper Albian to lower Cenomanian T-R GC9 and T-R GC10 sequences are not discernable from the middle to upper Albian T-R GC8 sequence in wireline log signatures from the Mississippi Interior Salt Basin and the Manila and Conecuh subbasins in the eastern Gulf coastal plain (Figure 12) because these sequences are not preserved or not deposited because of tectonic and environmental conditions in this basin and subbasins, or they are not recognized because of a lack of diverse lithologies and an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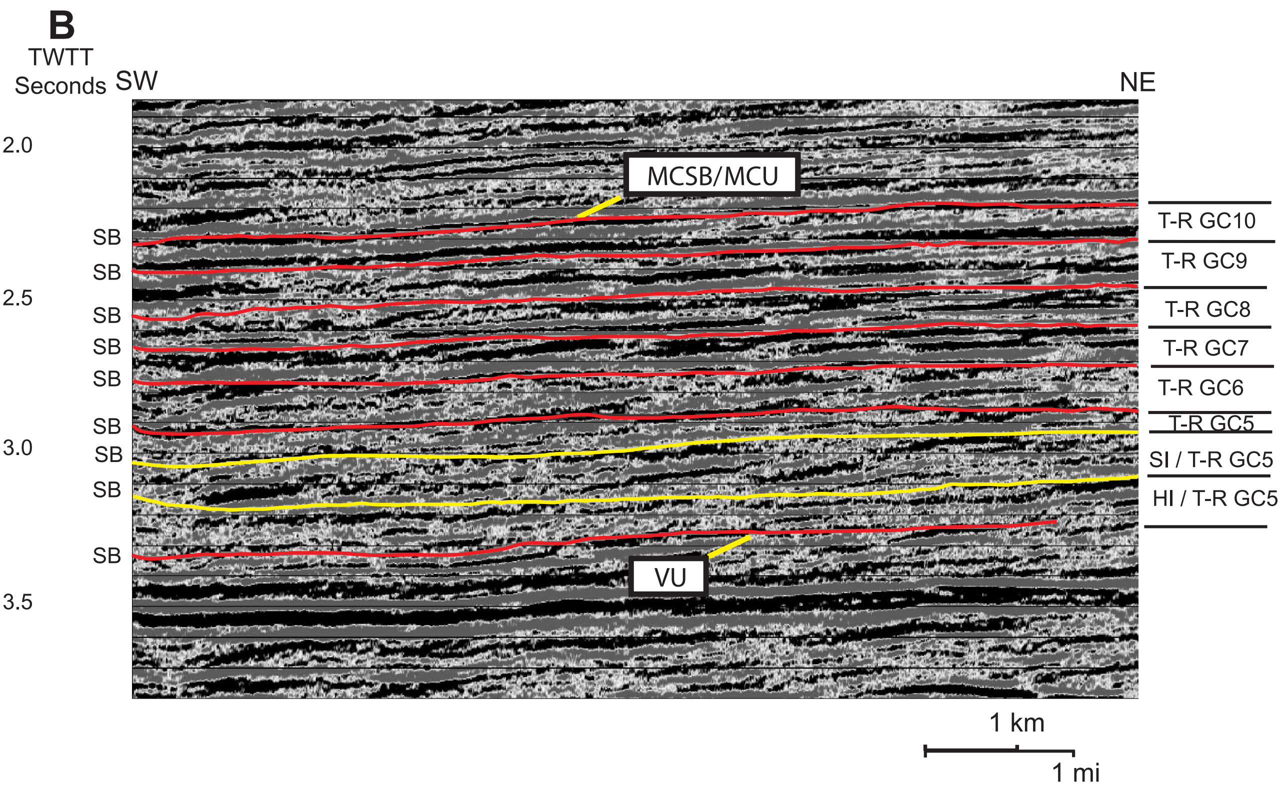
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absence of distinctive stratal surfaces. Also, Badali (2002) recognized two additional seismic sequences in the Valanginian to Aptian stratigraphic interval in the offshore northeastern Gulf of Mexico area (Figure 11B). These sequences approximate the stratal positions of the Hosston and Sligo stratigraphic intervals of the onshore eastern Gulf coastal plain.

Scott et al. (2003), based on outcrop studies, reported six upper Albian to lower Cenomanian higher order sequences in the Washita Group of the western Gulf coastal plain. Badali (2002) and Mancini and Puckett (2002b) also observed upper Albian to lower Cenomanian parasequences in the signature of wireline logs for the offshore northeastern Gulf of Mexico area. These higher order sequences can be recognized in outcrop and in the subsurface using wireline logging tools and seismic reflection techniques because the Lower Cretaceous to lower Upper Cretaceous section in parts of the northern Gulf of Mexico is typified by diverse lithologies and sediment textures and distinctive stratal surfaces. Variations in siliciclastic sediment influx into these areas have produced a stratigraphic section composed of alternating siliciclastic and carbonate strata with characteristic primary and secondary sedimentary rock properties. These higher order sequences consisting of alternating siliciclastic and carbonate strata do not appear to be regionally continuous across the Gulf coastal plain.

This case study demonstrates the usefulness of an integrated sequence-stratigraphic and biostratigraphic framework for correlation of Lower Cretaceous to lower Upper Cretaceous nonmarine to marine shelf strata across the Gulf coastal plain. In using this framework, strata as observed in outcrop in the western Gulf coastal plain (Mancini and Scott, 2006) can be correlated with strata as observed in wireline log and seismic data of the eastern Gulf coastal plain and the offshore northeastern Gulf of Mexico region (Badali, 2002; Mancini and Puckett, 2002a). This case study also shows that the identification of stratigraphic sequences and associated stratal surfaces is dependent on the contrast in sedimentary and lithologic characteristics of the rocks, the presence of distinctive stratal surfaces, and the resolution of the tools used for sequence-stratigraphic analysis. The recognition of the T-R GC9 and T-R GC10 sequences in outcrop in the western Gulf coastal plain (Figure 5B, C) and in seismic data of the offshore northeastern Gulf of Mexico (Figure 11B), but not in wireline log patterns of the Mississippi Interior Salt Basin and Manila and Conecuh subbasins of the Gulf coastal plain (Figures 12, 13), illustrates this point. The ability to identify these sequences in the western Gulf coastal plain and the offshore northeastern Gulf of Mexico is attributed to the diverse lithologies and sediment textures and distinctive stratal surfaces that are characteristic of the alternating siliciclastic and carbonate strata characteristic of the Washita interval in these areas.

Upper Cretaceous Example

The Upper Cretaceous T-R sequences recognized in the Gulf coastal plain are bracketed at the base by the middle Cenomanian unconformity or MCSB (Figure 6C, D) and at the top by the Cretaceous-Paleogene boundary (Prairie Bluff Chalk-Clayton Formation, Arkadelphia Marl-Kincaid Formation, and Kemp Clay-Kincaid Formation contacts) as described by Mancini et al. (1989) (Figure 5D).

Deposition in the Gulf coastal plain during this time was characterized chiefly by nearshore marine siliciclastic sediment and shelf chalk and marl accumulation (Mancini and Puckett, 2003a). The

Figure 11. Seismic reflection sections from the offshore northeastern Gulf of Mexico: (A) Section showing transgressive-regressive (T-R) sequences recognized in Upper Jurassic to lowermost Cretaceous strata (seismic interpretation by Obid, 2006). (B) Section showing T-R sequences recognized in Lower Cretaceous strata (seismic interpretation by Badali, 2002). GC = Gulf Coast; SB = sequence boundary; DLS = downlap surface; pSRS = possible shoreface ravinement surface; TST = transgressive systems tract; RST = regressive systems tract; SI = Sligo interval; HI = Hosston interval; COU = Callovian–Oxfordian unconformity as reported by Salvador (1991); VU = Valanginian unconformity as reported by McFarlan and Menes (1991); MCSB = middle Cretaceous sequence boundary as described by Buffler (1991), which is the informal MCU or middle Cretaceous unconformity of Buffler and Sawyer (1985) (middle Cenomanian unconformity); TWTT = two-way traveltime.

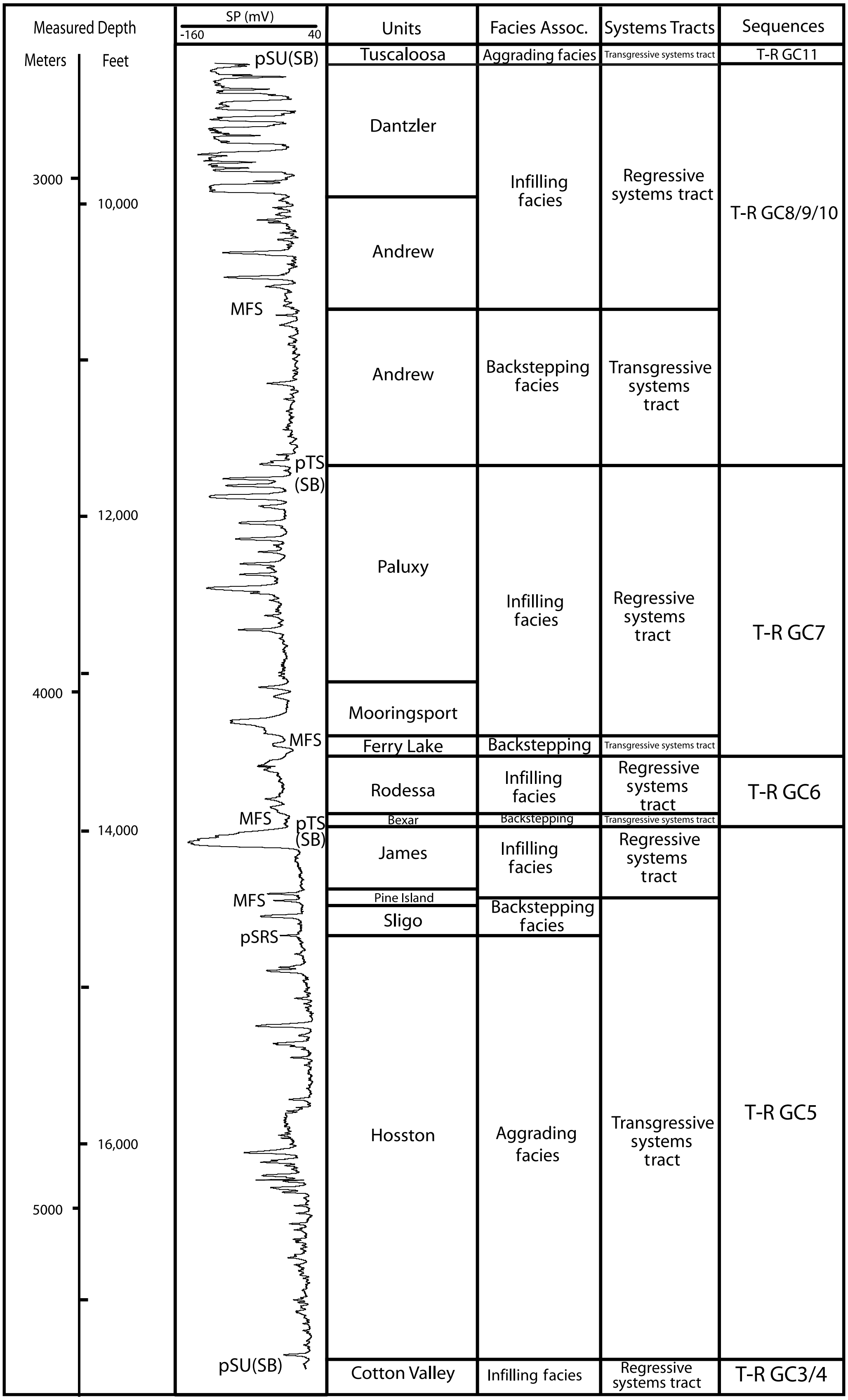

Figure 12. Wireline log patterns for the Exxon 1 Southern Minerals well, Pearl River County, Mississippi, showing the spontaneous potential (SP) log signature for the Lower Cretaceous transgressive-regressive (T-R) sequences in the subsurface of the onshore eastern Gulf coastal plain. See Figure 2 for the location of the well. GC = Gulf Coast; SB = sequence boundary; pSU = possible subaerial unconformity; pSRS = possible shoreface ravinement surface; pTS = possible transgressive surface; MFS = maximum flooding surface; ST = systems tract. Sequence boundaries, maximum flooding surfaces, and other inferred surfaces are recognized based on observed discontinuities or changes in trend in the signature of wireline log records in combination with facies analysis, core and well cutting sample study, and outcrop analog data.

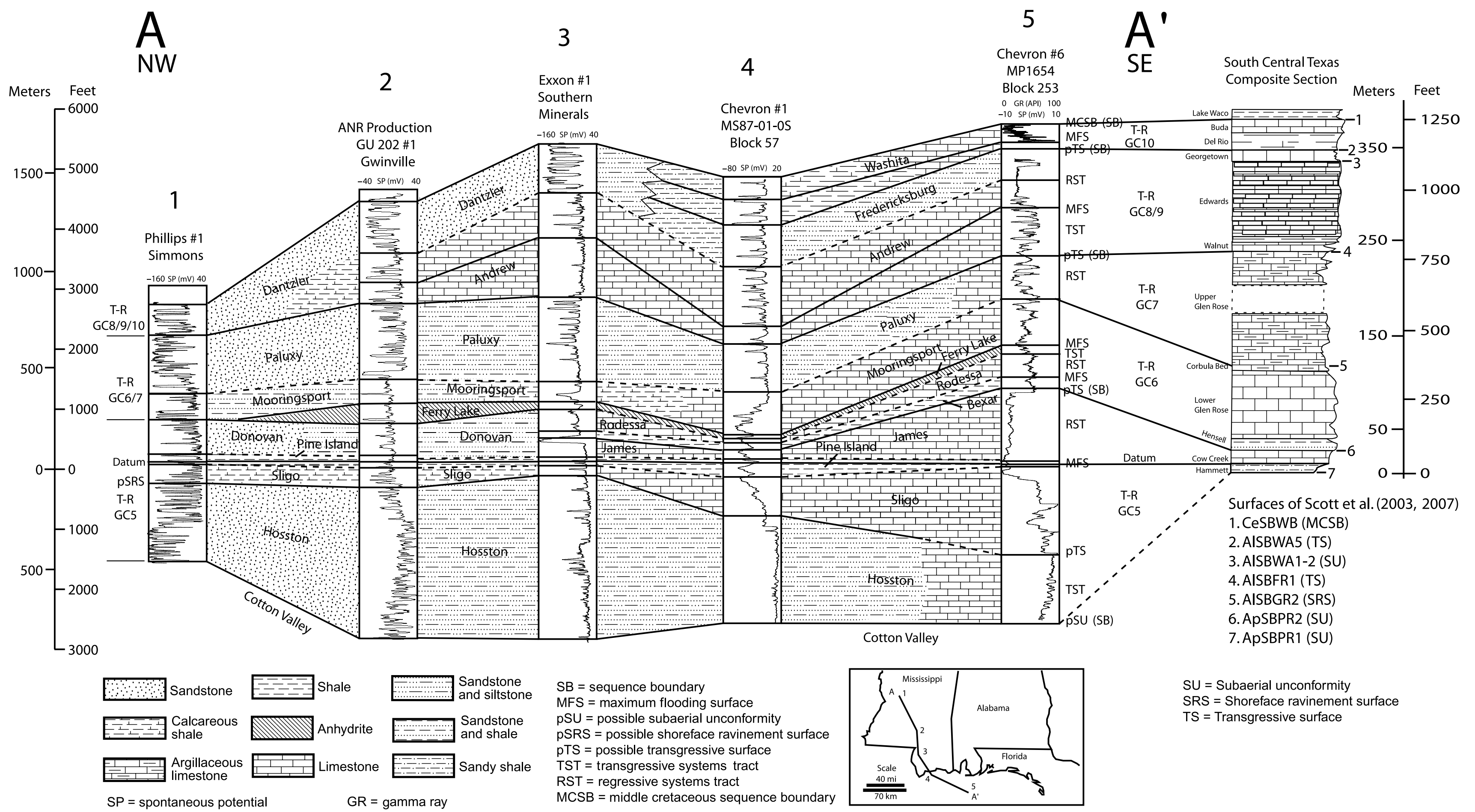

Figure 13. Northwest to southeast cross section AA′ showing the correlation of Lower Cretaceous strata from an inner shelf setting to an outer shelf setting and the correlation to Lower Cretaceous strata in outcrop along the Guadalupe and Blanco Rivers, Comal and Hayes counties, south-central Texas, western Gulf coastal plain. The Lake Waco Formation is part of the Eagle Ford Group. The Del Rio Clay is equivalent to the Grayson Formation, and the Hensell Sand Member is equivalent to the Bexar Shale Member (Figure 3). See Figure 1 for the site of the Lower Cretaceous composite measured section, and Figure 2 for the location of wells and line of cross section. T-R = transgressive-regressive; GC = Gulf Coast.

Selma Group (Mooreville, Demopolis, and Prairie Bluff Chalk units) of the eastern Gulf coastal plain and the Annona and Saratoga chalk units of the central Gulf coastal plain were deposited during the Campanian and Maastrichtian (Pessagno, 1969; Mancini et al., 1996). The Austin chalk beds accumulated in the western Gulf coastal plain during the Coniacian to Campanian (Thompson et al., 1991). Erosion of local uplifts, primarily in the Cenomanian, Coniacian, and Campanian, provided terrigenous sediments in the Gulf coastal plain area periodically throughout the Late Cretaceous as a result of the reactivation of bounding basement faults and igneous activity (Miller, 1982; Sawyer et al., 1991; Zimmerman and Sassen, 1993; Adams, 2006).

Four Upper Cretaceous (Cenomanian–Maastrichtian) T-R sequences are identified across the Gulf Coast and the offshore northeastern Gulf of Mexico region based on outcrop, paleontologic, wireline log, core, and seismic data (Figure 3). These sequences include an upper transgressive interval of backstepping chalk, shale, sandstone, and interbedded sandstone and siltstone facies and a regressive interval of infilling chalk, shale, sandstone, and interbedded sandstone and siltstone facies. The middle Cenomanian to upper Turonian T-R GC11 sequence in the subsurface and the lower to lower upper Maastrichtian T-R GC14 sequence in outcrop also include a lower transgressive interval of aggrading coastal sandstone facies (Mancini and Puckett, 2003a). Although the middle to upper Campanian T-R GC13 sequence is recognized in outcrop across the Gulf coastal plain (Mancini and Puckett, 2003a) and in wireline log data in the North Louisiana Salt Basin (Mancini et al., 2008a), this sequence is not discerned in wireline log or seismic data in the eastern Gulf coastal plain and offshore northeastern Gulf of Mexico (Figures 7, 14, 15) because in these areas the lithologies of this sequence are similar to those of the underlying middle Coniacian to upper Campanian T-R GC12 sequence. This Coniacian to Campanian stratigraphic interval consists of a section composed of alternating marl and chalk strata, which includes a conformable maximum regressive surface in these areas. Therefore, detailed field studies are required to map the diagnostic stratal surfaces.

This case study demonstrates the use of an integrated biostratigraphic and sequence-stratigraphic framework for the correlation of Upper Cretaceous shoreline to slope strata in the northern Gulf of Mexico. Strata in the eastern Gulf coastal plain are correlated with strata in the western Gulf coastal plain using paleontologic and outcrop data (Figure 3). Also, strata in the eastern Gulf coastal plain are correlated with strata in the offshore northeastern Gulf of Mexico using outcrop, paleontologic, wireline log, core, and seismic reflection data (Mancini et al., 1996; Mancini and Puckett, 2002a; Liu, 2005).

This case study also shows that the identification of stratigraphic sequences and associated stratal surfaces is dependent on a contrast in sedimentary and lithologic characteristics of the rocks, the presence of distinctive stratal surfaces, and the resolution of the tools used for sequence-stratigraphic analysis. The ability to identify the T-R GC13 sequence in outcrop but not in the signature of wireline logs in the eastern Gulf coastal plain or in seismic refection data in the offshore northeastern Gulf of Mexico area illustrates this point. The regressive systems tract of the middle Coniacian to middle Campanian T-R GC12 sequence and the transgressive systems tract of the T-R GC13 sequence consist essentially of shelf chalk and marl from east-central Mississippi to the Cretaceous shelf edge in the offshore northeastern Gulf of Mexico. Changes in relative sea level were minimal, and significant siliciclastic influx into the area was low as evidenced by the Campanian section primarily consisting of marl and chalk. In east-central Mississippi, this sequence boundary is recognizable based on paleontologic criteria and subtle changes in sedimentary characteristics that indicate a change from a shallowing-upward section to a deepening-upward section in the basal part of the Demopolis Chalk (Figure 6A). However, field mapping has shown that the conformable maximum regressive surface within this chalk and marl section dividing this stratigraphic interval into two sequences in the middle shelf area of east-central Mississippi correlates to a shoreface ravinement surface, where lagoonal clay is overlain unconformably by nearshore glauconitic sand in the area of the Upper Cretaceous shoreline in northern Mississippi (Figure 6B).

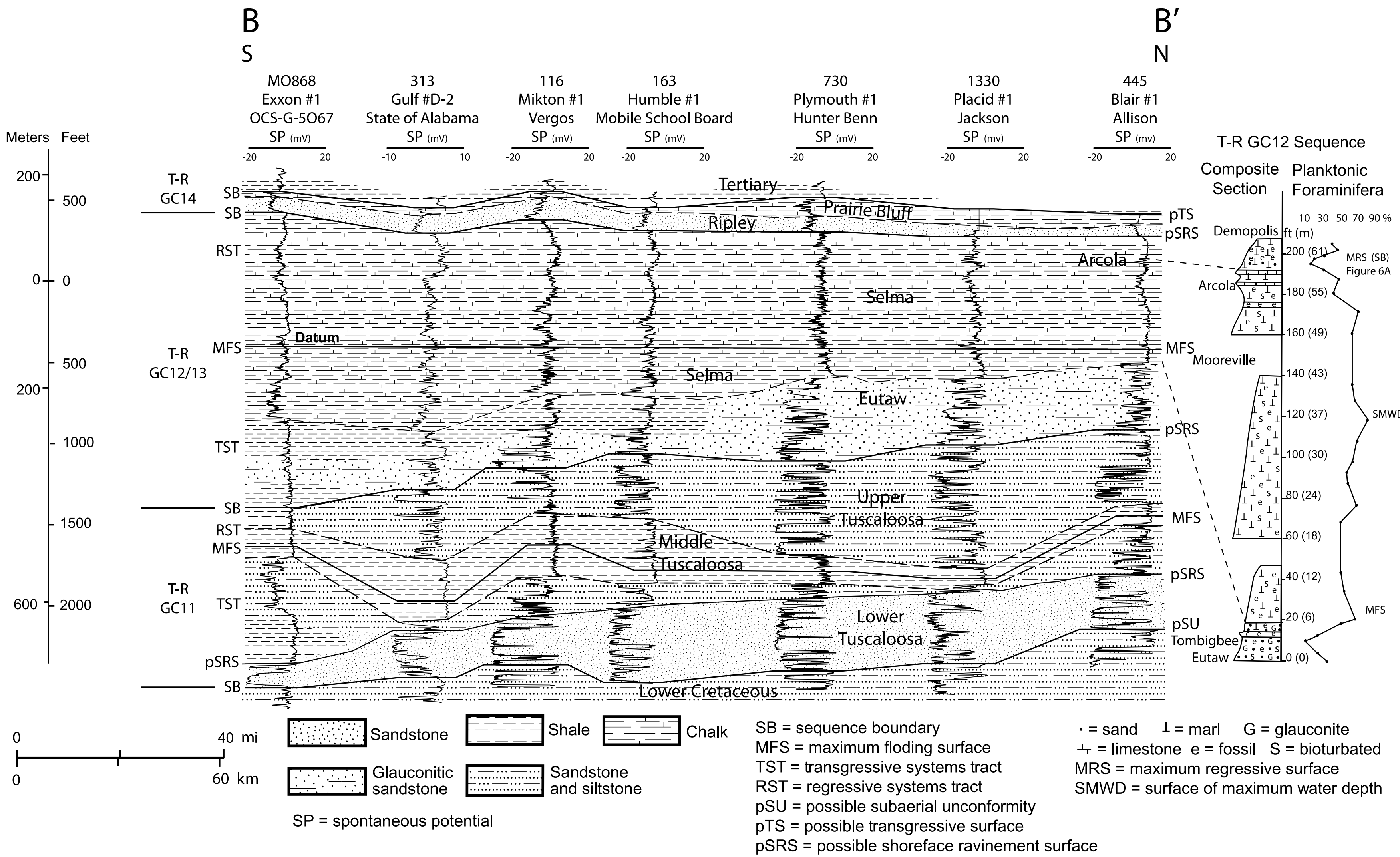

Figure 14. South to north cross section BB′ showing the correlation of Upper Cretaceous strata from an inner shelf setting to a middle shelf setting and the correlation of strata in outcrop along Tibbee Creek in eastern Mississippi to strata in the subsurface in the offshore northeastern Gulf of Mexico. See Figure 2 for the location of wells, site of the Upper Cretaceous composite measured section, and line of cross section. T-R = transgressive-regressive; GC = Gulf Coast.

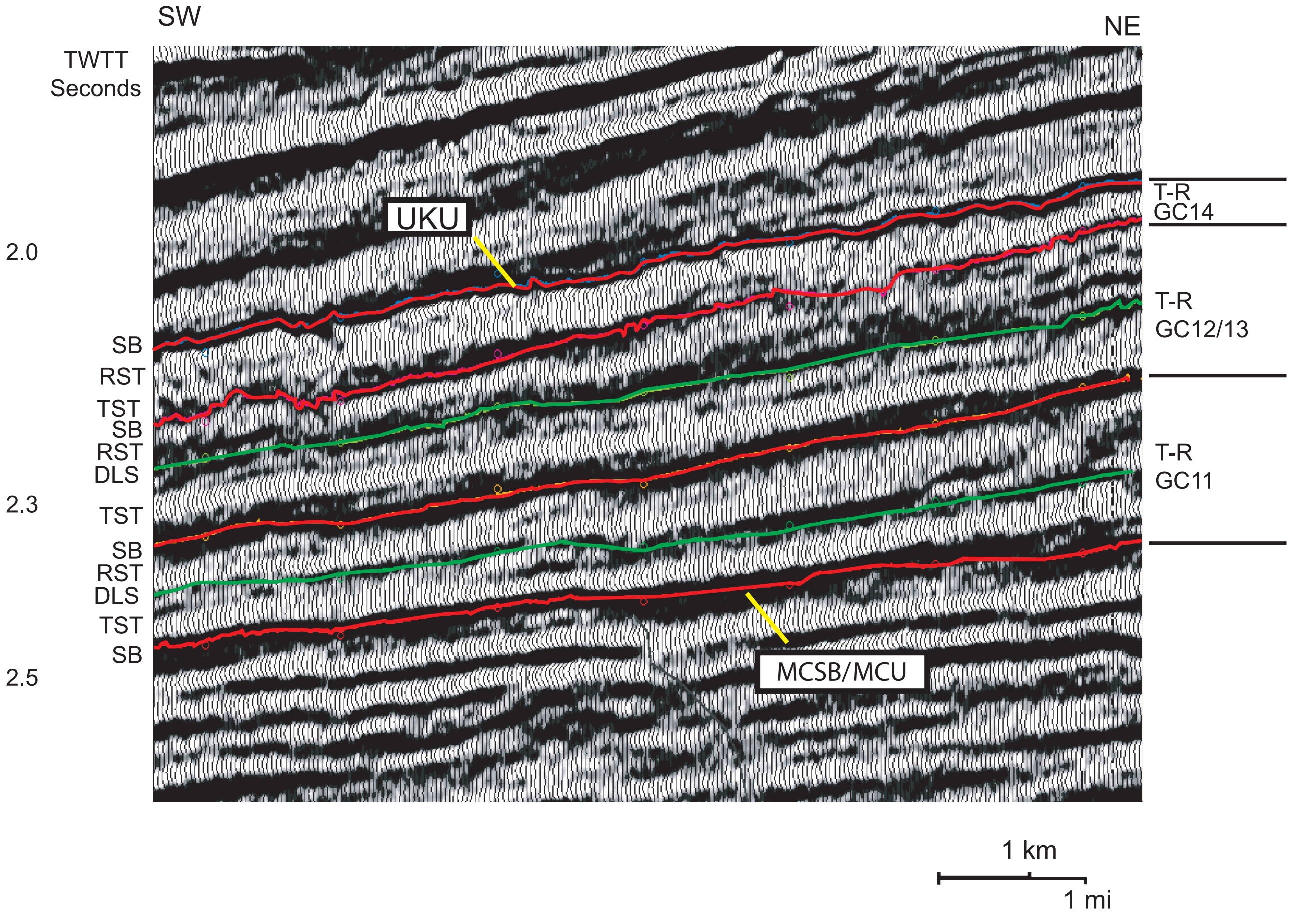

Figure 15. Seismic reflection section from the offshore northeastern Gulf of Mexico showing transgressive-regressive (T-R) sequences recognized in Upper Cretaceous strata (seismic interpretation by Liu, 2005). GC = Gulf Coast; SB = sequence boundary; DLS = downlap surface; TST = transgressive systems tract; RST = regressive systems tract; MCSB = middle Cretaceous sequence boundary; MCU = middle Cretaceous unconformity; UKU = Upper Cretaceous unconformity as described by Mancini et al. (1989); TWTT = two-way traveltime.

Thus, these facies and lithologic changes in association with the development of distinctive stratal surfaces are the main factors in the recognition of the T-R GC13 sequence in outcrop.

Vertical changes in the trend in the relative abundance of planktonic foraminifera (planktonic to benthic foraminiferal ratios) were used to identify regional marine flooding events and potential maximum flooding surfaces in this case study following the methodology of Armentrout et al. (1990) for recognizing condensed sections and maximum flooding surfaces. In studying Upper Cretaceous strata of the eastern Gulf coastal plain, Mancini et al. (1996) recognized four stratigraphic horizons, which were characterized by high counts of planktonic foraminifera, as potential maximum flooding surfaces. Two of the stratigraphic levels with high planktonic to benthic foraminiferal ratios included the Demopolis (upper Selma)-Ripley interval (T-R GC13 sequence) and the Ripley-Prairie Bluff interval (T-R GC14 sequence). Hancock (1993) also recognized these two horizons in the middle beds of the Demopolis and Prairie Bluff formations and referred to them as transgressive peaks. These two stratigraphic levels as seen in outcrop correspond to the subsurface horizons interpreted by Liu (2005) to represent maximum flooding surfaces in wireline log patterns (Figures 7, 14) and the downlap surfaces in seismic data (Figure 15) for these T-R sequences in southwest Alabama and the offshore northeastern Gulf of Mexico.

Mancini et al. (1996) recognized two additional horizons having higher counts in the relative abundance of planktonic foraminifera in the Tombigbee

(Eutaw)-Mooreville (lower Selma) interval. They selected the stratigraphic level in the middle to upper Mooreville beds with the highest counts of planktonic foraminifera as a potential maximum flooding surface, although they observed no sedimentologic evidence in these strata to support this interpretation. The stratigraphic level in the lower Mooreville directly above the Tombigbee-Mooreville contact also was characterized by a high planktonic to benthic foraminiferal ratio, but this count was not as high as the count of planktonic foraminifera as calculated for the horizon in the middle to upper Mooreville beds (Figure 14). The high count of planktonic foraminifera directly above the Tombigbee-Mooreville contact was interpreted by these authors to represent a change in facies. At this horizon, a transition from nearshore glauconitic sand to shelf marl and chalk is observed (Figure 14). Liu (2005) has shown that the maximum flooding surface for the T-R GC12 sequence as determined from the Mancini et al. (1996) study of outcrops does not correspond to the maximum flooding surface as recognized in the subsurface of southwest Alabama and the offshore northeastern Gulf of Mexico region. In the subsurface, the maximum flooding surface and downlap surface occur in the lower Selma (Mooreville) beds above the Eutaw-Selma contact (Liu, 2005). Therefore, in outcrop, the stratigraphic level in the transitional sandy marl beds of the lower Mooreville directly above the Tombigbee (Eutaw)-Mooreville (lower Selma) contact corresponds to the maximum flooding surface and downlap surface in the subsurface. The horizon with high counts of planktonic foraminifera in the middle to upper Mooreville beds probably represents the maximum water depth obtained in this interval. The surface of maximum water depth occurring stratigraphically above the surface of maximum sediment starvation and maximum flooding surface and in the lower part of the regressive systems tract or highstand systems tract is common because of differing rates and amounts of sediment accumulation and depositional conditions (Loutit et al., 1988; Naish and Kamp, 1997; Catuneanu et al., 1998; Liu, 2005). This example demonstrates that if only relative fossil abundance peaks are used to recognize a surface of maximum sediment starvation and maximum flooding surface, errors in stratal correlation can result.

INTRABASIN AND INTERBASIN CORRELATION

The Upper Jurassic and Cretaceous T-R sequences recognized provide a means for intrabasin and interbasin correlation of the strata in the Gulf coastal plain. Maximum flooding surfaces (and surfaces of maximum transgression of Mancini and Puckett, 2005) have been identified and correlated in this area by Mancini et al. (1996, 2004a), Puckett and Mancini (1998), Badali (2002), Mancini and Puckett (2002a, b; 2003a), Liu (2005), Mancini and Scott (2006), and Obid (2006) (Figure 3). These regional marine flooding surfaces have been observed to be the key for potential chronocorrelation by Mancini and Puckett (2005) because these surfaces are assumed to approximate synchronous horizons. Based on available biostratigraphic data, maximum flooding surfaces approximate synchroneity in strata of the eastern and western Gulf coastal plain areas (Mancini et al., 1996). Correspondence of these T-R sequences and their associated maximum flooding surfaces in the eastern Gulf coastal plain with those of the western Gulf coastal plain demonstrates the utility of constructing an integrated sequence-stratigraphic and biostratigraphic framework for regional correlation.

BASIN GEOHISTORY INTERPRETATION

By using an integrated sequence-stratigraphic and biostratigraphic approach for the northern Gulf of Mexico, the geohistory of the basins in this area can be interpreted. Integral to this interpretation is the assumption that maximum marine flooding surfaces identified and correlated provide reasonable data for chronocorrelation and that these surfaces approximate synchronous horizons. Major marine flooding events include the following: Oxfordian (Smackover), Kimmeridgian (Haynesville), Berriasian (Cotton Valley and Knowles), Aptian (Pine Island or Hammett and Bexar), Albian (Ferry Lake or Glen Rose , Fredericksburg, and lower Washita), Cenomanian (upper Washita), Turonian (Tuscaloosa or Eagle Ford), Campanian (Mooreville or Browstown and Demopolis or Marlbrook), Maastrichtian (Prairie Bluff or Arkadelphia or Corsicana). The Oxfordian, Aptian, Albian, Turonian, Campanian, and Maastrichtian events represent widespread marine transgressions in the northern Gulf of Mexico (Salvador, 1991; Mancini and Puckett, 2005).

During the late Callovian to early Oxfordian, middle Valanginian, and middle Cenomanian, tectonic subsidence rates and stratigraphic base level were high in the Gulf coastal plain, resulting in the production of substantial accommodation space (Mancini and Puckett, 2005). These conditions resulted in the accumulation of transgressive aggrading eolian and fluvial deposits of the Norphlet Formation, the aggrading fluvial and coastal deposits of the Hosston Formation, and the aggrading fluvial and coastal deposits of the lower sandstones of the Tuscaloosa Group (Mancini and Puckett, 2003b). These aggrading facies accumulated during an initial rise in stratigraphic base level that postdated the fall in base level that produced the widespread Callovian–Oxfordian, Valanginian, and Cenomanian regional unconformities recognized in the northern Gulf of Mexico (Buffler, 1991; McFarlan and Menes, 1991; Salvador, 1991; Mancini and Puckett, 2005). Salvador (1991) provided a series of paleogeographic maps for key time intervals for Mesozoic deposition in the northern Gulf of Mexico.

Major base-level falls in the Gulf coastal plain occurred during the Callovian–Oxfordian (Louann–Norphlet interval), Valanginian (Cotton Valley–Hosston interval), Cenomanian (Dantzler or Washita–Tuscaloosa and Washita–Woodbine intervals), Turonian to Coniacian (Tuscaloosa–Eutaw and Eagle Ford–Tokio or Austin intervals), and Campanian to Maastrichtian (Ripley, Nacatoch, and Nacatoch–Corsicana intervals) (Pessagno, 1990; Buffler, 1991; McFarlan and Menes, 1991; Salvador, 1991; Thompson et al., 1991; Mancini et al., 1996). The Callovian–Oxfordian, Valanginian, and Cenomanian unconformities are especially significant products of these episodes of base-level fall (Buffler, 1991; McFarlan and Menes, 1991; Salvador, 1991).

APPLICATION TO PETROLEUM EXPLORATION

As shown in the case studies for Upper Jurassic and Cretaceous strata in the Gulf coastal plain, the formulation of an integrated sequence-stratigraphic and biostratigraphic framework facilitates the reconstruction of the geohistory of a basin. Knowledge of this geohistory is vital in the design of an effective petroleum exploration strategy. Also, an understanding of the tectonic, depositional, burial, and thermal maturation histories is important in modeling fluid-flow pathways in sedimentary basins, in performing petroleum system analysis, and in assessing the oil and gas resources of a basin as demonstrated by Mancini et al. (1999, 2003, 2006a, 2008a, b).

Mancini et al. (2006a) used an integrated stratigraphic classification in categorizing the petroleum reservoirs in the Gulf coastal plain. These reservoirs were classified as T-R systems tracts and facies (Table 1). The major oil reservoirs for the North Louisiana Salt Basin are Upper Cretaceous transgressive backstepping marine sandstone facies of T-R sequences. The chief gas reservoirs in this basin are Cretaceous regressive infilling nearshore marine, shelf, and reef carbonate facies and Cretaceous fluvial and marine sandstone facies (Tables 1, 2). The main oil reservoirs for the Mississippi Interior Salt Basin are Upper Cretaceous transgressive aggrading fluvial and coastal sandstone facies, and Upper Jurassic regressive infilling ramp and reef carbonate facies. The primary gas reservoirs are Cretaceous transgressive aggrading fluvial and coastal sandstone facies and transgressive backstepping marine facies, and Upper Jurassic regressive infilling ramp and reef carbonate facies. Transgressive aggrading eolian facies of the Upper Jurassic Norphlet Formation are a major gas reservoir in the offshore Alabama area (Mancini and Puckett, 2003b). The transgressive aggrading eolian and fluvial sandstone facies of the Norphlet Formation, the fluvial and coastal sandstone deposits of the Lower Cretaceous Hosston Formation, and the fluvial and coastal lower sandstone facies of the Upper Cretaceous Tuscaloosa Group have produced some 36% of the total gas volume for the onshore Mississippi and Alabama and offshore Alabama area (Mancini and Puckett, 2003b).

Table 1. Oil and Gas Production for the North Louisiana and Mississippi Interior Salt Basins by Reservoirs and Facies Associations of Transgressive-Regressive (T-R) Sequences*

	North Louisiana Salt Basin		Mississippi Interior Salt Basin		
Reservoir	Oil (bbl)	Gas (mcf)	Oil (bbl)	Gas (mcf)	T-R Facies**
Upper Cretaceous					
Arkadelphia/Monroe gas rock	44,038	7,452,904,183			RI
Selma/Jackson gas rock			39,205,424	224,393,889	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
Eutaw			301,449,711	1,754,506,272	TB
Tuscaloosa/Eutaw	3,971,873	75,601,381			TB/RI
Upper Tuscaloosa			26,338,415	19,226,238	RI
Lower Tuscaloosa			610,702,463	1,805,166,543	TA/TB
Lower Cretaceous					
Dantzler			783,201	72,450,931	RI
Fredericksburg/Andrew	1,643,190	34,409,159	56,943,318	255,821,157	RI
Paluxy	6,206,760	88,408,279	56,544,588	568,991,732	RI
Mooringsport	312,309	1,171,999	11,633,767	215,885,662	RI
Ferry Lake			7,381	8,175	TB
Rodessa/Donovan	198,858,232	5,615,080,804	235,162,019	314,331,628	RI
James	12,409	2,869,335	902,320	80,356,905	RI
Pine Island	8,745,072	545,229,418	543,856	676,027	TB
Sligo	140,715,109	3,557,065,945	30,927,220	157,859,597	TB
Hosston	12,896,970	1,641,948,296	54,887,990	995,065,210	TA
Upper Jurassic					
Cotton Valley	114,348,835	2,223,486,076	106,461,276	146,163,240	RI
Haynesville	13,923,298	152,081,744	6,421,491	349,786,844	RI
Smackover	33,800,601	271,765,406	522,979,535	4,069,721,819	RI
Norphlet			12,664,335	331,269,443	TA

*Production data for Louisiana are from the 2002 International Oil Scout Association Yearbook (2006, personal communication), production data for 2005 for Mississippi are from the Mississippi Oil and Gas Board (2006, personal communication), and production data for 2005 for Alabama are from the Alabama Oil and Gas Board (2006, personal communication).
**T-R facies associations: TA = transgressive aggrading; TB = transgressive backstepping; RI = regressive infilling.

Table 2. Summary of Oil and Gas Production from the North Louisiana and Mississippi Interior Salt Basins by Facies Associations of Transgressive-Regressive (T-R) Sequences*

Basin	T-R RI** Oil (billion/bbl)	T-R RI** Gas (tcf)	T-R TB** Oil (billion/bbl)	T-R TB** Gas (tcf)	T-R TA** Oil (billion/bbl)	T-R TA** Gas (tcf)
North Louisiana Salt Basin	0.369	15.841	1.306	11.334	0.013	1.642
Mississippi Interior Salt Basin	1.063	6.345	0.337	1.061	0.373	2.229
Total	1.432	22.186	1.643	12.395	0.386	3.871

*Production data for Louisiana are from the 2002 International Oil Scout Association Yearbook (2006, personal communication), production data for 2005 for Mississippi are from the Mississippi Oil and Gas Board (2006, personal communication), and production data for 2005 for Alabama are from the Alabama Oil and Gas Board (2006, personal communication).
**T-R facies associations: T-R RI = regressive infilling; T-R TB = transgressive backstepping; T-R TA = transgressive aggrading.

Petroleum source rocks in the central and eastern Gulf coastal plain are lime mudstone and marine shale of the transgressive backstepping facies association interval of T-R sequences (Figure 3). The Upper Jurassic Smackover transgressive lime mudstone beds are an effective regional source rock in the Gulf coastal plain, and Upper Cretaceous Tuscaloosa transgressive shale beds are an effective local source rock in the Mississippi Interior Salt Basin (Mancini et al., 2008a, b). Additional transgressive backstepping marine facies that have favorable petroleum source rock characteristics include Upper Jurassic and Lower Cretaceous Bossier, Pine Island, and Mooringsport shale beds. The Smackover lime mudstone and the uppermost Jurassic and Lower Cretaceous shale beds also serve as petroleum seal rocks along with anhydrite beds of the Upper Jurassic Buckner (mainly regressive infilling facies association) and of the Lower Cretaceous Ferry Lake (transgressive backstepping facies association).

The prediction of potential reservoir facies is important in the design of a cost-effective oil and gas exploration strategy. As illustrated by the hydrocarbon productivity of the transgressive aggrading reservoirs in the eastern Gulf coastal plain, these facies have excellent potential as exploration targets. The targets include Norphlet eolian and fluvial, Hosston fluvial and coastal, and lower Tuscaloosa fluvial and coastal sandstone facies. These aggrading facies association intervals exceed a thickness of hundreds of feet and have a widespread geographic distribution. The sandstone deposits are quartz rich having porosities of 12 to 28.5% and permeabilities of 4 to 495 md (Mancini and Puckett, 2003b). Other high-potential reservoir intervals include Upper Jurassic and Cretaceous regressive infilling fluvial to nearshore marine Haynesville, Cotton Valley, Rodessa (Donovan), Mooringsport, Paluxy, Fredericksburg, and Eutaw sandstone facies, and Upper Jurassic Smackover and Upper Cretaceous Selma (Jackson gas rock) marine shelf, ramp, and reef carbonate facies in the Mississippi Interior Salt Basin. In the North Louisiana Salt Basin, Upper Cretaceous transgressive backstepping nearshore marine sandstone facies of the Tokio, Ozan, and Nacatoch formations and regressive infilling nearshore marine, shelf, ramp, and reef carbonate facies of the Upper Jurassic Smackover, Lower Cretaceous Rodessa and Sligo, and Upper Cretaceous Arkadelphia (Monroe gas rock) formations and fluvial to marine sandstone facies of the Cotton Valley Group constitute high-potential reservoir intervals.

The T-R sequences, systems tracts, and facies associations are recognized by their characteristic wireline log signatures and seismic reflection configurations. The transgressive aggrading nonmarine and coastal facies association interval is typically characterized by a boxlike smooth gamma ray or static SP wireline log pattern (Figure 7) and by a thick (several seismic cycles) interval of seismic reflectors exhibiting an aggradational reflection configuration. The transgressive backstepping marine facies association interval is identified by an overall increase in gamma ray or a change to a more positive SP wireline log response (bell shaped) (Figure 7) and by a thin (commonly one to two seismic cycles) interval of seismic reflectors exhibiting a retrogradational reflection configuration (Figure 8). The regressive infilling marine to nonmarine facies association interval is recognized by an overall decrease in gamma ray or a change to a more negative SP wireline log pattern (funnel shaped) (Figure 7) and by a thick (several cycles) interval of seismic reflectors exhibiting a progradational reflection configuration (Figure 8).

CONCLUSIONS

In studying the interior salt basins and subbasins of the Gulf coastal plain of the United States that are filled primarily with Mesozoic postrift nonmarine to marine siliciclastic and carbonate deposits, the establishment of an integrated sequence-stratigraphic and biostratigraphic framework for these sedimentary basins was critical in the interpretation of basin geohistory and in the formulation of an effective strategy for petroleum exploration.

In using T-R sequences as the sequence-stratigraphic component of this classification, 14 sequences are recognized in Upper Jurassic and

Cretaceous strata of the Gulf coastal plain. The sequences consist of a transgressive systems tract that includes an aggrading nonmarine and coastal facies association and backstepping marine facies association and a regressive systems tract that consists of an infilling marine to nonmarine facies association. These sequences, systems tracts, facies associations, and their associated maximum flooding surfaces are useful for the correlation of Jurassic–Cretaceous strata in the northern Gulf of Mexico.

Knowledge of the characteristic wireline log signatures and seismic reflection configurations of the transgressive aggrading and backstepping and regressive infilling facies associated with the systems tracts of the T-R sequences facilitates the design of a petroleum exploration strategy to identify and delineate potential Upper Jurassic and Cretaceous nonmarine to marine siliciclastic and carbonate reservoir facies in the Gulf coastal plain.

The integrated sequence-stratigraphic and biostratigraphic classification described in this article is for Mesozoic postrift nonmarine to marine siliciclastic and carbonate strata in interior salt basins of the northern Gulf of Mexico. This classification has potential for application in other interior salt basins filled with postrift Mesozoic deposits.

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