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Principal Author

Ernest A. Mancini (205/348-4319)
Department of Geological Sciences
Box 870338
202 Bevill Building
University of Alabama
Tuscaloosa, AL 35487-0338

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Name and Address of Participants

Ernest A. Mancini
Dept. of Geological Sciences
Box 870338
Tuscaloosa, AL 35487-0338

William C. Parcell
Department of Geology
Wichita State University
Wichita, KS 67260

Bruce S. Hart
Earth & Planetary Sciences
McGill University
Montreal, CANADA

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Abstract

The principal research effort for Year 1 of the project has been T-R cycle characterization and modeling. The research focus for the first nine (9) months of Year 1 was on outcrop study, well log analysis, seismic interpretation and data integration and for the remainder of the year the emphasis has been on T-R cycle model development. Information regarding the characteristics of T-R cycles has been assembled from the study of outcrops, from well log analyses, and from seismic reflection interpretation. From these studies, stratal boundaries separating T-R cycles have been found to be useful for the recognition and delineation of these cycles. The key stratal surfaces include subaerial unconformities, shoreface ravinement surfaces, transgressive surfaces, surfaces of maximum regression, and surfaces of maximum transgression. These surfaces can be identified and mapped in surface exposures and can be recognized in well log signatures and seismic reflection profiles as discontinuities. The findings from the study of outcrop, well log, and seismic reflection data are being integrated into a database for use in constructing a model for T-R cycle development.

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

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Introduction

The Eastern Gulf of Mexico area remains an underexplored region for hydrocarbon accumulations in deep (below 15,000 ft) petroleum reservoirs. In the USGS study of the world's oil and gas provinces, the hydrocarbon volume of the Mississippi Interior Salt Basin in combination with the North Louisiana Salt Basin ranked in the top 8% (33 out of 406) of the most petroliferous basins in the world. Based on USGS resource estimates and production, billions (2-3) of barrels of oil remain to be recovered from these basins. The assessment of these undiscovered and underdeveloped resources and the design of effective exploration strategies to reduce the risks and costs associated with finding these domestic resources requires the use of advanced methodologies for improved reservoir imaging, detection and delineation. Independent companies, who account for 50% of domestic oil production and 65% of gas production, have developed into the major players in drilling new exploration wells, particularly in the onshore Eastern Gulf of Mexico. These companies do not have the staffs or financial resources to conduct research in support of their exploration efforts. They realize, however, that the information and analysis resulting from these studies are beneficial in the design of effective exploration strategies. Therefore, the University of Alabama, Wichita State University and McGill University have undertaken a three-year applied research project, on T-R cycle characterization and imaging to assist companies in the design of new exploration strategies.

Executive Summary

The principal research effort for Year 1 of the project has been T-R cycle characterization and modeling. The research focus for the first nine (9) months of Year 1 has been on outcrop study, well log analysis, seismic interpretation, and data integration. During the remainder of the year, research emphasis has been on T-R cycle model development.

Information regarding the characteristics of T-R cycles has been assembled from the study of outcrops, from well log analyses, and from seismic interpretation. From these studies, stratal boundaries separating T-R cycles have been found to be useful for the recognition and delineation of these cycles. The key stratal surfaces include subaerial unconformities, shoreface ravinement surfaces, transgressive surfaces, surfaces of maximum regression, and surfaces of maximum transgression.

These surfaces can be recognized and mapped in surface exposures. In outcrop, typically the unconformable portion of the boundary of a T-R cycle is defined by a subaerial unconformity, shoreface ravinement surface, or transgressive surface. The conformable portion of the boundary can be marked by a surface of maximum regression, which is a conformable surface that separates a shallowing upward section from a deepening upward section. A surface of maximum transgression is evident usually in surface exposures. This surface separates the transgressive phase or deepening upward section of a T-R cycle from the regressive phase or shallowing upward section of a cycle.

With subsurface data, these surfaces can be recognized as discontinuities in well log signatures or in seismic reflection profiles. A change from higher to lower gamma ray and/or from more to less positive SP log responses identifies the discontinuity in the log records to recognize the surface of maximum transgression. A significant interruption in the gamma ray

and/or SP log patterns indicates a discontinuity that can be used to recognize a cycle boundary (inferred unconformity). A change from onlap reflection terminations to offlap (downlap) reflection terminations in seismic data identifies the discontinuity used to recognize the surface of maximum transgression or downlap surface in seismic reflection data. A strong reflector characterized by continuous, parallel seismic reflection configurations overlying and truncating oblique, progradational seismic reflection configurations (prograding clinoforms) identifies the discontinuity used to recognize a cycle boundary (inferred unconformity).

The findings from the study of outcrop, well log, and seismic data are being integrated into a database for use in constructing a model for T-R cycle development. In order to model changes in the non-marine realm, tectonics, sediment supply, and climate, in addition to sea level changes, are being examined as factors affecting the partitioning of these sediments. Using the concept of stratigraphic base level, deposition of non-marine strata above a subaerial unconformity can be better explained.

Project Objectives

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

Experimental

Work Accomplished

Outcrop Study—The assessment of potential outcrops to be studied in the Gulf Coastal Plain and in Wyoming and Montana has been completed. Photographic documentation of the types of surfaces to be examined and described has been completed. These physical surfaces include subaerial unconformities, transgressive surfaces, ravinement surfaces, surfaces of maximum regression, and surfaces of maximum transgression (Figures 1-4). The unconformable portion of a T-R cycle boundary is recognized generally by a subaerial unconformity, shoreface ravinement surface or transgressive source. The conformable portion of a T-R cycle boundary can be marked by a surface of maximum regression, which is a conformable surface that separates the shallowing upward section of a T-R cycle from the deepening upward section of an overlying cycle. A surface of maximum transgression separates the transgressive phase or deepening upward section of a T-R cycle from the regressive phase or shallowing upward section of a cycle. Knowledge of these surfaces will be used in the construction of the T-R cycle model.

Well Log Analysis—The following well log responses have been found to be useful in recognizing T-R cycles (Figures 5-8). A change from higher to 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. 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, 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

A.

B.

C.

D.

Figure 1. Photographs of outcrops showing physical surfaces: A. Subaerial unconformity at the contact of the Tuscaloosa Group (fluvial deposits) and the Eutaw Formation (tidal deposits); B. Ravinement surface at the contact of the unnamed member of the Eutaw Formation (shoreface deposits); C. Surface of maximum regression at the contact of the Arcola Limestone Member of the Mooreville Chalk (marine shelf deposits) and the Tibbee Creek Member of the Demopolis Chalk (marine shelf deposits); and D. Surface of maximum transgression in the Prairie Bluff Chalk.

A.

B.

C.

D.

Figure 2. Photographs of outcrops showing physical surfaces: A. Transgressive surface at the contact of the Tupelo Tongue of the Coffee Sand (marginal marine deposits) and the sands of the Demopolis Chalk (shoreface deposits); B. Subaerial unconformity at the intraformational unconformity in the Ripley Formation; C. Surface of maximum transgression in the Mooreville Chalk; and D. Marine flooding event at the contact of the Tombigbee Sand Member of the Eutaw Formation (shoreface deposits) and the Mooreville Chalk (marine shelf deposits).

A.

B.

C.

D.

Figure 3. Photographs of outcrops showing physical surfaces: A. Subaerial unconformity at the contact of the Oak Hill Member of the Naheola Formation (swamp deposits) and the Coal Bluff Marl Member of the Porters Creek Clay (prodelta deposits); B. Ravinement surface at the contact of the Naheola Formation (swamp deposits) and the Coal Bluff Marl Member of the Porters Creek Clay (prodelta deposits); C. Transgressive surface at the contact of the Oak Hill Member of the Naheola Formation (swamp deposits) and the Coal Bluff Marl Member of the Naheola Formation (shoreface deposits); and D. Transgressive surface at the contact of the Oak Hill Member of the Naheola Formation (swamp deposits) and the Coal Bluff Marl Member of the Naheola Formation (shoreface deposits).

A.

B.

C.

D.

Figure 4. Photographs of outcrops showing physical surfaces: A. Transgressive surface at the contact of the McBride Limestone Member of the Clayton Formation (marine shelf deposits) and the Porters Creek Clay (prodelta deposits); B. Transgressive surface at the contact of the Gravel Creek Member of the Nanafalia Formation (tidal deposits) and the Ostrea thirsae beds of the Nanafalia Formation (marine shelf deposits); C. Surface of maximum transgression in the Naheola Formation; and D. Surface of maximum transgression in the Yazoo Clay and Red Bluff Clay.

Figure 5. Well log patterns from the Jack L. Hopkins, Washington County, Alabama, showing the well log signature characteristics for the Upper Jurassic transgressive-regressive sequences and their associated sections. SP=spontaneous potential, ILD=deep induction (resistivity), SB=sequence boundary, SA=subaerial unconformity, SMT=surface of maximum transgression, TS=transgressive surface, SMR=surface of maximum regression, L.S.A.=Louann Salt, N.=Norphlet Formation, L.S.=lower Smackover Formation, U.S.=upper Smackover Formation, B.=Buckner Anhydrite Member, L.H.=lower Haynesville Formation, U.H.=upper Haynesville Formation, L.C.V.=lower Cotton Valley Group, U.C.V.=upper Cotton Valley Group, H.=Hosston Formation.

Figure 6. Well log patterns from the Simmons 'A' 1 well, Yazoo Co., MS, showing the well log signature characteristics of the T-R K1 Cycle and associated transgressive-regressive subcycles from the updip area of the Mississippi Interior Salt Basin. SP = spontaneous potential. ILM = medium induction (resistivity). TA = transgressive aggrading interval. TB = transgressive backstepping interval. RI = regressive infilling interval. RS = inferred ravinement surface. SMT = surface of maximum transgression. SMF = surface of marine flooding. K1h = Hosston Fm. K1s = Sligo Fm. K1pi = Pine Island Shale. K1'd' = 'Donovan' sandstone.

Figure 7. Well log patterns from the Southern Minerals No. 1 well, Pearl River Co., MS, showing the well log signature characteristics of the T-R K1, T-R K2, and T-R K3 cycles and associated transgressive-regressive subcycles from the southern portion of the Mississippi Interior Salt Basin. GR = gamma ray. SP = spontaneous potential. ILD = deep induction (resistivity). TB = transgressive backstepping interval. RI = regressive infilling interval. SA = subaerial unconformity. TS = transgressive surface. SMR = surface of maximum regression. SMT = surface of maximum transgression. SMF = surface of marine flooding. MCU = mid-Cretaceous (mid-Cenomanian) unconformity. K1s = Sligo Fm. K1pi = Pine Island Shale. K1j = James Limestone. K1b = Bexar Fm. K1r = Rodessa Fm. K1fl = Ferry Lake Anhydrite. K1m = Mooringsport Fm. K1p = Paluxy Fm. K1a = Andrew Fm. K1d = Dantzler Fm.

Figure 8. 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), K1d=Lower Cretaceous Dantzler Formation, K2'\"ms\"=Upper Cretaceous Tuscaloosa Group, \"Massive sand,\" K2lt=Lower Tuscaloosa Formation, K2mt= \"Marine Tuscaloosa,\" \"Marine shale,\" K2ut=Upper Tuscaloosa Formation.

surface of maximum transgression to the base of a discontinuity (unconformity) in log pattern reflects a regressive infilling interval. 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. The correlation of Upper Cretaceous strata illustrates the diachronous nature of a sequence boundary (Figure 9). The Upper Cretaceous strata above the sequence boundary (T-R 6/7) have been dated as older geologically in well #0051 than the strata above this boundary in well #0445. The correlation shows the time-transgressive nature of this surface and the importance of such a correlation for mapping potential reservoir facies.

Seismic Reflection Interpretation—The following generalizations regarding seismic reflection configurations and terminations have been found to be useful in recognizing 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. 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 (Figure 10). These seismic reflection configurations and terminations have been found to have application to recognize T-R cycles in Upper Jurassic (Figure 11), Lower Cretaceous (Figure 12) and Upper Cretaceous strata (Figure 13).

T-R Cycle Model Development—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

Figure 9. Cross section showing the diachronous nature of sequence boundary.

Figure 10. Diagram illustrating various possible seismic reflection terminations.

Courtesy of WesternGeco

Figure 11. Seismic reflection profile showing Upper Jurassic T-R cycle designations (see Figure 5 for formation and T-R cycle designations).

Courtesy of WesternGeco

Figure 12. Seismic reflection profile showing Lower Cretaceous T-R cycle designations (see Figure 6 for formation and T-R cycle designations).

Courtesy of WesternGeco

Figure 13. Seismic reflection profile showing Upper Cretaceous T-R cycle designations.

point, sea level is held constant in Figure 14 to determine the behavior of strata relative to the sediment surface, sea level and stratigraphic base level. In this case, stratigraphic base level, sea level and the sediment surface intersect at the shoreline. This convergence produces an erosional ravinement or transgressive surface. In a direction seaward of the shoreline, base level and sea level are converged and accommodation space is created and is defined as the interval between the sediment surface and sea level. Landward of the shoreline, sea level and base level diverge, with base level rising to some elevation above sea level. This divergence and the rise of stratigraphic base level above the sediment surface produces accommodation space and results in the accumulation of sediments as part of the transgressive phase of the cycle. This early portion of a T-R cycle is the aggrading interval. Thus, in the non-marine realm, accommodation space is defined as the interval between the sediment surface and stratigraphic base level. Tectonics, sea level, sediment supply, and climate are factors affecting the partitioning of these sediments.

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

Figure 14. Diagram illustrating conceptual model of factors affecting stratal architecture. The model is based on stratigraphic base level changes controlling T-R cycle development in the non-marine and marine realm. In this model, sea-level is held constant to determine the behavior of strata relative to the sediment surface, sea level, and stratigraphic base level.

marine deposits accumulate. With a sea-level rise above the sediment surface, marine sediments are deposited.

Work Planned

Outcrop Study—This task has been designed to characterize stratal architecture, patterns and geometries and the nature of the bounding surfaces of T-R cycles as observed from the study of surface exposures in the eastern Gulf Coastal Plain and in Wyoming and Montana (Table 1). The field work in the eastern Gulf Coastal Plain has essentially been completed, except for field checking the models that are developed. Preliminary field work has been accomplished in Wyoming and Montana, but more extensive work is required in Wyoming for field checking the models.

Data Integration—This task will continue to compile and integrate the data resulting from characterization by outcrop, by well log and by seismic study of strata of T-R cycles. This database is being used to develop the T-R cycle model and will be used in developing the depositional sequence and sequence stratigraphy models.

T-R Cycle Model Development—The development of a T-R cycle model has been initiated and will be completed in this phase of the project. The characterization information resulting from the study of outcrops, well logs, and seismic sections is being utilized in developing this model.

Depositional Sequence Model—The development of a depositional sequence model will be initiated and completed in this phase of the project. The characterization information resulting from the study of outcrops, well logs, and seismic sections will be used in developing this model.

Table 1
Milestone Chart—Year 2

Sequence Stratigraphy Model—The development of a sequence stratigraphy model will be initiated in this phase of the project. The characterization information resulting from the study of outcrops, well logs, and seismic sections will be used in developing this model.

Results and Discussion

At the time of its inception, sequence stratigraphy represented a revolutionary advancement in geosciences because it provided a means for regional correlation and mapping of strata through the recognition of sequences that are bounded by unconformities or correlative conformities. Although stratal architecture on passive continental margins was recognized to be affected by changes in sea level, climate, tectonics and sediment supply, the stable nature of passive margins led to the assumption that sea level changes were the principal factors controlling stratal patterns. Therefore, current stratigraphic analysis and resulting seismic stratigraphy and imaging are based on a sequence stratigraphy model that utilizes depositional sequences that are controlled by eustasy. That is, third-order (1-10 million years in duration) unconformity-bounded depositional sequences, as defined by Mitchum et al. in 1977 and van Wagoner et al. in 1988, and the associated physical surfaces and inherent systems tracts are the cornerstones of the sequence stratigraphy model. This model has provided a reliable means to perform stratigraphic analysis and correlate marine facies that were deposited in shelf environments (highstand systems tract deposits) with those that accumulated in slope and abyssal plain environments (lowstand systems tract deposits). The development of this model resulted in the design of new exploration strategies and advanced seismic detection techniques for deep water sandstone reservoirs and stratigraphic and combination petroleum traps. These exploration strategies and techniques have been highly successful in the discovery of new hydrocarbon resources. However, a sequence stratigraphy model based solely on eustasy has very little or no

application when applied to potential continental reservoirs, which are deposited above sea level. This is because the current sequence stratigraphy model focuses on changes in marine stratal patterns and is based on the premise that stratal patterns are controlled by changes in global sea level. That is, with the current model, sea level falls produce exposure of the shelf area which results in sediments by-passing the shelf and being deposited in slope and abyssal plain environments (lowstand systems tract deposits). Sea level rises produce flooding of the shelfal areas and an increase in accommodation space (transgressive systems tract deposits); and with increased sediment accumulation there is a decrease in accommodation space in the marine realm resulting in shoreline progradation (highstand systems tract deposits). Such an interpretation of sequence stratigraphy does not provide an adequate means for stratigraphic analysis and resulting seismic stratigraphy and imaging of continental strata. The architecture of continental strata is controlled by changes in stratigraphic base level (surface of equilibrium between sediment accumulation and erosion) that is independent from changes in eustasy. Factors affecting stratal patterns in these continental deposits include tectonics, sediment supply and climate, but not sea level. In marine systems, stratigraphic base level is equal to sea level, and in coastal plain systems, stratigraphic base level is affected by changes in sea level. The understanding of the controls on stratal patterns of continental deposits is important to imaging fluvial and eolian reservoirs. This is particularly significant in the Mississippi Interior Salt Basin because these strata are excellent petroleum reservoirs in this area. Therefore, a need exists for a sequence stratigraphy model that has application for characterizing, correlating, mapping and imaging the lithofacies associations of continental depositional systems. The evolving concept of T-R cycles fulfills this need and has great potential to be a new successful exploration methodology.

T-R cycles or sequences have been described for Devonian and Mesozoic strata. Embry in 2002 reviewed the merits of T-R sequences as compared to depositional sequences for stratigraphic analysis. He identified major deficiencies in the use of depositional sequences for stratigraphic analysis and advocated the use of T-R sequences. Further, Shanley and McCabe in 1994 and Embry in 2002 argued the limitations of using the concept of sequence stratigraphy based on depositional sequences and eustasy in its application for the understanding of the controls on stratal architecture and patterns of continental deposits. They believe that the successful application of sequence stratigraphic concepts to continental strata require a more complete understanding of the elements of stratigraphic base level, accommodation space, tectonics, climate, and sediment supply rather than only sea level. These evolving concepts of sequence stratigraphy have utility in the stratigraphic analysis of strata and in the design of new exploration strategies and technologies, involving improved geologic modeling and seismic imaging of continental and coastal plain facies which have potential as petroleum reservoirs.

T-R cycles (sequences) have been found by Mancini and Puckett in 2002 to have excellent utility for establishing a stratigraphic framework for Lower Cretaceous strata in the Mississippi Interior Salt Basin area, for correlation of these strata, and for reconstructing the geohistory of this basin. T-R cycles consist of a transgressive phase that includes an upward deepening event, and a regressive phase that includes an upward shallowing event. The transgressive portion of the T-R cycles consists of a backstepping phase, but may include an aggrading phase; the regressive portion of these cycles consists of an infilling phase, but may include a forestepping phase. In terms of systems tract terminology, the backstepping phase approximates the transgressive systems tract and the infilling phase approximates the highstand systems tract. The forestepping phase approximates the lowstand systems tract. The aggrading phase corresponds,

in part, to the lowstand systems tract. The events of the aggrading phase mark the change from stratigraphic base level fall and erosion to base level rise and sediment accumulation. This aggrading phase signals the initiation of the creation of accommodation space. The aggrading phase represents the early portion of the transgressive event of a T-R cycle, and a siliciclastic aggrading sequence generally consists of widespread and thick deposits that are a result of a high terrigenous sediment supply that keeps pace with the creation of shelf accommodation. Thus, the continental strata of the aggrading phase overlie a subaerial unconformity and, in turn, are disconformably overlain by a ravinement or transgressive surface. This surface separates the aggrading phase from the backstepping phase of the transgressive event of a T-R cycle. In regard to the current sequence stratigraphy model, lowstand system tract deposits unconformably overlie a subaerial unconformity and are disconformably overlain by a transgressive surface. Therefore, these continental strata would be assigned to the lowstand systems tract even though these deposits are nonmarine rather than deep water and are characterized by a widespread, continuous distribution rather than being discontinuous in occurrence and/or confined to incised valleys. Recognition of T-R cycles is dependent upon the nature of the physical surface defining the cycles. Embry in 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. He used a maximum flooding surface to divide a T-R sequence into transgressive and regressive systems tracts.

Mancini and Puckett in 2002 recognized T-R cycles (sequences) in Lower Cretaceous strata by a combination of factors including stratal geometries, nature of cycle boundaries, facies stacking patterns within cycles, and large-scale shifts in major facies belts. The cycles are

separated by discontinuities in the sedimentary record as recognized by abrupt changes or interruptions as observed in seismic reflection profiles, in well log signature patterns, and/or in cored sections obtained from the drilling of wells. A discontinuity may consist of an unconformable surface, such as a subaerial unconformity, ravinement surface, or transgressive surface at the cycle boundary. In the marine system, the boundary of a T-R cycle may be recognized by a conformable surface of maximum regression, which separates an upward shallowing interval from an upward deepening interval. The aggrading section of the transgressive phase rests on a subaerial unconformity, and the top of this section is delimited by an erosional ravinement surface or transgressive surface. The top of the overlying backstepping section of the transgressive phase is marked by a surface of maximum transgression. The surface of maximum transgression separates the upward deepening interval of the T-R cycle (transgressive phase) from the upward shallowing interval of the cycle (regressive phase). The regressive phase in shelfal strata consists of an infilling section. The forestepping section of the regressive phase occurs in continental slope deposits. The top of the regressive phase is delimited by a surface of maximum regression. A T-R cycle is composed of one or more cycles, each of which consists of an upward deepening event and an upward shallowing event. If the T-R cycle consists of more than one cycle, the couplet of upward deepening and upward shallowing is referred to as a subcycle. A surface of marine flooding separates the transgressive and regressive sections of a subcycle. Generally, these subcycles occur in the transgressive backstepping phase of a T-R cycle. The marine transgressive and flooding events of the backstepping phase of a T-R cycle are widespread and provide regional correlation datums. However, during this transgressive event, a minor decrease in shelfal accommodation may produce an upward shallowing event that results in a regressive infilling section. Although this

event defines a shift in facies belts, it is not of the magnitude of the progradational event of the regressive infilling phase of a T-R cycle that represents a major influx of siliciclastic sediments into the basin. The subcycle boundary generally consists of an erosional transgressive surface landward and a conformable surface of maximum regression seaward. Mancini and Puckett in 2002 recognized Lower Cretaceous T-R cycles and subcycles based on an integrated study of well log signatures, core analyses, lithologic well log descriptions, and regional seismic reflection profiles. The T-R cycles are recognized on the basis of large-scale landward or seaward shifts of major lithofacies belts. The tops of these cycles are identified by major progradational sandstone beds, and the bases are recognized by the occurrence of marine shale and argillaceous limestone. Well log signatures provide the primary means for the recognition and correlation of the T-R cycles in their study. Facies stacking patterns within cycles, as recognized from well log signature patterns, are used to characterize the T-R cycles and subcycles. Abrupt changes or discontinuities in well log records are utilized to delimit cycle boundaries and phase changes within a cycle. Where available, core and lithologic well log descriptions are used to identify the lithologies and facies of the transgressive and regressive phases. Interruptions in sedimentation or discontinuities are recognized from core and lithologic well log data, and unconformities are observed from the core data or inferred from changes in well log patterns. A change from higher to lower gamma ray identifies the discontinuity in the log records used to recognize the surface of maximum transgression, which separates the transgressive phase from the regressive phase of a cycle. Reflection configuration and termination are recognized using seismic reflection profiles. Thin (one seismic cycle), concordant, parallel seismic reflection configurations are interpreted as marine strata of the transgressive backstepping phase. These reflectors are characterized by onlap reflection

termination. 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 termination. The characteristics of the seismic sections are used to support the interpretations regarding the T-R cycles based on well log signatures, core analyses, and lithologic well log descriptions.

Conclusions

The principal research effort for Year 1 of the project has been T-R cycle characterization and modeling. The research focus for the first nine (9) months of Year 1 has been on outcrop study, well log analysis, seismic interpretation, and data integration. During the remainder of the year, research emphasis has been on T-R cycle model development.

Information regarding the characteristics of T-R cycles has been assembled from the study of outcrops, from well log analyses, and from seismic interpretation. From these studies, stratal boundaries separating T-R cycles have been found to be useful for the recognition and delineation of these cycles. The key stratal surfaces include subaerial unconformities, shoreface ravinement surfaces, transgressive surfaces, surfaces of maximum regression, and surfaces of maximum transgression.

These surfaces can be recognized and mapped in surface exposures. In outcrop, typically the unconformable portion of the boundary of a T-R cycle is defined by a subaerial unconformity, shoreface ravinement surface, or transgressive surface. The conformable portion of the boundary can be marked by a surface of maximum regression, which is a conformable surface that separates a shallowing upward section from a deepening upward section. A surface of maximum transgression is evident usually in surface exposures. This surface separates the transgressive

phase or deepening upward section of a T-R cycle from the regressive phase or shallowing upward section of a cycle.

With subsurface data, these surfaces can be recognized as discontinuities in well log signatures or in seismic reflection profiles. A change from higher to lower gamma ray and/or from more to less positive SP log responses identifies the discontinuity in the log records to recognize the surface of maximum transgression. A significant interruption in the gamma ray and/or SP log patterns indicates a discontinuity that can be used to recognize a cycle boundary (inferred unconformity). A change from onlap reflection terminations to offlap (downlap) reflection terminations in seismic data identifies the discontinuity used to recognize the surface of maximum transgression or downlap surface in seismic reflection data. A strong reflector characterized by continuous, parallel seismic reflection configurations overlying and truncating oblique, progradational seismic reflection configurations (prograding clinoforms) identifies the discontinuity used to recognize a cycle boundary (inferred unconformity).

The findings from the study of outcrop, well log, and seismic data are being integrated into a database for use in constructing a model for T-R cycle development. In order to model changes in the non-marine realm, tectonics, sediment supply, and climate, in addition to sea level changes, are being examined as factors affecting the partitioning of these sediments. Using the concept of stratigraphic base level, deposition of non-marine strata above a subaerial unconformity can be better explained.

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