Jurassic and Cretaceous Transgressive-Regressive (T-R) Cycles, Northern Gulf of Mexico, USA

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ABSTRACT: Establishment of a chronostratigraphic framework is fundamental to the correlation of strata and for the interpretation of the geohistory of a basin. For the onshore basins in the northern Gulf of Mexico, an integrated sequence stratigraphic and biostratigraphic approach has utility as a method for establishing such a framework. Eleven transgressive-regressive (T-R) cycles and numerous biozones are recognized in Jurassic and Cretaceous non-marine, coastal and marine shelf strata of basins of the northern Gulf of Mexico. The cycles consist of a transgressive phase (aggrading and backstepping intervals) and a regressive phase (infilling interval). Cycle recognition is based on stratal geometries, the nature of the cycle boundaries, facies stacking patterns and large-scale shifts in major facies belts. Cycles are primarily controlled by the change in accommodation space resulting from stratigraphic base-level changes (eustatic and tectonic effects) and sediment supply. Utilizing this integrated approach, 12 regional unconformities and 11 surfaces of maximum transgression (regional marine flooding surfaces) were identified as major events in the Mesozoic geohistory of the northern Gulf of Mexico region. The surfaces of maximum transgression have potential as events for chronocorrelation.

INTRODUCTION

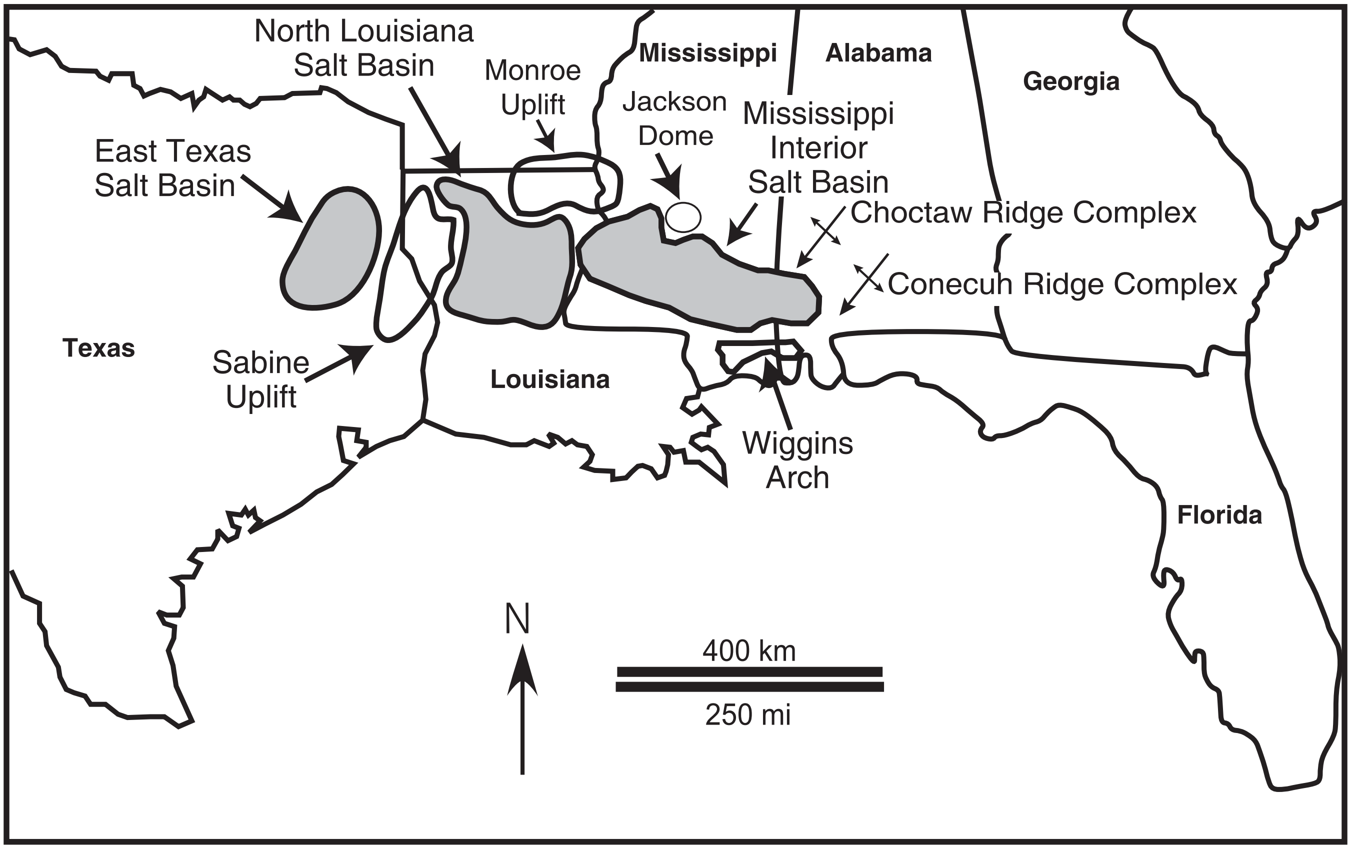
Stratigraphic analysis of sedimentary basins is critical for stratal correlation and the reconstruction of the geohistory of a basin. Many geoscientists utilize the concepts of sequence stratigraphy, and particularly third-order (1 to 10 million years in duration), unconformity-bounded depositional sequences 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) to provide the stratigraphic framework. These depositional sequences, bounded by unconformities or correlative conformities and their inherent systems tracts, 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). However, as demonstrated by Mancini and Puckett (2002a,b), stratigraphic analysis based on the cyclicity (transgressive-regressive cycles) recorded in the strata has utility as a method for establishing a stratigraphic framework for correlation and for interpreting the geohistory of basins in the northeastern Gulf of Mexico area (text-fig. 1).

Although the stratigraphic architecture on passive continental margins, such as the Gulf of Mexico, is created by the complex interaction of sea level, climate, sediment supply and tectonics, the effect of each of these factors is difficult to discern. Due to the relatively stable nature of passive margins, changes in sea level typically have been attributed as the primary force driving stratal patterns (Jervey 1988). However, factors governing the geometry of non-marine strata accumulating above sea level are principally controlled by base level changes (Schumm 1993; Shanley and McCabe 1994; Currie 1997; Martinsen et al. 1999). Thus, the stratal patterns of the Jurassic and Cretaceous non-marine and coastal sediments deposited in shelfal areas of the northern Gulf of Mexico are affected by changes in sediment supply, climate and tectonics in addition to sea level changes. The stratal patterns of these strata are better viewed as being affected by changes in stratigraphic base level as defined by Martinsen et al. (1999) as a point above which sediments erode and below which sediments accumulate.

The purpose of this paper is to demonstrate the merits of using an integrated sequence stratigraphic and biostratigraphic approach for establishing a chronostratigraphic framework for the correlation of strata and for interpreting the geohistory of a basin. This exercise is accomplished by analyzing the Jurassic and Cretaceous strata of the northern Gulf of Mexico. The transgressive-regressive cycle interpretation is integrated with the existing biostratigraphic data available for the region and the resulting stratigraphic framework is compared to that of the Jurassic and Cretaceous for Western Europe.

TRANSGRESSIVE-REGRESSIVE CYCLES

The transgressive-regressive (T-R) cycles used in this paper follow the concept of these cycles (sequences) as discussed by Johnson et al. (1985), Steel (1993), Embry (1993, 2002), Jacquin and de Graciansky (1998) and Mancini and Puckett (2002a,b). T-R cycles are comprised of a transgressive phase that consists of an upward deepening event and a regressive phase that consists of an upward shallowing event (Johnson et al. 1985). Jacquin and de Graciansky (1998) recognized T-R facies cycles in basins in Western Europe. They considered these facies cycles to be second order and stated that the cycles were comprised 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. Not all T-R facies cycles included all four phases. Mancini and Puckett (2002a) used these terms as phases or intervals of a single T-R cycle rather than as a sequence consisting of third order depositional sequences. Embry (1993) divided a



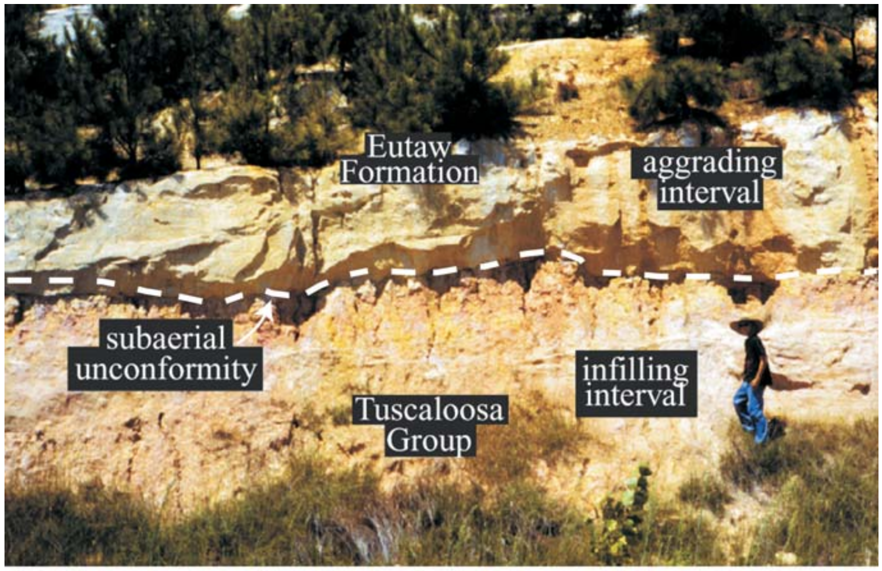
TEXT-FIGURE 1
Sedimentary basins in the onshore area of the northern Gulf of Mexico.

T-R sequence into a transgressive system tract and a regressive system tract separated by a maximum flooding surface. He (2002) employed a subaerial unconformity or shoreface ravinement unconformable surface to identify the unconformable portion of the boundary of a T-R sequence and a maximum regressive surface to recognize the conformable portion of a sequence boundary. Mancini and Puckett (2002a) recognized T-R cycles based on a combination of factors including the nature of the cycle boundaries, stratal geometries, facies stacking patterns within cycles and large-scale shifts in major facies boundaries. These cycles are separated by unconformities, such as a subaerial unconformity (text-fig. 2A,B), ravinement surface (text-fig. 3A), transgressive surface (text-fig. 3B) or discontinuities that may be conformable, such as a surface of maximum regression (text-fig. 4A), which separates an upward shallowing interval from an upward deepening interval. An early transgressive aggrading interval generally rests on a subaerial unconformity (text-fig. 2A,B). An erosional ravinement surface (text-fig. 3A) or transgressive surface separates the aggrading interval from the late transgressive backstepping interval. The transgressive phase or upward deepening section (aggrading and backstepping intervals) is separated from the regressive phase or upward shallowing section (infilling interval) by a surface of maximum transgression (text-fig. 4B).

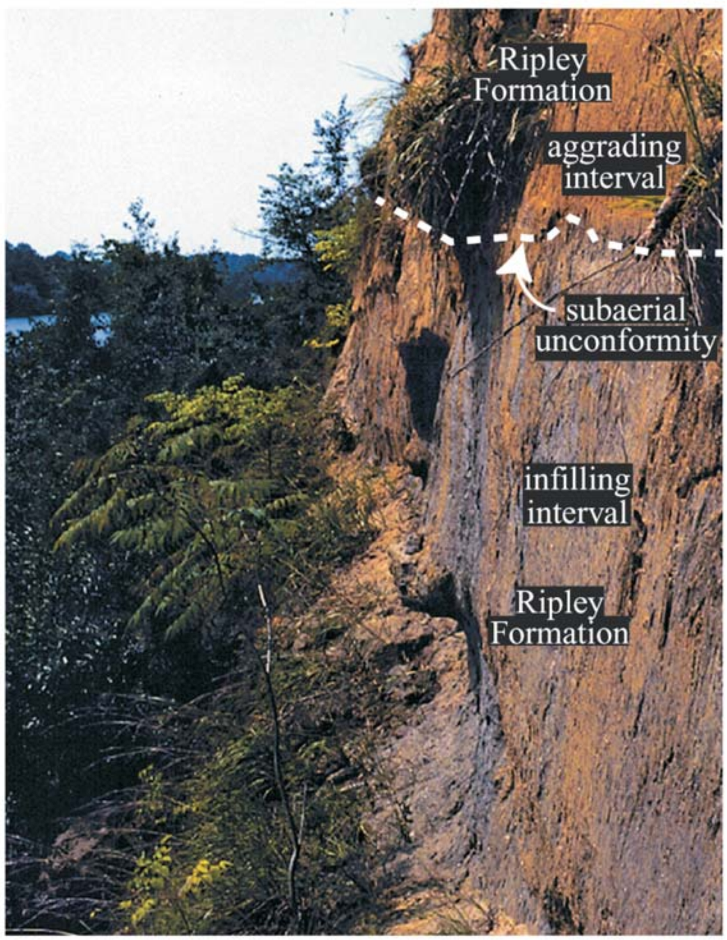
Controls on T-R Cycles

Some geoscientists working in the non-marine realm (Schumm 1993; McCabe 1994; Currie 1997; Martinsen et al. 1999) have concluded that stratigraphic base level is the key factor driving non-marine stratal architecture. For non-marine sediments to accumulate, base level must be at a higher elevation than sea level. To illustrate this point, sea level is held constant in Figure 5 to determine the behavior of strata relative to the sediment surface, sea level and stratigraphic base level. In this case, stratigraphic base level, sea level and the sediment surface intersect at the shoreline. This convergence produces an erosional ravinement or transgressive surface. In a direction seaward of the shoreline, base level and sea level are converged and accommodation space is created and is defined as the interval between the sediment surface and sea level. Landward of the shoreline, sea level and base level diverge, with base level rising to some elevation above sea level. This divergence and the rise of stratigraphic base level above the sediment surface produces accommodation space and results in the accumulation of sediments as part of the transgressive phase of the cycle. This early portion of a T-R cycle is the aggrading interval. Thus, in the non-marine realm, accommodation space is defined as the interval between the sediment surface and stratigraphic base level. Tectonics, sea level, sediment supply, and climate are factors affecting the partitioning of these sediments.

Using the concept of stratigraphic base level, deposition of non-marine strata above a subaerial unconformity is explained. With an increase in accommodation space and continuing siliciclastic sediment influx into an area, aggradational and progradational processes remain active. With a reduction in accommodation space and where sediment input is insufficient to support continued progradation, the agents of erosion shift the sediment in a seaward direction resulting in the development of an unconformable surface. This shift represents a drop in strati-

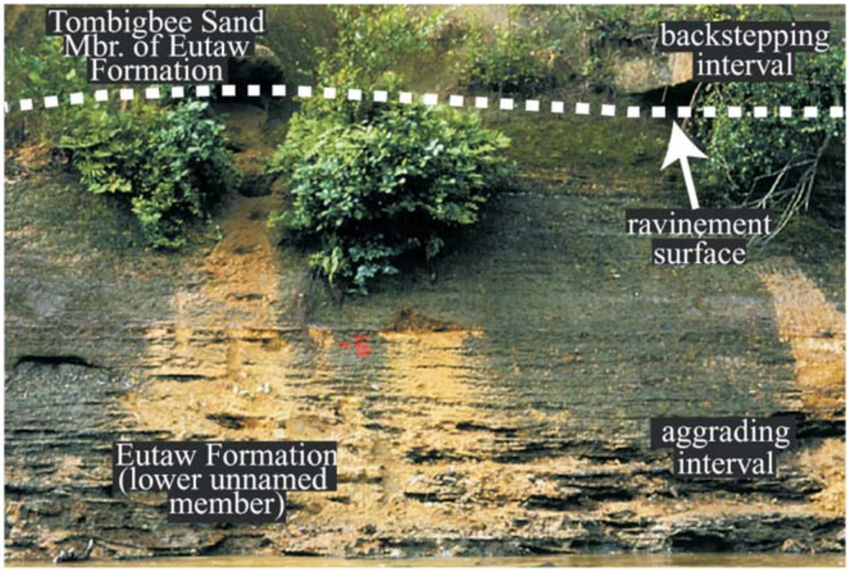


A.

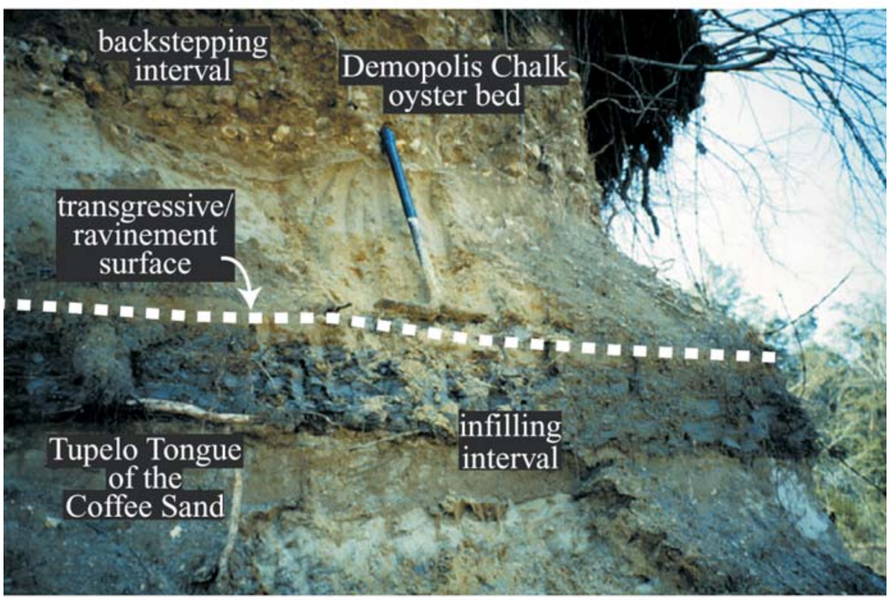


B.

TEXT-FIGURE 2
Photographs of outcrops showing significant T-R cycle surfaces. A. Subaerial unconformity at the contact of the Tuscaloosa Group (fluvial deposits) and the Eutaw Formation (tidal deposits) in Phenix City, Russell County, Alabama. This unconformity marks the base of the T-R K6 cycle; and B. Subaerial unconformity in the Ripley Formation at Red Bluff on the Alabama River, southwest of Selma, Dallas County, Alabama. This intraformational unconformity marks the base of the T-R K8 cycle.



A.



B.

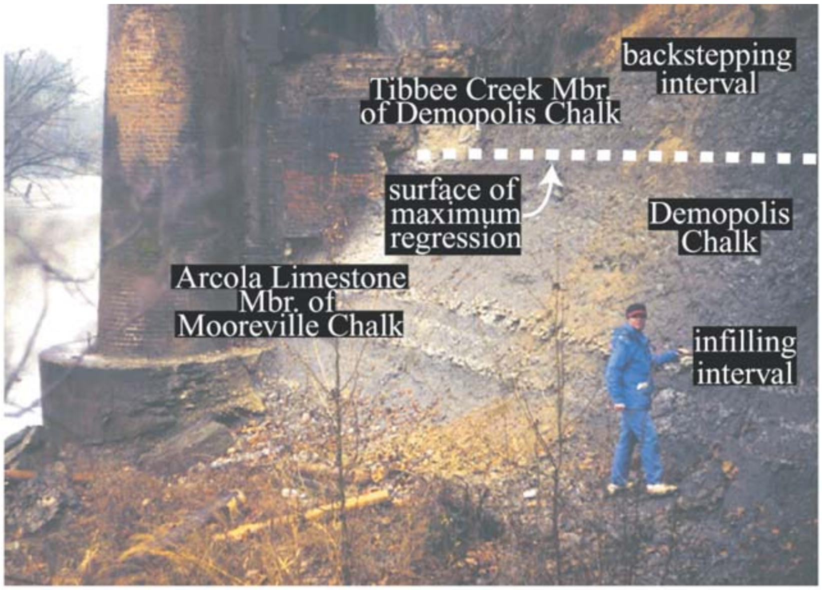
TEXT-FIGURE 3
Photographs of outcrops showing significant T-R cycle surfaces. A. Ravinement surface at the contact of the lower unnamed member of the Eutaw Formation (tidal deposits) and the Tombigbee Sand Member of the Eutaw Formation (shoreface deposits) at Barton's Bluff on the Tombigbee River, northeast of West Point, Clay County, Mississippi. This surface marks the base of the transgressive backstepping interval of the T-R K6 cycle; and B. Transgressive surface at the contact of the Tupelo Tongue of the Coffee Sand (nearshore deposits) and the Demopolis Chalk (marine shelf deposits) at Frankstown, Prentiss County, Mississippi. This surface marks the base of the transgressive backstepping interval of the T-R K7 cycle.

graphic base level below the sediment surface and results in a loss of accommodation space. As long as stratigraphic base level remains below the sediment surface over a large geographic area, a regional subaerial unconformity results. With renewed sediment influx, stratigraphic base level rises above the sediment surface, accommodation space is created and sediments are deposited. As the sediment surface remains between sea level and stratigraphic base level, non-marine deposits accumulate. With a sea-level rise above the sediment surface, marine sediments are deposited.

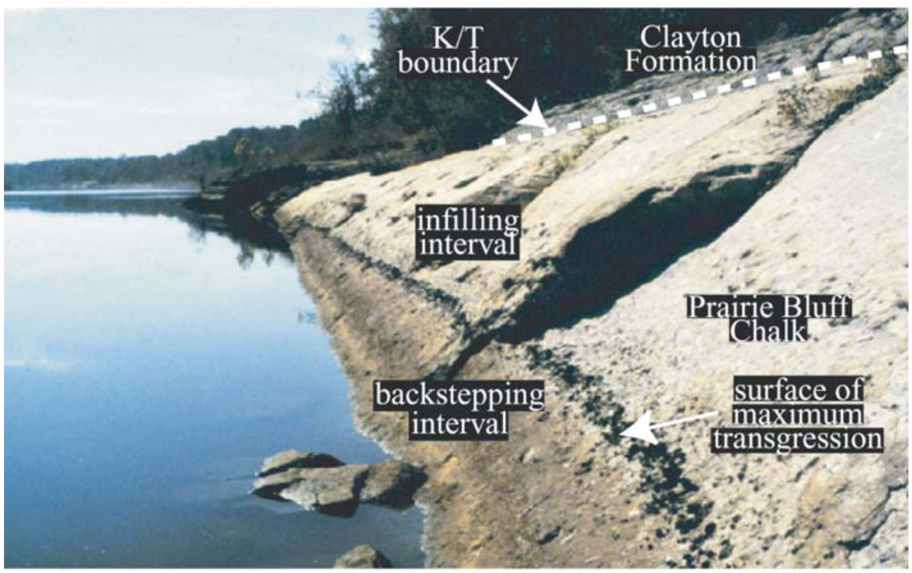
Jurassic and Cretaceous T-R Cycles

Eleven T-R cycles are recognized in Jurassic and Cretaceous strata of the northern Gulf of Mexico based on seismic reflection, wireline log, well core, paleontologic and outcrop data. For strata observed in outcrop, stratal geometries, the nature of the cycle boundaries, and facies stacking patterns can be viewed and determined.

For subsurface strata, the following well log responses were used to recognize the T-R cycles. A change from higher to



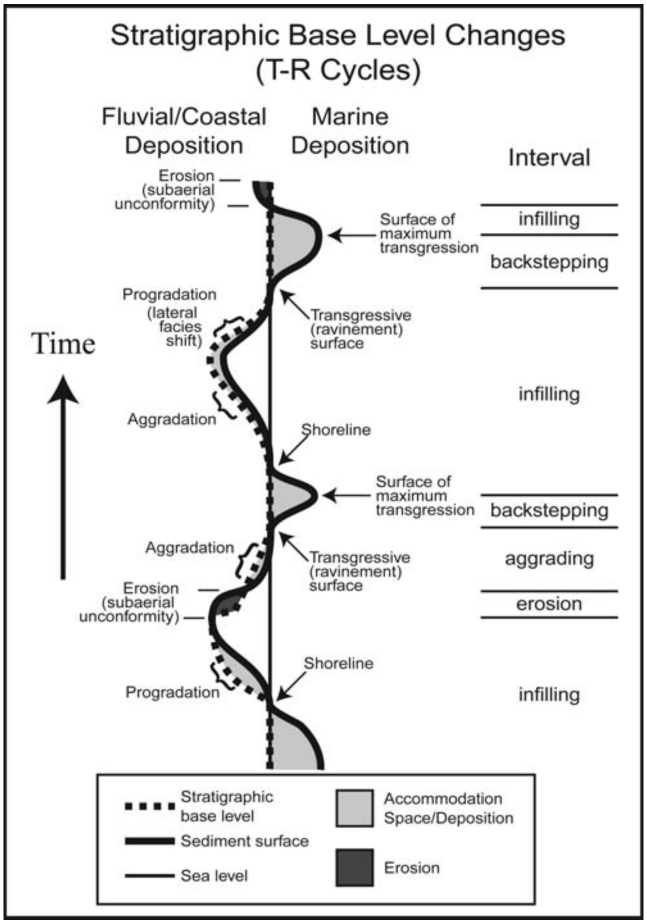
A.



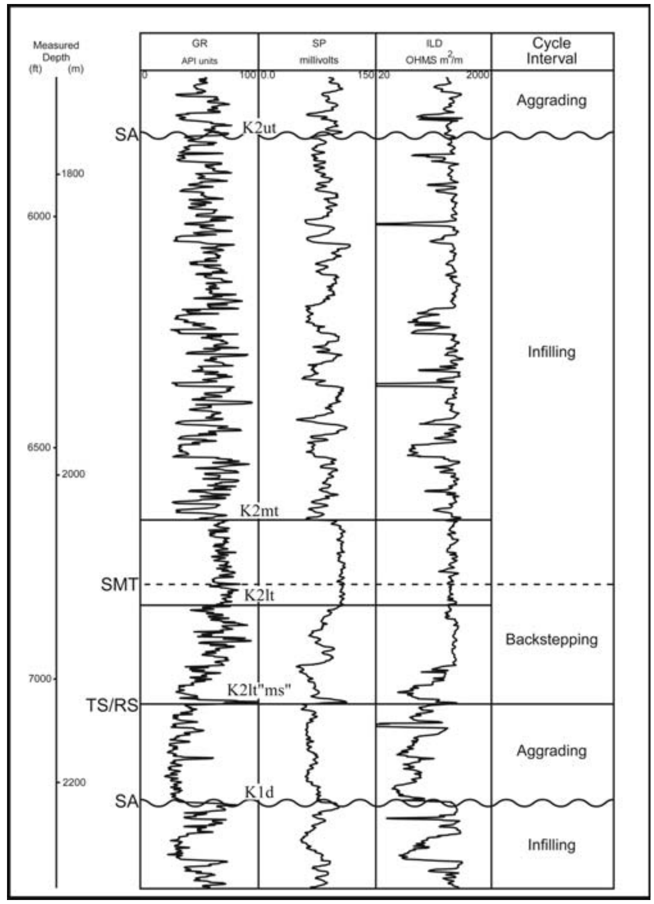
B.

TEXT-FIGURE 4
Photographs of outcrops showing significant T-R cycle surfaces. A. Surface of maximum regression at the contact of the Arcola Limestone Member of the Mooreville Chalk (marine shelf deposits) and the Tibbee Creek Member of the Demopolis Chalk (marine shelf deposits) on Tibbee Creek near Tibbee, Clay County, Mississippi. This conformable surface corresponds to the transgressive surface observed at Frankstown (text-fig. 3B) that marks the base of the transgressive backstepping interval of the T-R K7 cycle; and B. Surface of maximum transgression in the Prairie Bluff Chalk at Moscow Landing on the Tombigbee River, southwest of Demopolis, Sumter County, Alabama. This surface divides the transgressive backstepping marine shelf marl section from the regressive infilling marine shelf chalk section of the T-R K8 cycle.

lower gamma ray and/or from more to less positive SP log responses identifies the discontinuity in the log records used to recognize the surface of maximum transgression (text-fig. 6). This discontinuity separates the transgressive phase from the regressive phase of a T-R cycle. In general, an overall increase in gamma ray or change to more positive SP log response (bell-shaped or fining upward trend) from the top of a discontinuity (unconformity) in log pattern to the base of the surface of maximum transgression reflects a transgressive backstepping interval (Figs. 6, 7A,B), and an overall decrease in gamma ray or change to more negative SP log response (funnel-shaped or coarsening upward trend) from the top of the surface of maximum transgression to the base of a discontinuity (unconformity) in log pattern reflects a regressive infilling interval (Figs. 6, 7C). The infilling interval frequently consists of a series of these coarsening upward stacking patterns. A cylindrical gamma ray or SP log pattern is used to recognize the transgressive aggradational interval (Figs. 6, 7D).



TEXT-FIGURE 5
Diagram illustrating the factors affecting stratal architecture emphasizing the effect stratigraphic base level changes have on T-R cycle development in the non-marine and marine realm. Sea level is held constant to determine the behavior of strata relative to the sediment surface, sea level, and stratigraphic base level.



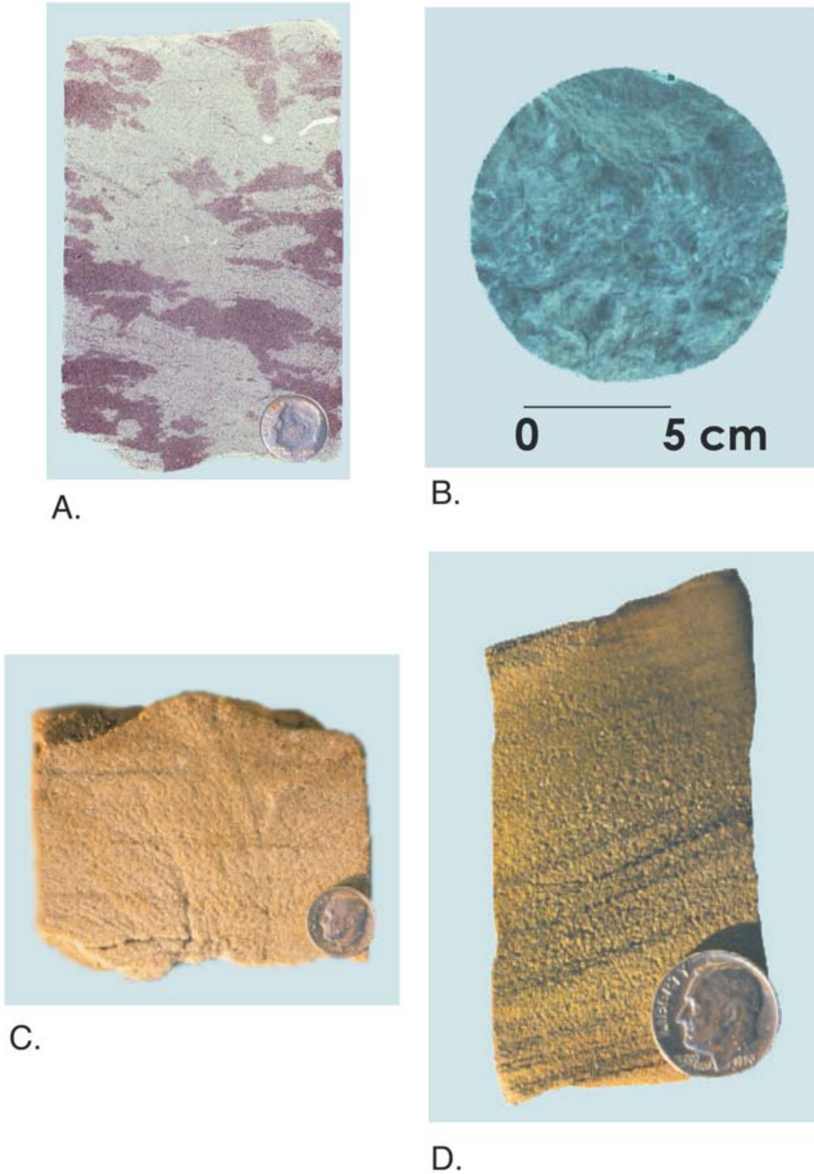
TEXT-FIGURE 6
Well log patterns from the Harrison #1 well, North Clark Field, Wayne County, Mississippi, showing the well log signature characteristics for the T-R K5 cycle and associated transgressive-regressive intervals. GR=gamma ray, SP=spontaneous potential, ILD=deep induction (resistivity). Kld=Lower Cretaceous Dantzler Formation; K2lt"ms"=Upper Cretaceous Tuscaloosa Group, "Massive sand"; K2lt=Lower Tuscaloosa Formation; K2mt=Marine Tuscaloosa, "Marine shale"; K2ut=Upper Tuscaloosa Formation. SA=subaerial unconformity, TS/RS=transgressive surface/ravinement surface, SMT=surface of maximum transgression.

With seismic reflection data, the following generalizations are used to recognize the T-R cycles. Thin (one or two seismic cycles), continuous, parallel seismic reflection configurations are interpreted as strata of the transgressive backstepping phase. These reflections are characterized by onlap reflection terminations (text-fig. 8). Thick (several seismic cycles), oblique, progradational seismic reflection configurations are interpreted as prograding clinoforms of the regressive infilling phase. These reflectors are characterized by offlap (downlap) reflection terminations.

Three T-R cycles (T-R J1, T-R J2 and T-R J3) of 7 to 10 million years in duration are recognized in Jurassic to Lower Cretaceous strata of the northern Gulf of Mexico (text-fig. 9). These cycles consist of a transgressive backstepping interval and a regressive infilling interval. The T-R J1 cycle also includes a lower transgressive aggrading interval.

Three T-R cycles (T-R K1, T-R K2 and T-R K3) of 5 to 19 million years in duration comprise the Lower Cretaceous section in the northern Gulf of Mexico (text-fig. 10). The T-R K1 cycle consists of a lower transgressive aggrading interval, an upper transgressive backstepping interval, and a regressive infilling interval. The T-R K2 and T-R K3 cycles include a transgressive backstepping interval and a regressive infilling interval. The transgressive backstepping interval of these cycles is characterized by marine shale and argillaceous lime mudstone, and the regressive phase includes progradational fluvial-deltaic siliciclastic beds that cap the cycles.

Five T-R cycles (T-R K4, T-R K5, T-R K6, T-R K7 and T-R K8) of 2.5 to 9 million years in duration comprise the Upper Cretaceous section in the northern Gulf of Mexico (text-fig. 11). The T-R K5, T-R K6 and T-R K8 cycles consist of a lower transgressive aggrading interval, an upper transgressive backstepping interval, and a regressive infilling interval. The T-R K4 and T-R K7 cycles include only transgressive backstepping and regressive infilling intervals. The transgressive aggrading interval of these cycles is composed of coastal plain and transitional marine siliciclastics. The trans-



TEXT-FIGURE 7
Photographs of well core slabs showing intervals of T-R cycles. A. Lower Tuscaloosa fine-grained, glauconitic marine sandstone of the transgressive backstepping interval of the T-R K5 cycle, Belden and Blake 3-9 well, Clarke County, Alabama, 1,616 m; B. Marine Tuscaloosa black claystone of the transgressive backstepping interval of the T-R K5 cycle, Belden and Blake 3-9 well, Clarke County, Alabama, 1,607 m; C. Dantzler fine- to medium-grained, fluvial, sandstone of the regressive infilling interval of the T-R K3 cycle, Boteler 10-7 well, Forrest County, Mississippi, 2,970 m; and D. Lower Tuscaloosa "Massive sand", fine- to medium-grained, coastal barrier sandstone of the transgressive aggrading interval of the T-R K5 cycle, Boone Clarke 1 well, Forrest County, Mississippi, 2,500m. Diameter of coin is 18mm.

gressive backstepping interval of these Upper Cretaceous T-R cycles consists of carbonate-rich marine deposits (fossiliferous shale, glauconitic and calcareous sandstone, marl and chalk beds), and the regressive infilling interval of these cycles includes progradational fluvial-deltaic siliciclastic beds that cap the cycles.

AGE DATING OF T-R CYCLES

The chronostratigraphic definitions for the Gulf Coast Jurassic and Cretaceous stage boundaries in this study are based on ammonite, foraminiferal, calcareous nannofossil and palynomorph biochronozones. The Jurassic (Oxfordian to Tithonian stages) ammonite zonation used is based on the work of Imlay and Hermann (1984) and Young and Oloriz (1993) (text-fig. 9). This ammonite zonation is supplemented with palynomorph data for the Callovian Stage from Kirkland and Gerhard (1971), calcareous nannofossil data for the upper Tithonian to Barremian stages from Cooper and Schaffer (1976), and tintinnid data for the upper Berriasian to Valanginian stages from Scott (1984). The Lower Cretaceous (Aptian and Albian stages) and Upper Cretaceous (Cenomanian Stage) ammonite zonation employed is based on the work of Young (1967, 1986) and Hancock et al. (1993) (text-fig. 10). This ammonite zonation is supplemented with benthic foraminiferal data for the lower Aptian from Petty et al. (1995). The Upper Cretaceous

(Cenomanian to Maastrichtian stages) planktonic foraminiferal zonation used is based on the work of Pessagno (1969), Smith and Pessagno (1973), Mancini (1979), and Caron (1985) (text-fig. 11).

Strata assigned to the various T-R cycles described in this paper are age-dated based on the occurrence of the key ammonite, foraminifera, calcareous nannofossil, and palynomorph species described from these strata. The work of Kirkland and Gerhard (1971), Cooper and Schaffer (1976), Scott (1984), Imlay and Hermann (1984), and Young and Oloriz (1993) was used for the Jurassic to the lower part of the Lower Cretaceous section. The work of Young (1966, 1967, 1986), Hancock et al. (1993) and Petty et al. (1995) was used for the Lower Cretaceous to the lower part of the Upper Cretaceous section. The work of Pessagno (1969), Smith and Pessagno (1973), Mancini (1979), and Mancini et al. (1980), Puckett (1995) and Mancini et al. (1996) was used for the Upper Cretaceous section. Based on the occurrence of the key species, biozones, biochronozones, and stage assignments were made. The Jurassic-Cretaceous time-scale of Gradstein et al. (1995) was used to determine the chronology of the T-R cycles.

Intrabasin and Interbasin Correlation

The Jurassic and Cretaceous T-R cycles recognized in the northern Gulf of Mexico provide a means for correlation of the strata within basins (Mississippi Interior Salt Basin) in the northeastern Gulf of Mexico and a means for correlation of Jurassic and Cretaceous strata in this area to Callovian to Maastrichtian strata in the northwestern Gulf of Mexico (East Texas Salt Basin) (text-fig. 1). Eleven surfaces of maximum transgression (regional marine flooding events) have been identified and correlated in the northern Gulf of Mexico area. These events include the following: late Oxfordian (Smackover), late Kimmeridgian (Haynesville), middle Berriasian (Cotton Valley), early Aptian (Pine Island), early Albian (Ferry Lake), middle Albian (Andrew), early Cenomanian (Washita), early Turonian (Tuscaloosa), middle Campanian (Mooreville), late Campanian (Demopolis), and early Maastrichtian (Prairie Bluff) (text-figs. 9-11). Correspondence of these T-R cycles and their associated surfaces of maximum transgression in the northeastern Gulf of Mexico with those of the northwestern Gulf of Mexico demonstrates the utility of T-R cycles when integrated with biostratigraphic data for regional correlation across the northern Gulf of Mexico area.

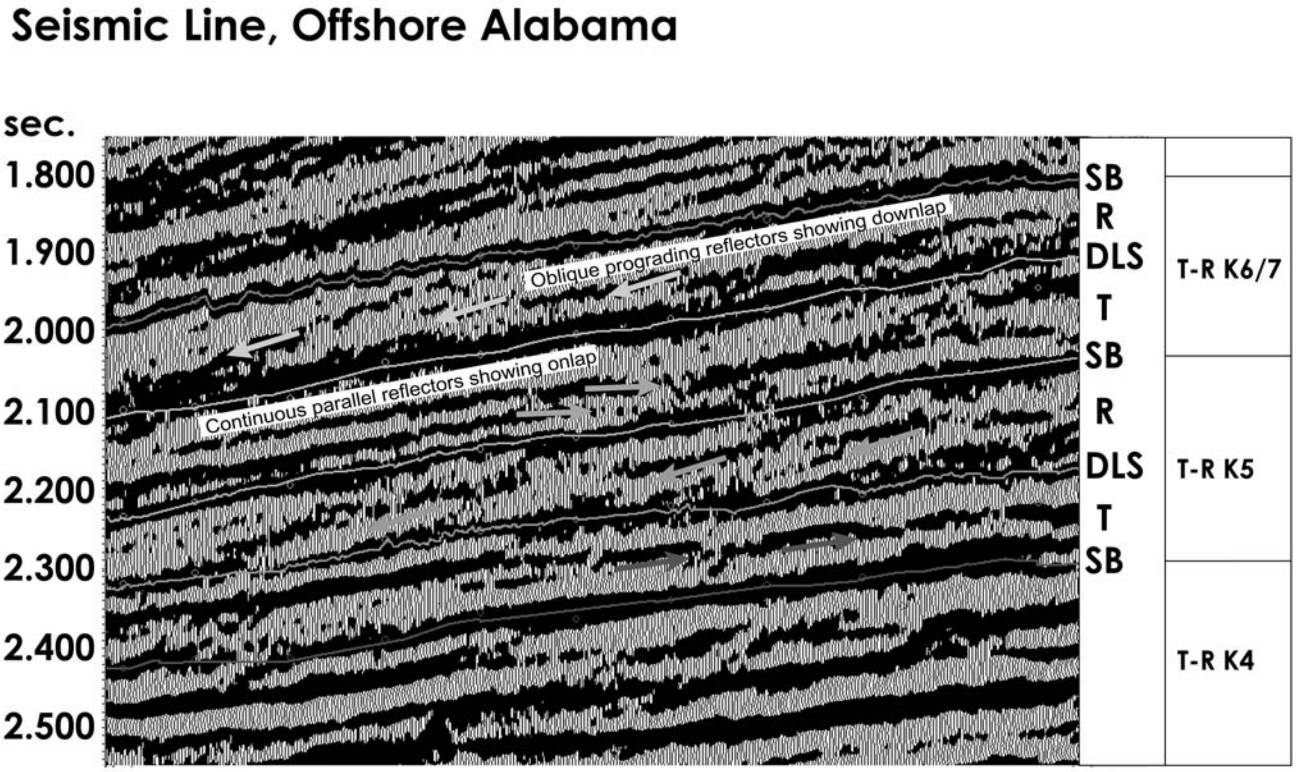
Global Correlation

The Jurassic and Cretaceous stratigraphic framework based on T-R cycles and biostratigraphy for the northern Gulf of Mexico when compared to the Jurassic and Cretaceous framework for Western Europe illustrates the degree of viability of this approach for global correlation. The surfaces of maximum transgression or regional marine flooding events observed for each region appear to be the key for potential chronocorrelation for these surfaces/events and are assumed to approximate synchronous horizons. Based on available biostratigraphic data, surfaces of maximum transgression (maximum flooding surfaces, regional marine flooding events) approach synchroneity in Upper Cretaceous strata of the northeastern Gulf of Mexico area (Mancini et al. 1996; Puckett and Mancini 1998).

The Jurassic and Cretaceous T-R cycles recognized for the northern Gulf of Mexico relate to the Jurassic and Cretaceous T-R facies cycles reported by Jacquin et al. (1998a, 1998b) and Hardenbol et al. (1998) for the Boreal areas of Western Europe. The Cretaceous T-R cycles for the northern Gulf of Mexico show some correlation with the T-R facies cycles for Western Europe; however, the Jurassic T-R cycles for the Gulf of Mexico indicate less correspondence with the T-R facies cycles for Western Europe. These correlation results are explained by the fact that the Jurassic strata in the northern Gulf of Mexico reflect the effects of the tectonic and depositional histories associated with origin of the Gulf of Mexico, while the Jurassic strata of Western Europe reflect the effects of the tectonic and depositional histories associated with the origin of the North Atlantic. The Jurassic deposits of the northern Gulf represent early post-rift sediments that accumulated during a time of maximum accommodation as a result of thermal cooling and subsidence. The Upper Cretaceous deposits in this region represent late post-rift sediments during a time of minimal tectonic activity and of the availability of less accommodation space, and therefore, stratal patterns are influenced more by changes in sea level. The post-rift Lower Cretaceous deposits in the northern Gulf of Mexico represent a transition from the Late Jurassic thermal subsidence event to a time of highstand of global sea level during the Late Cretaceous.

The T-R J1 cycle of the northern Gulf has a major marine flooding event in the late Oxfordian (text-fig. 12), while the major marine flooding during the Oxfordian in Western Europe occurs in the early Oxfordian (Hardenbol et al. 1998). This event in Western Europe occurs within the middle Callovian to upper Oxfordian Facies Cycle 8b of Jacquin et al. (1998a). The marine flooding event in the late Kimmeridgian associated with the T-R J2 cycle of the northern Gulf approximates the major marine flooding event in the late Kimmeridgian of Western Europe as indicated by Hardenbol et al. (1998). This event occurs in the upper Oxfordian to upper Tithonian Facies Cycle 9 of Jacquin et al. (1998a). Jacquin et al. (1998a) identify two subcycles in their Facies Cycle 9. Golonka and Kiessling (2002) reported a global transgression from the late Bathonian to the middle Tithonian with Jurassic sea level reaching its maximum during the Kimmeridgian. The T-R J3 cycle of the northern Gulf has a marine flooding event in the Early Cretaceous (Berriasian), which may correspond to the middle Berriasian marine flooding event associated with the upper Tithonian to upper Berriasian Facies Cycle 10 of Jacquin et al. (1998b). A major unconformity occurs in the lower to upper Valanginian strata in the northern Gulf. Golonka and Kiessling (2002) reported a middle Valanginian unconformity associated with what they considered to be the greatest fall in global sea level during the Late Jurassic and Cretaceous.

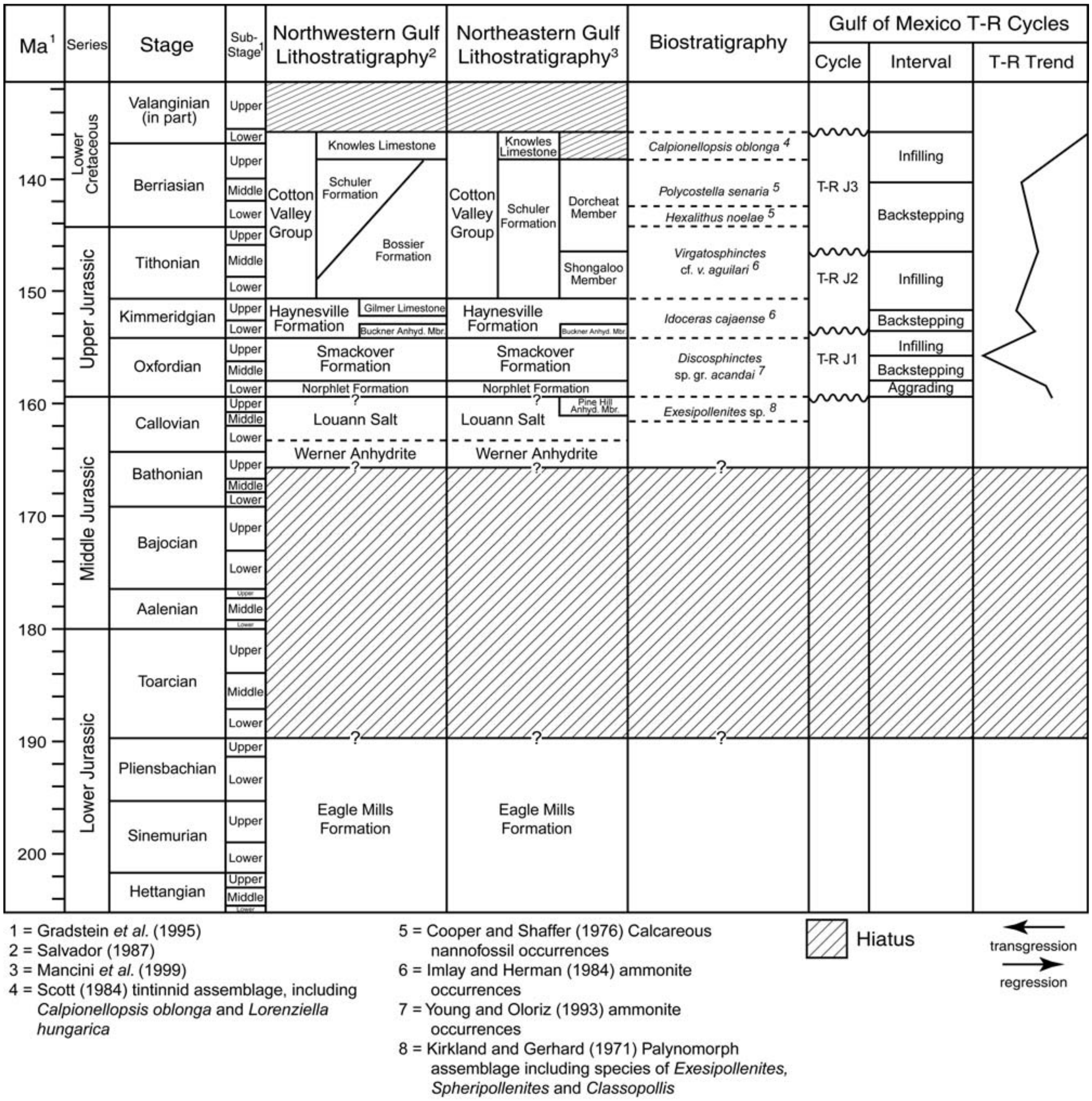
The Lower Cretaceous T-R cycles recognized in the northern Gulf (text-fig. 13) correlate somewhat with the Valanginian-Cenomanian facies cycles of Jacquin et al. (1998b) for Western Europe. The transgressive aggrading interval of the T-R K1 cycle broadly relates to the upper Valanginian-lower Aptian T-R Facies Cycle 12 of Western Europe. In this region, the basal unconformity of Facies Cycle 12a is a major erosional unconformity, and Facies Cycle 12d is a highly aggradational cycle (Jacquin et al. 1998b). In the Gulf, the T-R K1 cycle is defined by the Cotton Valley Group-Hosston Formation boundary. This cycle boundary is a major subaerial unconformity in this region. The transgressive backstepping and regressive infilling intervals (lower-upper Aptian) of the T-R K1 cycle of the Gulf show correspondence to the lower-upper Aptian T-R Facies Cycle 13 of Western Europe. This cycle represents one of the most widespread and correlatable events in the Mesozoic record of this region (Jacquin et al. (1998b). In the northern Gulf of Mexico,



TEXT-FIGURE 8
Seismic reflection profile from the offshore area of the northeastern Gulf of Mexico showing the seismic reflection configuration and termination characteristics of strata in the transgressive backstepping interval and the regressive infilling interval of the T-R K5 and T-R K6/7 cycles. SB=sequence boundary, T=transgressive phase, DLS=downlap surface, R=regressive phase. Interpretation of seismic line by Kaiyu Liu. Seismic line provided courtesy of WesternGeco.

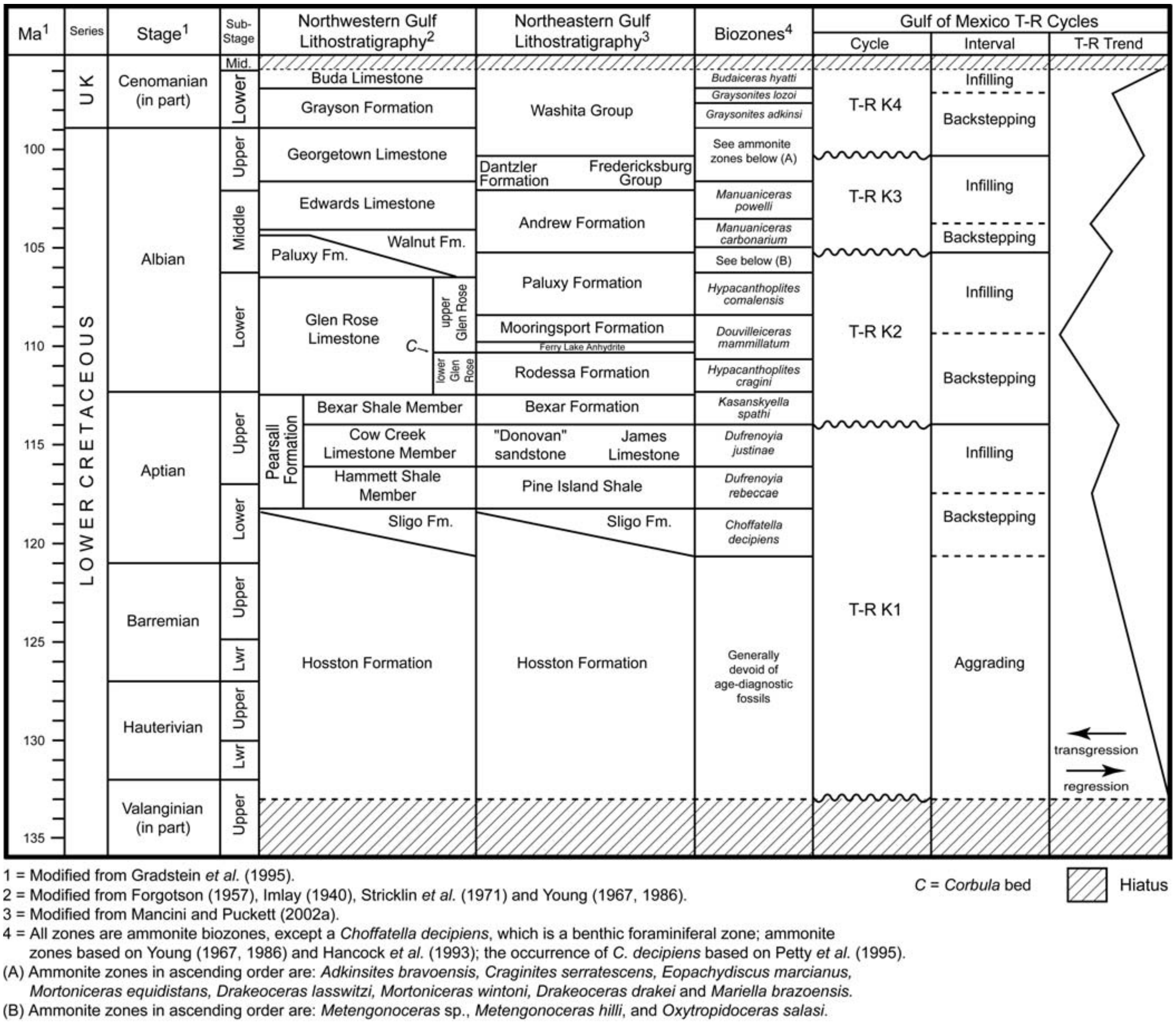
this cycle, in particular the transgressive backstepping interval (Pine Island Shale), has excellent utility for correlation in the onshore area of the Gulf. The upper Aptian-middle Albian T-R K2 cycle of the Gulf shows some correspondence with the upper Aptian-lower Albian T-R Facies Cycle 14a of Western Europe. Facies Cycle 14a is a widespread and correlatable event in this region, and in Tethyan areas it merges with Facies Cycle 14b producing Facies Cycle 14, which is one of the major marine flooding events in the Mesozoic record of Western Europe (Jacquin et al. 1998b). The T-R K2 cycle is the best correlation marker (Ferry Lake Anhydrite) in the Lower Cretaceous section in the northern Gulf of Mexico and represents the major transgression and maximum landward shift of Lower Cretaceous deposits in this region. Concurrent development of the regionally extensive Lower Cretaceous shelf margin reef complex during the T-R K2 cycle transgression resulted in widespread evaporite deposition at this maximum landward position of marine-related strata. The middle-upper Albian T-R K3 cycle of the Gulf relates to the lower-upper Albian T-R Facies Cycle 14b of Western Europe.

The Upper Cretaceous T-R cycles of the northern Gulf of Mexico show some correspondence to the Cenomanian to Maastrichtian T-R facies cycles of Western Europe (text-fig. 13). The upper Albian to lower Cenomanian T-R K4 cycle of the Gulf relates to the upper Albian to lower Cenomanian Facies Cycle 16 of Western Europe of Jacquin et al. (1998b) and Hardenbol et al. (1998). In Western Europe, Facies Cycle 16 may continue into the middle Cenomanian, which is a major relative sea level downward shift, and the duration of Facies Cycle 15 in this region is in question (Jacquin et al. 1998b). The mid-Cenomanian also was a time of major relative sea-level fall and erosion in the northern Gulf of Mexico producing the mid-Cretaceous (mid-Cenomanian age) subaerial unconformity of Salvador (1991) and associated hiatus of less than 1 to more than 20 million years (Mancini et al., 2002a). The upper middle Cenomanian to upper Turonian T-R K5 cycle shows correspondence with the middle Cenomanian to upper Turonian Facies Cycle 17 of Western Europe of Jacquin et al. (1998b) and Hardenbol et al. (1998). The early Turonian marine flooding event associated with this cycle represents a widespread transgression in the northern Gulf of Mexico (Salvador 1991) and in Western Europe (Hardenbol et al. 1998). In the northeastern Gulf of Mexico (Mancini et al. 1996) and in Western Europe (Hardenbol et al. 1998), an upper Turonian to Coniacian subaerial unconformity and associated hiatus of about 2 million years separates this cycle from the overlying cycle (Mancini et al., 2002b). The middle Coniacian to middle Campanian T-R K6 cycle of the northeastern Gulf of Mexico relates to the lower Coniacian to middle Campanian Facies Cycle 18 of Western Europe as defined by Jacquin et al. (1998b) and Hardenbol et al. (1998). Two subcycles are recognizable in Facies Cycle 18 in Western Europe. Golonka and Kiessling (2002) reported that globally the highest Phanerozoic sea level was recorded in the late Cenomanian to early Campanian. The T-R K6 cycle includes a late Santonian marine-flooding event. This marine



TEXT-FIGURE 9
Absolute ages, chronostratigraphic units, lithostratigraphic units, biostratigraphic units, and transgressive-regressive cycles of the Jurassic section of the northern Gulf of Mexico.

flooding event is also recognized in Western Europe in the late Santonian by Hancock (1993) and Hardenbol et al. (1998). Although the late Santonian event is recorded in the sediments of the northeastern Gulf of Mexico (Mancini et al. 1996), it has not been used to define an additional cycle for the updip area of this region because defining criteria, such as large-scale shifts in major facies belts and facies stacking patterns, have not been observed in association with this event. The middle to upper Campanian T-R K7 cycle of the northeastern Gulf of Mexico shows some correspondence to the middle Campanian to lower Maastrichtian T-R Facies Cycle 19 of Jacquin et al. (1998b) and Hardenbol et al. (1998). Two subcycles are recognizable in Facies Cycle 19 in Western Europe. In the northeastern Gulf of Mexico, the upper boundary of the T-R K7 cycle is defined by a major subaerial unconformity associated with about a 1.5 million year hiatus in the late Campanian to early Maastrichtian (Mancini et al., 2002b). The late Campanian marine flooding event associated with this cycle represents a widespread transgression in the northeastern Gulf of Mexico (Salvador 1991) and in Western Europe (Hancock 1993; Hardenbol et al. 1998). In Western Europe, the lower boundary of the uppermost facies cycle of the Upper Cretaceous (T-R Facies Cycle 20) is marked by an erosional unconformity in the early Maastrichtian (Hardenbol et al. 1998). The lower to lower upper Maastrichtian



TEXT-FIGURE 10
Absolute ages, chronostratigraphic units, lithostratigraphic units, biostratigraphic units, and transgressive-regressive cycles of the Lower Cretaceous section of the northern Gulf of Mexico (modified from Mancini and Puckett, 2002a).

T-R K8 cycle of the northeastern Gulf of Mexico generally relates to this lower to upper Maastrichtian Facies Cycle 20 of Western Europe of Jacquin et al. (1998b) and Hardenbol et al. (1998). The early Maastrichtian marine flooding event associated with this cycle represents a significant transgression in the northern Gulf of Mexico (Mancini et al. 1996) and in Western Europe (Hardenbol et al. 1998).

BASIN GEOHISTORY

By using an integrated sequence stratigraphic (T-R cycles) and biostratigraphic approach to establish a chronostratigraphic framework for the northern Gulf of Mexico, the geohistory of the basins in this area can be reconstructed. Key to this interpretation is the assumptions that the surfaces of maximum transgression (regional marine flooding events) identified and correlated provide reasonable datums for chronocorrelation and that these surfaces approximate synchronous horizons.

Subsidence rates observed for the Jurassic and Cretaceous strata in the northern Gulf of Mexico reflect the large-scale geological events of the region. During the Late Jurassic, tectonic subsidence rates were 40 m/my or 130 ft/my (Mancini et al., 2003). Thus, stratigraphic base level during this time was high resulting in the creation of substantial accommodation space. During the Early Cretaceous, tectonic subsidence rates were 22 m/my or 72 ft/my and during the Late Cretaceous, tectonic subsidence rates were 14 m/my or 46 ft/my. This progression from higher to lower subsidence rates was a function of the evolution from syn-rift to post-rift passive margin development.

During the earliest Oxfordian, early post-rift continental alluvial, fluvial, wadi, and eolian deposits of the Norphlet Formation accumulated in the northern Gulf of Mexico. Paleotopography had a significant impact on the distribution of Norphlet sediments (Mancini et al. 1985). With continued base-level rise, these continental deposits were reworked by marine processes resulting in the deposition of marine Norphlet sandstones followed by the accumulation of Smackover carbonates. Maximum marine flooding occurred in the late Oxfordian and resulted in the accumulation of Smackover lime mudstone. Smackover coral-microbial reefs formed in the western Gulf Coastal Plain and microbial reefal buildups developed in the eastern Gulf Coastal Plain at this time. With a reduction in the rate of sea-level rise, Smackover shoreface, shoal and tidal flat sediments were deposited. This reduction in accommodation space and the establishment of supratidal conditions produced the accumulation of sabkha anhydrite deposits of Buckner Anhydrite Member of the Haynesville Formation.

This fall in base level pre-dated the deposition of subaqueous (saltern) anhydrite beds of the Buckner Anhydrite Member in the eastern Gulf Coastal Plain and the accumulation of carbonates of the Gilmer Limestone in the western Gulf Coastal Plain. These arid and evaporitic conditions continued into the Kimmeridgian resulting in the deposition of interbedded lagoonal shale and anhydrite beds in the eastern Gulf Coastal Plain. Haynesville salt beds formed behind major barriers to ocean circulation, such as the Wiggins Arch, at this time. Base level continued to rise producing a marine flooding event and the deposition of interbedded shallow marine shale and limestone beds. With a reduction in accommodation and an increase in siliciclastic sediment supply in the late Kimmeridgian and Tithonian, interbedded marginal marine shale and sandstone beds of the upper Haynesville and marginal marine and coastal plain deposits of the Shongaloo Member of the Schuler Formation of the Cotton Valley Group accumulated. Offshore, seaward of the Wiggins Arch, Haynesville deposition consisted chiefly of carbonate deposits.

A rise in sea level post-dated this late Kimmeridgian to Tithonian base level fall and resulted in the deposition of the marine shelf shale beds of the Dorcheat Member of the Schuler Formation. A marine flooding event occurred in the middle Berriasian. With a reduction in siliciclastic sediment supply, marine shelf, shoal and reef deposits of the Knowles Limestone accumulated. This cycle is not evident in the eastern part of the eastern Gulf Coastal Plain. In this area, Lower Cretaceous (Valanginian) fluvial sandstones of the Hosston Formation unconformably overlie Upper Jurassic (Tithonian) Cotton Valley fluvial-deltaic sandstones. Throughout much of the northern Gulf of Mexico, this drop in base level is recorded in the Valanginian and results in the Hosston beds unconformably overlying the Knowles Limestone. The hiatus between the Cotton Valley Group and the Hosston Formation is represented by most of the Valanginian Stage. This unconformity and hiatus are recognized throughout the northern Gulf of Mexico .

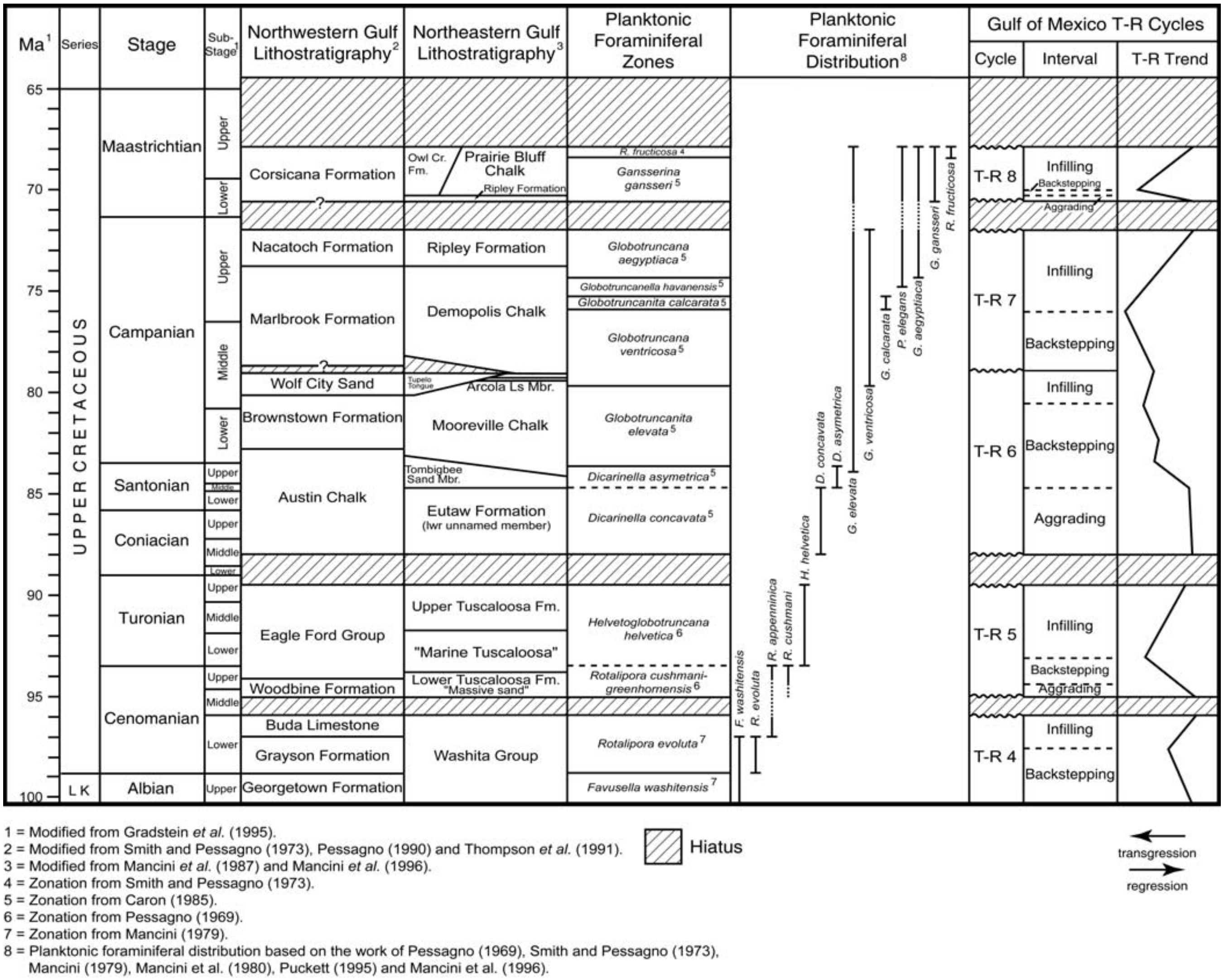
Coastal plain sandstone beds of the Hosston Formation were deposited during an initial rise in base level and increase in shelfal accommodation during the late Valanginian that post-dated a fall in base level and regional unconformity. Hosston fluvial-deltaic sediments later aggraded and prograded across the updip areas of the northern Gulf of Mexico. In offshore areas, where siliciclastic sediment supply was diminished, coastal fine-grained sandstone and shallow marine shale were deposited concurrently with Hosston fluvial-deltaic coarse-grained sandstone in updip areas during the late Valanginian to earliest Aptian. This interval is a highly aggradational to progradational section in the northern Gulf of Mexico, indicating the creation of shelfal accommodation during a time characterized by high rates of sediment supply.

During the early to late Aptian, marine shale, siltstone, and limestone of the Sligo Formation, Pine Island Shale, and Hammett Shale Member of the Pearsall Formation were deposited, representing a major rise in base level and marine flooding. In offshore areas and in the northwestern Gulf of Mexico, marine shelf and shelf margin reef limestone beds of the Sligo Formation, James Limestone, and Cow Creek Limestone Member of the Pearsall Formation were deposited at this time. This Aptian interval represents a widespread transgression in the northern Gulf of Mexico . The Pine Island, in particular, represents a regional transgression and transgressive peak . With a reduction in shelfal accommodation and an increase in siliciclastic sediment supply, fluvial sandstone deposits of the "Donovan" sandstone prograded across the updip areas and cap this cycle.

A base-level rise, which occurred during the latest Aptian to early Albian in the northern Gulf of Mexico, began with the transgressive deposits of the Bexar Formation, continued with the accumulation of marine shale beds of the Mooringsport Formation, and resulted in the development of the Glen Rose (Rodessa, Mooringsport) shelf margin reef. With decreased shelfal accommodation, cessation of siliciclastic deposition, and periodic restriction of basin circulation, the evaporite deposits of the Ferry Lake Anhydrite accumulated during the early Albian. In offshore areas, Mooringsport sedimentation included marine shelf limestone deposition, which was part of the development of the Glen Rose shelf margin reef complex. A major influx of siliciclastic sediments and decrease in shelfal accommodation occurred during the late early to early middle Albian and resulted in fluvial and coastal siliciclastic deposition of the Paluxy Formation, which caps this cycle. This cycle represents a major transgression and marine flooding event in the northern Gulf of Mexico (McFarlan 1977; Salvador 1991).

During the late middle Albian, a rise in base level and increase in shelfal accommodation occurred, resulting in deposition of the transgressive fossiliferous limestone and marine shale beds of the Andrew Formation and Edwards Limestone of the Fredericksburg Group. Fluvial sandstone and shale deposits of the Dantzler Formation cap this middle to upper Albian cycle in updip areas, and signal a major base-level fall represented by the mid-Cretaceous unconformity (mid-Cenomanian age). The regressive phase of this cycle represents an aggrading and prograding interval in updip areas.

During the late Albian to early Cenomanian, a stratigraphic base-level rise and increase in accommodation occurred in the northern Gulf of Mexico. The increase in accommodation space produced deposition of transgressive deposits of the Washita Group. With the loss of accommodation space due to an increase in sediment supply, regressive siliciclastic and carbonate sediments of the Washita Group were deposited. In the mid-Cenomanian, a fall in stratigraphic base level took place



TEXT-FIGURE 11
Absolute ages, chronostratigraphic units, lithostratigraphic units, biostratigraphic units, and transgressive-regressive cycles of the Upper Cretaceous section of the northern Gulf of Mexico (modified from Mancini and Puckett 2002b).

that resulted in the exposure of the Lower Cretaceous shelf. In the northern Gulf of Mexico (Salvador 1991), the post mid-Cenomanian was a time of major sea-level fall.

Coastal sandstone beds of the Tuscaloosa Group and Woodbine Formation were deposited during an initial rise in base level and increase in accommodation during the late middle Cenomanian that post-dated the fall in base level that produced the mid-Cenomanian regional unconformity. The post mid-Cenomanian interval is characterized by the aggradational deposition of the "Massive sand" in the northeastern Gulf of Mexico (Mancini et al. 1987), indicating the creation of accommodation during a time characterized by high rates of sediment supply.

During the late Cenomanian to Turonian, marine shale of the Tuscaloosa Group and Eagle Ford Group were deposited, representing a major rise in base level and marine flooding event. This interval represents a widespread transgression in the northern Gulf of Mexico (Salvador 1991). With a reduction in accommodation and an increase in siliciclastic sediment supply, fluvial sandstone deposits of the Tuscaloosa Group prograded across updip areas and cap this cycle.

A fall in base level occurred during the late Turonian to middle Coniacian in the northern Gulf of Mexico (Salvador 1991). This base-level fall produced a regional unconformity at the top of the Tuscaloosa Group and Eagle Ford Group in the northern Gulf of Mexico (Salvador 1991). The hiatus between the Tuscaloosa Group and the Eutaw Formation is represented by part of the Turonian and Coniacian stages. This unconformity and hiatus are recognized in outcrop throughout the eastern Gulf Coastal Plain (Mancini et al. 1996) and in the western Gulf Coastal Plain (Pessagno 1990).

Tidal and shallow marine beds of the Eutaw Formation were deposited during an initial rise in base level and increase in accommodation during the middle Coniacian to middle Santonian that post-dated a fall in base level and regional unconformity. This interval is characterized by aggradational deposition in the northeastern Gulf of Mexico (Mancini et al. 1996), indicating the creation of accommodation during a time characterized by high rates of sediment supply. In the western Gulf Coastal Plain, the Austin Chalk accumulated during this time (Thompson et al. 1991).

During the late Santonian and early middle Campanian, glauconitic and fossiliferous sandstone of the Tombigbee Sand Member of the Eutaw Formation and marl and chalk of the Mooreville Chalk were deposited, representing two pulses of base-level rise and marine flooding in the eastern Gulf Coastal Plain (Mancini et al. 1996). These events represent marine transgressions in the northern Gulf of Mexico (Salvador 1991; Mancini et al. 1996). With a reduction in accommodation and increase in siliciclastic sediment supply, sandy deposits of the Demopolis Chalk and Tupelo Tongue accumulated in the middle Campanian in the eastern Gulf Coastal Plain (Mancini et al. 1996). Sandy deposits of the Wolf City Sand were deposited in the western Gulf Coastal Plain at this time (Thompson et al. 1991).

During the late middle to early late Campanian, chalk of the Demopolis Chalk was deposited, representing a major rise in base level and a flooding event in the northern Gulf of Mexico (Salvador 1991). The early late Campanian interval represents a widespread transgression in the eastern Gulf Coastal Plain (Mancini et al. 1996). With a reduction in accommodation and increase in siliciclastic sediment supply, marl of the Bluffport Marl Member of the Demopolis Chalk, sandy marl of the Ripley Formation and sandstone of the Ripley Formation accumulated in the late Campanian in the eastern Gulf Coastal Plain (Mancini et al. 1996). In the western Gulf Coastal Plain, sandy marl of the Marlbrook Formation and sandstone of the Nacatoch Formation were deposited during this time (Thompson et al. 1991).

A fall in base level occurred during the latest Campanian in the northeastern Gulf of Mexico (Mancini et al. 1996). This base-level fall produced a regional unconformity within the Ripley Formation in the eastern Gulf Coastal Plain (Mancini et al. 1996) and at the top of the sandstone beds of the Nacatoch Formation in the western Gulf Coastal Plain (Thompson et al. 1991). The hiatus associated with this unconformity is represented by the uppermost part of the Campanian Stage and the lower part of the Maastrichtian Stage.

During the early to early late Maastrichtian, marl and chalk of the Prairie Bluff Chalk were deposited, representing a major rise in base level and marine flooding event in the eastern Gulf Coastal Plain (Mancini et al. 1996). The early Maastrichtian interval represents a widespread transgression in the northern Gulf of Mexico (Salvador 1991). In the western Gulf Coastal Plain, marl of the Corsicana Formation was deposited during this time (Smith and Pessagno 1973). With a reduction in accommodation and an increase in siliciclastic sediment supply, siliciclastic deposits of the Owl Creek Formation accumulated in updip areas of the eastern Gulf Coastal Plain in the early late Maastrichtian (Mancini et al. 1996).

CONCLUSIONS

1. Stratigraphic analysis and the establishment of a chronostratigraphic framework for sedimentary basins are critical for stratal correlation and for reconstructing the geohistory of a basin. In studying the shelfal areas of basins that are characterized by non-marine, coastal and marine shelf deposition and in which stratal patterns are driven by low-frequency, tectonic-eustatic events, a stratigraphic framework based on the cyclicity recorded in the strata (transgressive-regressive cycles) and integrated with biostratigraphy has utility as a method for stratal correlation and basin geohistory interpretation.

2. In using the method of transgressive-regressive (T-R) cycles, eleven T-R cycles are recognized in Jurassic and Cretaceous strata of the northern Gulf of Mexico. The cycles consist of a transgressive (aggrading and backstepping intervals) phase and a regressive (infilling interval) phase. These cycles and their associated surfaces of maximum transgression are useful for correlation of Jurassic-Cretaceous strata in the region and have some potential for chronocorrelation with Mesozoic strata of Western Europe. Twelve regional unconformities and eleven regional marine flooding surfaces (surfaces of maximum transgression) were identified as major events in the geohistory of basins in the northern Gulf of Mexico.

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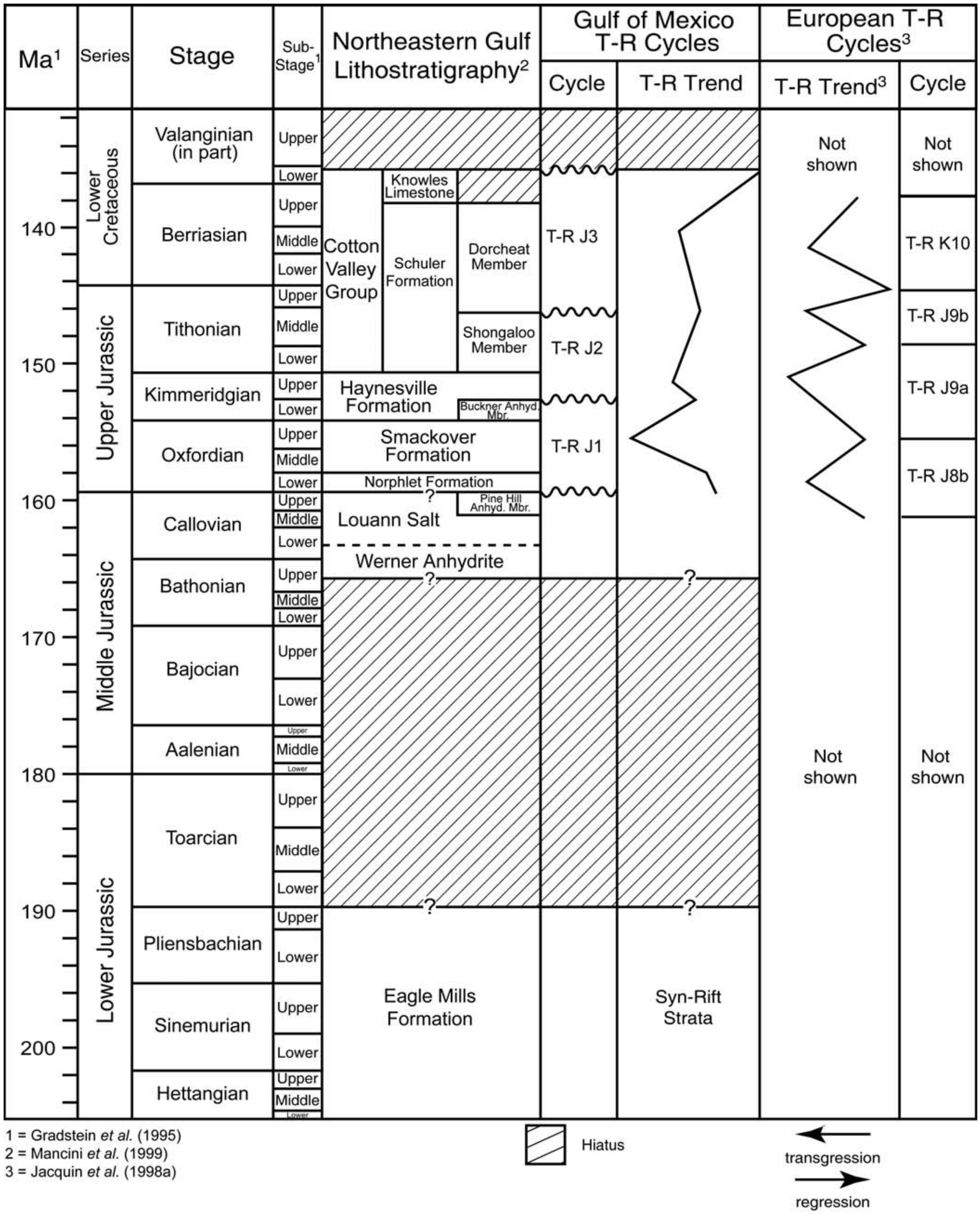
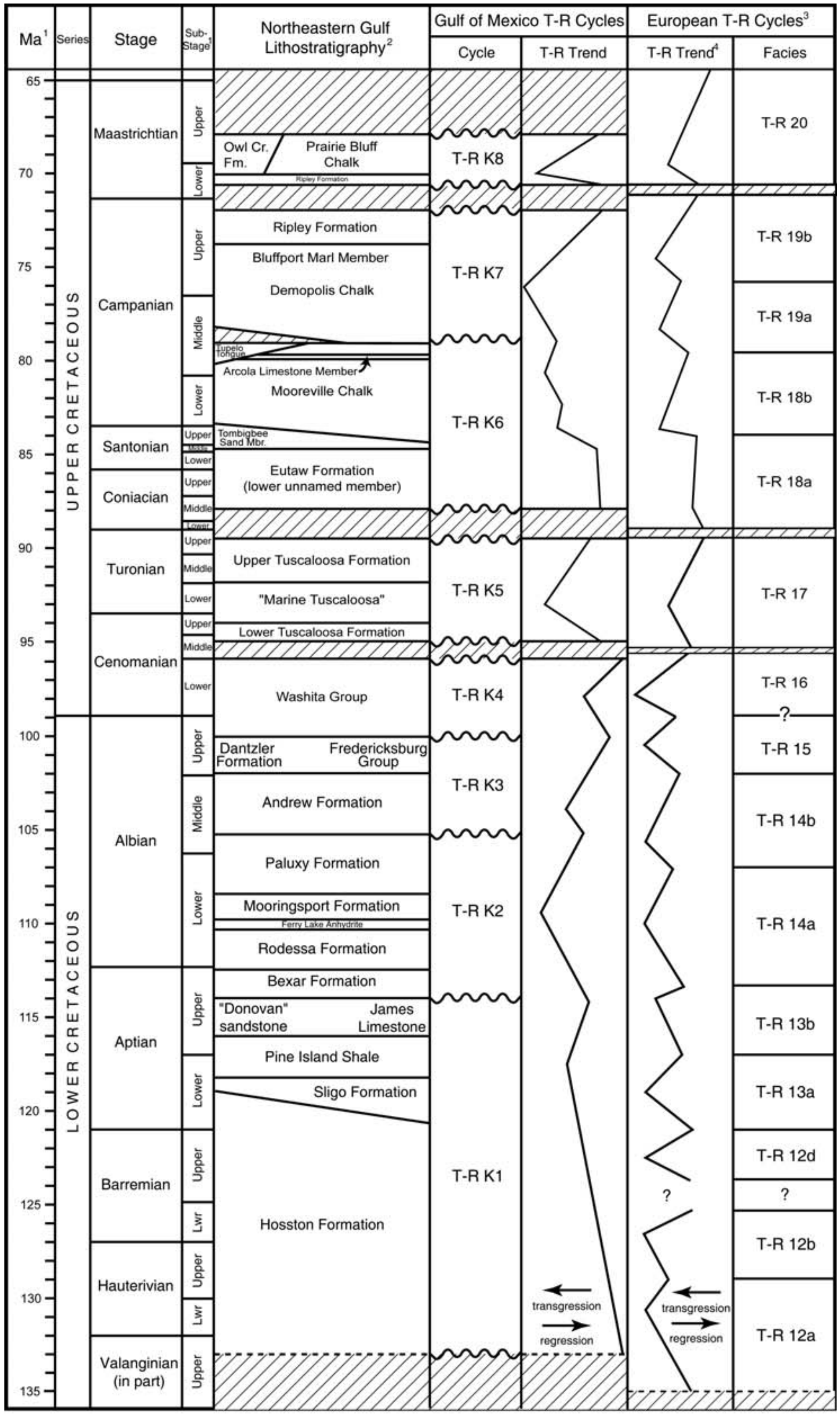


TEXT-FIGURE 12
Absolute ages, chronostratigraphic units, lithostratigraphic units, and transgressive-regressive cycles of the Jurassic section of northeastern Gulf of Mexico and transgressive-regressive facies cycles for Western Europe.



1 = Modified from Gradstein et al. (1995).
2 = Modified from Mancini et al. (1987), Mancini et al. (1996), and Mancini and Puckett (2002a).
3 = Modified from Jacquin et al. (1998b) and Hardenbol et al. (1998).
4 = Modified from Hancock (1993) and Hardenbol et al. (1998).

TEXT-FIGURE 13
Absolute ages, chronostratigraphic units, lithostratigraphic units, and transgressive-regressive cycles of the Cretaceous section of the northeastern Gulf of Mexico and transgressive-regressive facies cycles for Western Europe.

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