Computer Simulation of the Yates Formation (Permian, Delaware Basin) - Sequence Stratigraphy and Shelf-to-Basin Correlation Implications*

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Search and Discovery Article #60044 (2009)
Posted June 4, 2009

*Reprint of Borer, J.M., and P.M. Harris, 1995, Computer Simulation of the Yates Formation (Permian, Delaware Basin) - Sequence Stratigraphy and Shelf-to-Basin Correlation Implications, *in* R.L. Martin, ed., In Search of New Permian Basin Oil and Gas Fields: Using Today's Technologies and Tomorrow's Ideas for Exploration, Development, and 3D Seismic in a Mature Basin: West Texas Geological Society Symposium, Publication No. 95-98, p. 111-132. Appreciation is expressed to WTGS (http://www.wtgs.org/Home/tabid/36/Default.aspx) and to Paula Mitchell, Executive Director, for permission to post this article.

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Abstract and Contents

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High-resolution stratigraphic analyses shows that at least three orders of cyclicity produced the stratigraphy of the Yates Formation on the shelf as well as the time-equivalent basinal deposits of the Bell Canyon formation. Evidence suggests that orbitally forced, 400- and 100-k.y. (4th- and 5th-order, respectively) duration sea-level cycles (Milankovitch, long and short eccentricity cycles) were predominant events.

Stratigraphic computer modeling illustrates how a distinct Yates accommodation profile, hierarchical sea-level history, and the interaction of carbonate and siliciclastic systems were fundamental controls on Yates stratigraphy. Simulations show how the Yates topography (flat platform with a steep margin), low subsidence, and "keep up" carbonate factory provided a distinct accommodation profile that resulted in rapid fluctuations between highstand- and lowstand-shoreline settings with only minor fluctuations in relative sea level. Modeling suggests strong reciprocation between shelfal deposition during (decreasing rates of) relative sea-level rise and basinal deposition during (increasing and then decreasing rates of) relative sea-level fall occurred on a much shorter time scale (5th-order, 100-k.y.) than appreciated by previous workers.

Modeling and outcrop stratal geometries show how increased accommodation near the shelf edge resulted in a zone of greatest potential for cyclostratigraphic analysis and suggests than "fall-in" beds were the byproduct of a hierarchical sea level operating across an outer shelf accommodation gradient. Periods of "fall in" occurred during 4th-order, sea-level lowstands when accommodation space shifted seaward and off a previously deposited carbonate bank. Modeling results also point out the fundamental

importance of evaluating high-frequency cycles to understand shelf evolution and siliciclastic bypass. In the Yates model, sediment bypass to the basin is a high-frequency phenomena that are varied by longer term cycles. Furthermore, 4th-order cycle (sequence) boundaries are defined by zones of closely spaced 5th-order bypass surfaces and 3rd-order sequence boundaries are, in turn, defined by zones of low-accommodation, 4th-order cycles.

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ABSTRACT

High-resolution stratigraphic analyses shows that at least three orders of cyclicity produced the stratigraphy of the Yates Formation on the shelf as well as the time-equivalent basinal deposits of the Bell Canyon Formation. Evidence suggests that orbitally-forced, 400- and 100-k.y. (4th- and 5th-order, respectively) duration sea-level cycles (Milankovitch, long and short eccentricity cycles) were predominant events.

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INTRODUCTION

With it's readily apparent cyclicity in both core and outcrop, the Yates Formation, one of three shelf equivalents to the shelf margin Capitan reef and basinal siliciclastics of the Bell Canyon Formation (Fig. 1), is an excellent opportunity to use modern stratigraphic techniques, including computer forward modeling, to investigate the genesis of high-frequency carbonate-siliciclastic depositional cycles and their relationship to larger-scale sequences. In this paper, the importance of high-frequency (4th- and 5th-order) depositional cycles is considered in terms of 1) stratigraphic relationships for the outer-shelf (aggradation/progradation couplets, fall-in beds, and low accommodation "zones" versus discrete sequence boundaries), 2) timing of siliciclastic bypass to the

**Editor's Note - Figures 6,7,8,9, and 10 for this paper are located in the back pocket inside the back cover of the book.*

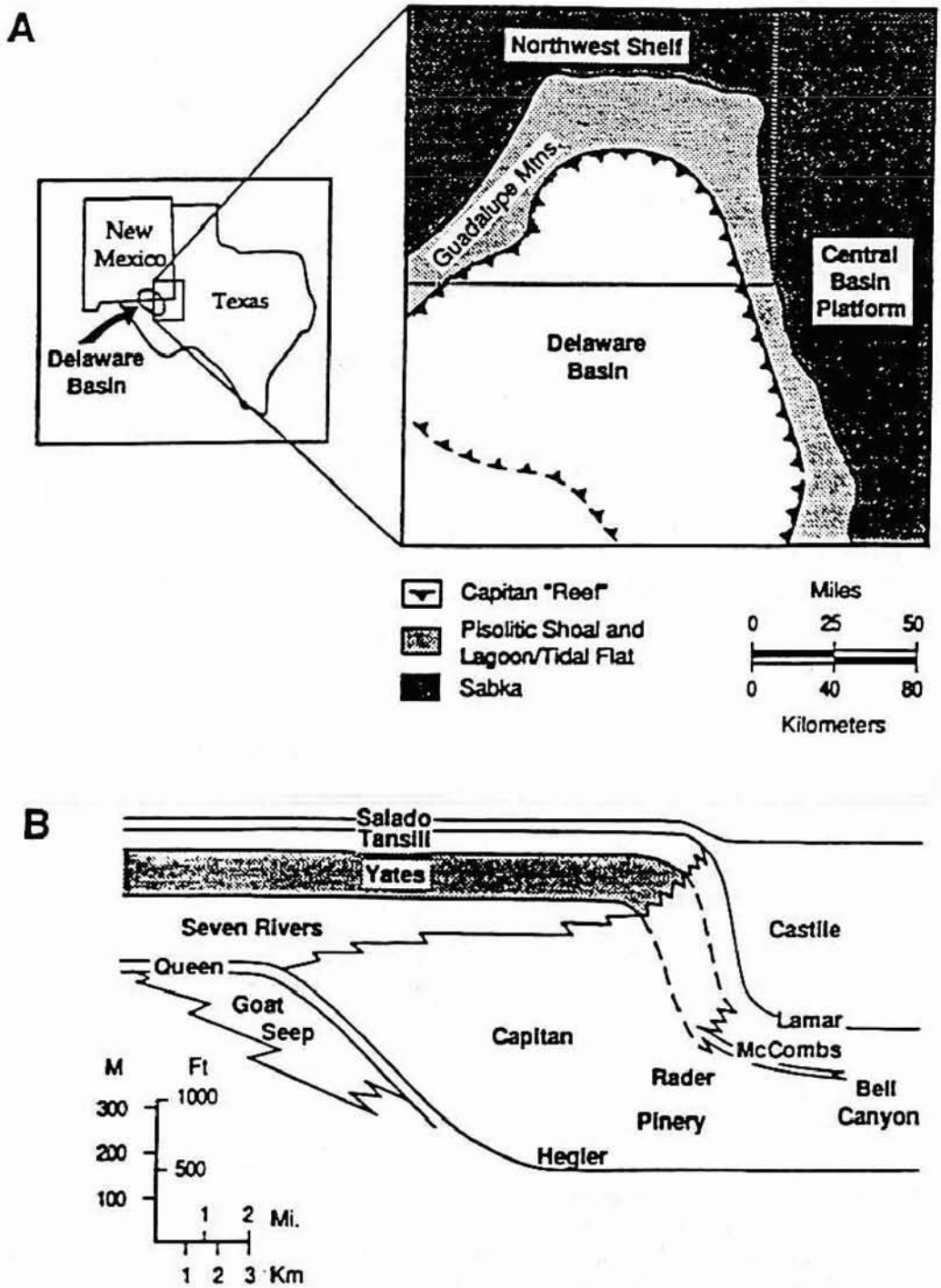

Figure 1. (A) Location of the Delaware Basin within the Permian Basin of West Texas and southeastern New Mexico. The siliciclastics, carbonates, and evaporites of the Yates Formation were deposited on a broad, shallow shelf that rimmed the Delaware Basin in Late Guadalupian (Late Permian) time. (B) Schematic cross section showing Upper Guadalupian stratigraphy of the Permian Basin. The Yates formation is a shelf equivalent to the Capitan reef and basinal siliciclastics of the Bell Canyon Formation.

basin, and 3) utility as a shelf-to-basin correlation tool.

Results of this study indicate how a sequence stratigraphic model needs to be tailored to the intrinsic attributes of a depositional system. A few important attributes of the Yates depositional system ultimately control the stratigraphy. These include: (1) the style of mixed carbonate - siliciclastic deposition; (2) a marginal mound topographic profile with a flat platform top and gradually increasing declivity towards a steep shelf margin; (3) low subsidence rates with a subtly hinged profile that combines with the topographic profile to provide the signature Yates "accommodation profile"; and (4) a strongly hierarchical, high-frequency, allocyclic forcing function

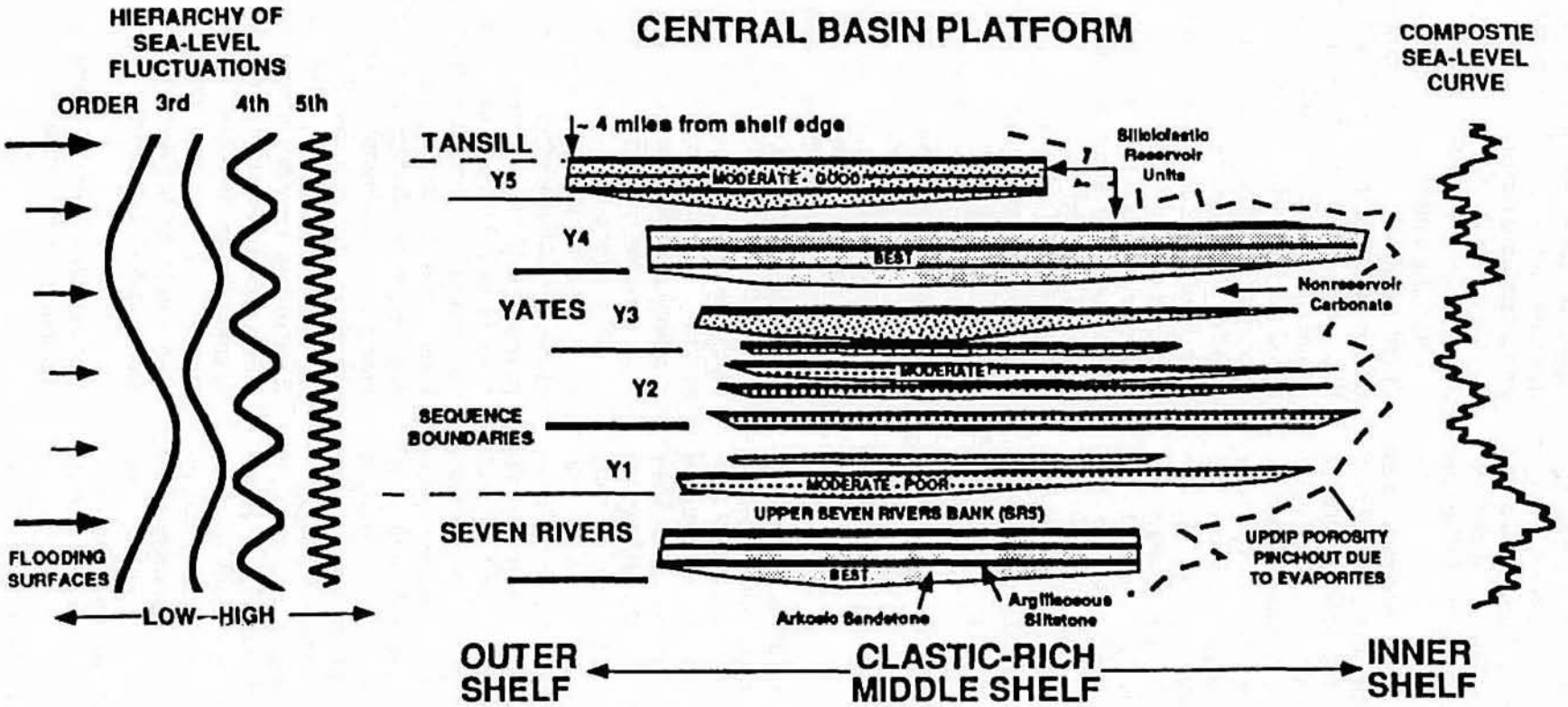

Figure 2. Schematic illustration based on subsurface cross sections of Borer and Harris (1991a) showing how heterogeneity in siliciclastic reservoirs of the Yates Formation middle shelf is controlled by a hierarchy of depositional cycles. Reservoir zones are largely a function of 4th-order cyclicity. These, probably 400-k.y., cycles, are labeled Y1 to Y5. Siliciclastic portions of the 400-k.y. depositional cycles are separated by 400-k.y. and 100-k.y. carbonates that are probable barriers to vertical flow. The thickness, vertical continuity, and reservoir quality of individual reservoir zones are controlled, in part, by the position of the 4th-order cycles relative to 3rd-order fluctuations. The best reservoir zones correspond to substantial 4th-order highstands (to form highstand shorelines) that occurred subsequent to substantial lowstands (to provide abundant sand supply). Heterogeneity within a particular reservoir unit is controlled by high-frequency, 100-k.y. depositional cycles that consist of alternating reservoir sandstones and poor to non-reservoir argillaceous siltstones and/or carbonates.

(probably Milankovitch climate cycles) that drives relative sea level, carbonate versus clastic deposition, and aggradation versus progradation. The hierarchical, high-frequency relative sea-level fluctuations operate across the Yates accommodation profile, resulting in complex but ordered stratigraphic pattern in both shelf and basin equivalents.

This paper builds upon our previous studies of the Yates Formation (Borer and Harris, 1991a and b) where the depositional facies and porosity characteristics of the shelf strata, shelf-wide stratigraphic correlations, regional variations in cycle stacking patterns, and implications for reservoir heterogeneity are examined in greater detail. We herein attempt to (a) build upon the earlier cyclostratigraphic framework and analyze the same system from a sequence perspective by integrating outcrop and computer modeling data with subsurface information, and (b) "test" our ideas on aspects of the stratigraphic framework for the shelf deposits by investigating parallels in the time-equivalent basinal setting.

STRATIGRAPHIC FRAMEWORK

Subsurface Data - Cycle Hierarchy And Reservoir Heterogeneity

Borer and Harris (1991a and b), using core, log, and limited outcrop data, divided the Yates shelf into inner-, middle-, and outer-shelf (shelf margin) regions based on distinct associations of siliciclastic and carbonate/evaporite facies. Their high-resolution stratigraphic (cyclostratigraphic) analyses suggest that much of the heterogeneity in hydrocarbon reservoirs of the Yates Formation in the middle shelf region is related to the complex stacking of high-frequency depositional cycles in response to at least three orders of relative sea-level fluctuations (Fig. 2). Several lines of evidence (e.g., distinct cycle bundling, a good fit between depositional cycles and plots of astronomical parameters, and limited chronostratigraphic constraints based on calculated subsidence/accumulation rates and regional stratigraphy) were used to suggest that two of the sea-level fluctuations were orbitally forced events with 100- and 400-k.y. durations (Milankovitch eccentricity cycles). Long-term (3rd-order) accommodation (sea-level) cycles with durations of 0.8 to 2 m.y. were also apparent from Fischer plots (cycle thickness corrected for regional linear subsidence plotted against time) and regional cross sections.

Borer and Harris (1991a and b) used Fischer plots and stratigraphic analysis (average slope/cycle data calculated from regional cross sections) to suggest that all the sea-level fluctuations had relatively low amplitudes. Stratigraphic modeling results presented in a subsequent section of this paper refine the previous estimates and suggest amplitudes ranging from about 4-8 m for the 100-k.y. cycles, 8-12 m for the 400-k.y. cycles, and 8-20 m for the 3rd-order cycles.

The hierarchical sea-level fluctuations produced a distinctly cyclic stratigraphy on both the Central Basin Platform and Northwest Shelf portions of the Permian Basin with logical and consistent updip-to-downdip facies changes and facies shifts related to the cycles. The stratigraphic framework includes siliciclastic-dominated, middle-shelf depositional cycles (stacked highstand siliciclastic shorelines) that produce heterogeneity in hydrocarbon reservoirs at various scales (Fig. 2). Regional (field-scale) heterogeneity occurred as the complex sea-level signal operated on portions of the shelf with different topographic and/or subsidence profiles. A steeper profile on the Central Basin Platform enhanced the reworking (and reservoir quality) of the reservoir sandstone bodies and resulted in a strong vertical component to the stacking of reservoir units. In contrast, a lower gradient on the Northwest Shelf may have resulted in generally poorer reservoir quality sandstones, a more updip location to the reservoir trend, and a greater horizontal component to reservoir unit stacking. The third-order sea-level fluctuation controls the lateral position of successive sandstone depocenters and the general onlap/offlap (transgression/ regression) configuration of the reservoir.

Heterogeneity within a reservoir is related to all scales of sea-level fluctuation. The thickness, vertical continuity, and reservoir quality of individual sandstone reservoir units (i.e., siliciclastic portions of 400-k.y. depositional cycles) are controlled largely by the phase interaction of the various components that make up the composite sea-level curve. In general, the best reservoir zones were deposited during 4th-order highstands (to create accommodation and reworked highstand shorelines) that occurred during and/or subsequent to substantial (3rd- and 4th-order) lowstands (to provide abundant sand to the shelf). Heterogeneity within a particular reservoir unit is controlled by 5th-order (100-k.y.) depositional cycles that consist of alternating reservoir sandstones and poor- to non-reservoir argillaceous siltstones and/or carbonates.

Outcrop Data - Stratal Geometries And Sequence Architecture

A large perspective, dip-oriented view of the Yates depositional cycles occurs along the north

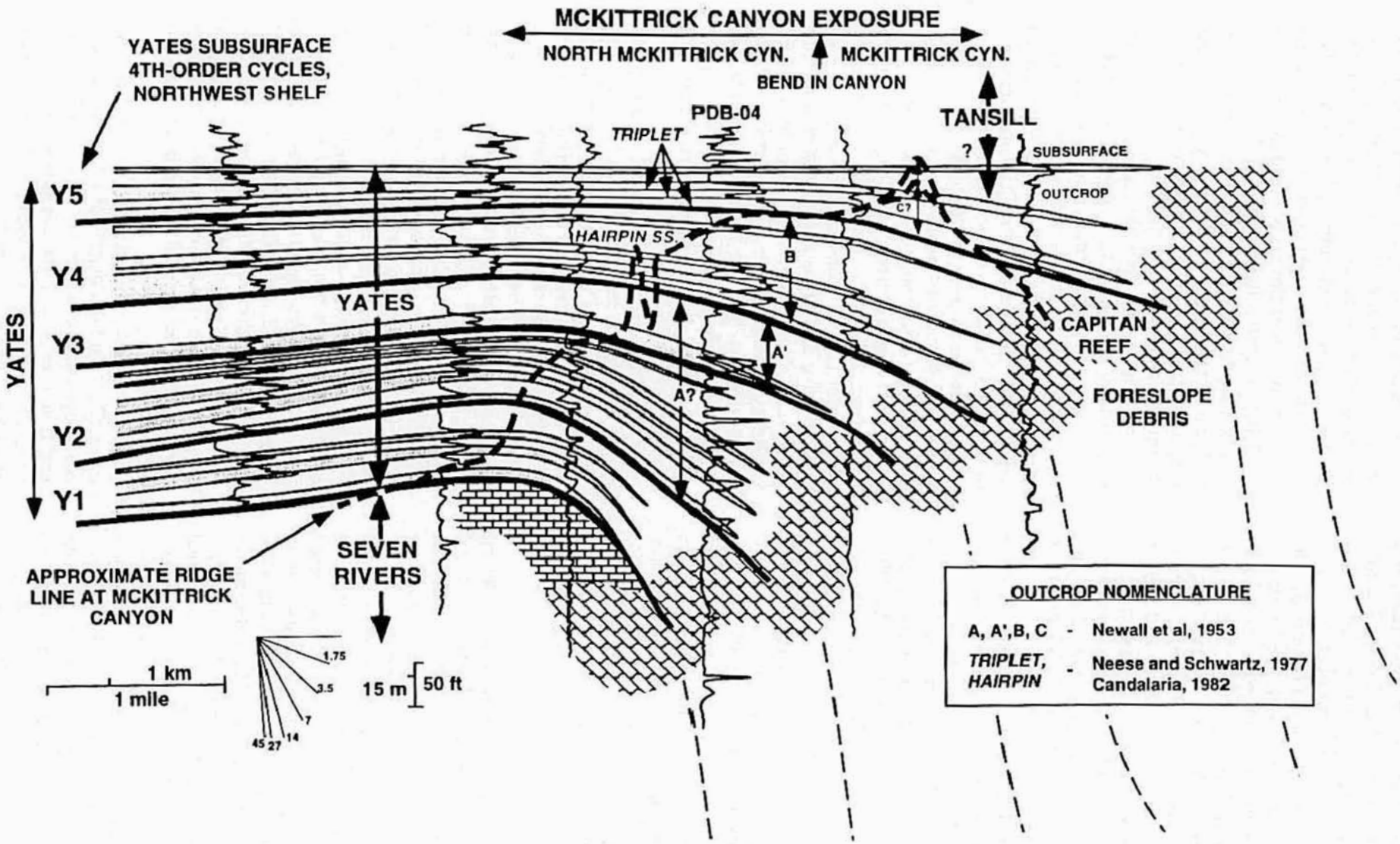

Figure 3. Cross section based on that of Borer and Harris (1991a) comparing the subsurface Yates stratigraphy with that of the McKittrick Canyon outcrops. Gamma-Ray logs from six wells are shown; only the Gulf PDB-04 well is labeled. Nomenclature and stratigraphic picks used by previous outcrop workers are compared to the Yates 4th-order cycles. Note the approximate position of the ridge line at McKittrick Canyon on the cross section. The base of the Yates is not a uniform boundary to pick on either outcrop or subsurface sections because of the progradational and offlapping nature of the margin. In this study, the base of the Yates is considered to be the lowermost siliciclastic bed that progrades over a thick aggradational carbonate interval marking the top of the Seven Rivers. The Yates interval encountered in a single vertical section/well , i.e. thickness, number of cycles, etc., is strongly controlled by the position along depositional dip.

wall of McKittrick Canyon in the Guadalupe Mountains (Bebout and others, 1993). Multiple scales of stratigraphic cycles are apparent in these outcrops as they were in the subsurface data of Borer and Harris (1991 a and b) (Figure 3). The base of thick and/or closely spaced siliciclastics are interpreted as 4th-order cycle (sequence) bases (sequence boundaries) on Figure 3. Five, 4th-order cycles (labeled Y1-Y5) are recognized in the Yates interval and considered to be equivalent to the 400-k.y. cycles described in cores and logs by Borer and Harris (1991a and b). These same cycles are analogous to those identified by Kerans and others (1992; 1993) (their sequences G22-26) and Kerans and Harris (1993) (their Y1 - Y4 and Yates - Tansill sequences).

Fifth-order (100 k.y.) cycles are also apparent on Figure 3 as individual carbonate-clastic couplets. Thick, sandy intervals such as the base of cycles Y4 and Y5 likely consist of several sandstones with thin carbonate interbeds (Borer and Harris, 1991 a and b; Kerans and Harris, 1993). The base of individual sandstone beds are considered in this study to be 5th-order (100 k.y.) surfaces of sediment bypass. Distinct planar surfaces with little or no evidence for siliciclastics may also be high-frequency bypass surfaces.

The gamma ray log from the Gulf PDB-04 well (described in detail by Garber and others, 1989) is highlighted on Figure 3 as it provides a tie to the previous subsurface data of Borer and Harris (1991a and b). The outcrop nomenclature of Newell and others (1953), Neese and Schwartz (1977), and Candelaria (1992) is also shown on Figure 4 to further clarify the terminology of various outcrop studies on the Yates.

Stratal Patterns and Interpretation.—Stratal patterns (aggradation versus progradation, stratal termination) from Figure 3 and the McKittrick Canyon outcrops are used to make a sequence stratigraphic interpretation for the Yates that incorporates both longer-term (3rd-order) and high-frequency (4th- and 5th-order) relative sea-level fluctuations. Stratal patterns are commonly used to assign system tracts and infer relative sea-level fluctuations in ancient siliciclastic deposits (Vail and others, 1977; Jervey, 1988). With some modification, stratal patterns can be used to develop a sequence framework and understand sea-level history in carbonate settings (Sarg, 1988; Schlager, 1992; Handford and Loucks, 1993; Harris, 1994).

One important difference between carbonate and siliciclastic depositional systems that impacts stratal patterns is that high rates of in situ carbonate production can cause aggradation or even progradation during transgression. Also, in a pure carbonate system, a lowstand system tract may be poorly developed in the basin since this represents a time of no or only limited carbonate production on the shelf. The greatest shedding of fine carbonate debris into the basin occurs during transgressive to highstand times when the shelfal carbonate factory is widespread (Schlager, 1992; Brown and Loucks, 1993 a and b).

In a mixed system like the Yates, attributes of both carbonate and siliciclastic sequence stratigraphic approaches need to be considered, as do the important interactions between the two depositional styles. Also, in a hierarchical cyclic system such as the Yates, the assignment of 3rd-order system tracts and critical surfaces (sequence boundaries and flooding surfaces) is complex and somewhat misleading since major sequences are comprised of smaller and smaller sequences each of which has its own system tracts and surfaces.

For example, large-scale stratal geometries seen on Figure 3 (explained below) and the shape of a Fischer plot (Fig. 4) suggest that Yates 4th-order cycle (Y2) can be interpreted as a lowstand prograding wedge of a long-term (3rd-order) sequence, yet Y2 was actually deposited during the transgressive and highstand portions of shorter-term cycles. Furthermore, the 3rd-order sequence boundary/onlap surface is best considered as a zone (rather than single surface) encompassing two, closely-spaced (low accommodation), 4th-order cycles (Y2 and Y3) that in turn contain several thin 5th-order cycles.

The above scenario is based on an interpretation of long-term (3rd-order) maximum sea-level rises coinciding with the top of the Seven Rivers and base of the Tansill formations (Figs. 3 and 4). A thick dolomite at the top of the Seven Rivers is interpreted to represent an extra thick, "400-k.y." carbonate bank that formed (on the shelf top) during the transgressive to highstand portion of a longer-term cycle which enhanced (positively modulated) the 4th-order sea-level rise. The base of the Tansill (as picked on Figures 3 and 4) is considered to mark another long-term relative sea-level rise since thick carbonates again dominate the shelf (Neese, 1989; Parsley and Warren, 1989; Kerans and Harris, 1993). Between the upper Seven Rivers and lower Tansill (3rd-order) maximum transgressions are the five 4th-order Yates boundaries. In a standard sequence stratigraphic framework, one of these 4th-order boundaries should also be considered the 3rd-order sequence boundary.

As mentioned previously, the geometry of Yates cycle Y2, i.e., a high degree of updip thinning, is most suggestive of a long-term sea-level lowstand and therefore Y2 may be considered a lowstand prograding wedge. Interestingly, the well-developed geometry of apparent onlap is as much the

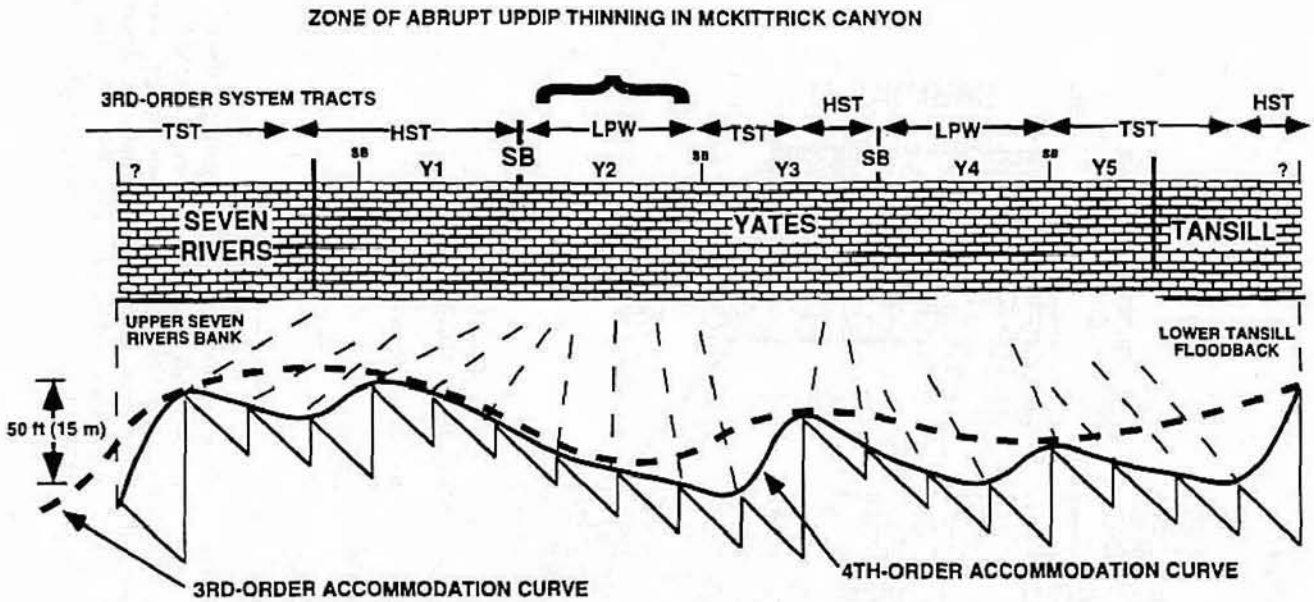

Figure 4. Fischer plot showing how Yates 4th-order cycles (Y1 to Y5) were deposited between two major long-term (3rd-order) highstands, while another lessor long-term highstand "3 1/2-order" coincided with the middle Yates. Cycles correspond to those annotated on Figures 2 and 3. The siliciclastics and carbonates of the Yates are interpreted at a 3rd-order scale using sequence stratigraphy terminology; however, the process response of the rocks during the various portions of a relative sea-level curve is substantially different than the classic Vail model. Cycle Y2, showing substantial updip thinning in McKittrick Canyon outcrops, can be considered a lowstand prograding wedge. The plot also provides an estimate of the magnitude of the 3rd-order fluctuations; the estimate is crude since it is highly dependent on the model used for subsidence correction (in this case average cycle thickness).

result of the extra-high highstand at the end of the Seven Rivers as it is the lowstand in the middle-lower Yates (Fig. 4). This is a function of the carbonate systems ability to "keep up" during the late Seven Rivers-early Yates sea-level rise and the inability of siliciclastics to prograde from the steep carbonate shelf margin during lowstands.

During the long-term sea-level rise (upper Seven Rivers and Yates Y1 time) accommodation was maximized, but rather than backstepping or "drowning", the carbonate system remained at "fill level", aggraded and even prograded. This is apparent from both stratal geometries (Figure 3; Bebout and others, 1993) and the shallow-water (shallow lagoon, shoal crest, and shoal front facies) carbonate facies that typify this interval (Borer and Harris, 1991a and b). Late "highstand time" was probably short-lived since a very low rate of relative sea-level fall would rapidly consume the little remaining accommodation, subaerially expose the shelf, and shift the siliciclastic facies tract seaward (and downward) of the thick, upper Seven Rivers carbonate bank. Stratigraphic modeling and analyses of the equivalent basinal deposits (presented in subsequent sections) suggests that the time missing during the formation of this sequence boundary and the amount of bypass to the basin was only slightly greater than previous or subsequent 4th-order cycles.

During lowstand time, progradation was minimal since the shelfal carbonate factory was restricted to a narrow belt that was perhaps stressed by the presence of a lowstand siliciclastic shoreline. Siliciclastic progradation was minimal due to the steep outer shelf slopes inherited from the carbonate system, so instead siliciclastics readily bypassed the shelf, through and/or over the reef, and into the basin. During the deposition of Yates cycle Y2 the area in front of the upper Seven Rivers bank was filled by aggradation and onlap during the transgressive and highstand portions of higher-frequency (5th-order) cycles. The onlap surface was not a single distinct surface but rather a zone that resulted in a general updip thinning rather than sharp discordance. By late Y2 time, high-frequency sea-level fluctuations once again transgressed the Seven Rivers and Yates Y1 bank, depositing thin carbonates. By Yates Y3 time, thicker carbonates were being deposited across the previous bank top well into the shelf interior.

The Fischer plot (Fig. 4) also suggests an intermediate highstand during middle Yates deposition (Y3 and Y4). This ("31/2-order") event seems to have been longer in duration than the typical 4th-order cycle and shorter in duration than the major transgressions at the top of the Seven Rivers and base of the Tansill. This cycle may represent yet another layer to the complex stratigraphic hierarchy. Figure 4 also indicates 10-15 m (30-50 ft) for the magnitude of the 3rd-order fluctuations. The estimate is highly dependent on the value

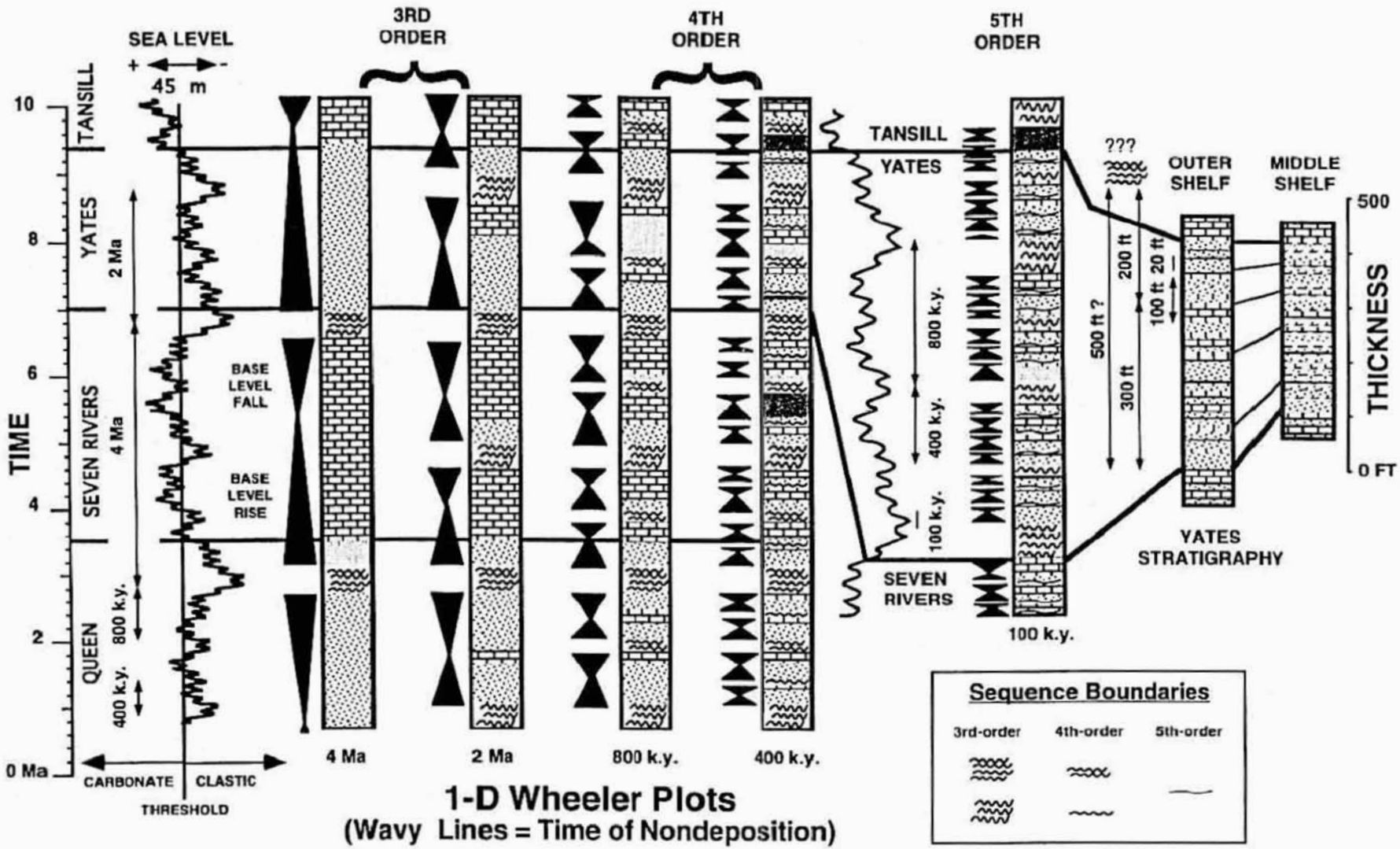

Figure 5. A conceptual model illustrating a stratigraphic hierarchy and carbonate-siliciclastic mixing for the Late Guadalupian of the Permian Basin. Model extrapolates the well-developed hierarchy found in the Yates to a larger stratigraphic interval. Long-term sea-level lowstands coincide with the Yates and Queen Formations, whereas the Seven Rivers and Tansill Formations were deposited during long-term sea-level highstands. The stratigraphy is depicted as a series of 1-D wheeler plots (time stratigraphy) in which the wavy lines (sequence boundaries) indicate times of nondeposition. From left to right, the time of nondeposition and carbonate-to-clastic alternations for higher frequency cycles are depicted. The resulting stratigraphic sections (in thickness) for the outer shelf and middle shelf of the Yates are shown at the far right. Triangles show schematic base-level transit cycles: narrowing-up triangles represent base-level rise (decreasing accumulation-accommodation ratio) and thickening-up triangles represent base-level fall (increasing accumulation-accommodation ratio).

used for subsidence correction (in this case average cycle thickness).

High-Frequency Sequence Framework.—The stratal pattern and sequence interpretation discussed above differs substantially from one made using the classic "Vail" model and may be considered a specific example for an attached mixed carbonate-siliciclastic shelf that experienced a complex hierarchy of high-frequency, relatively low-amplitude, sea-level fluctuations. Key differences from a "Vail" model interpretation include: (1) dominant transgressive and highstand progradation related to carbonate productivity; (2) high-frequency (4th- and 5th-order) sand bypass to basin; (3) 3rd-order critical surfaces (sequence boundaries, flooding surfaces) comprised of zones of multiple higher-frequency surfaces; (4) a relatively minor amount of time represented by single ("3rd-order") surfaces of erosion and/or nondeposition (lots of time represented by high-frequency surfaces throughout entire shelf section); and (5) a rapid seaward-shift in (siliciclastic) facies with only minor (not maximum) rate of relative sea-level fall.

In the Yates formation, relatively short-duration (4th- and 5th-order) cycles show many of the same attributes as longer-duration, seismic-scale sequences. These include critical surfaces (erosion, bypass and flooding), spatial shifts in deposition through time systems tracts), and internal facies stacking patterns. The basic components of the shelf cycles are (1) a surface of nondeposition or erosion formed during maximum sea-level fall (time of greatest increase in accumulation-accommodation ratio), (2) transgressive siliciclastic-rich beds deposited during sea-level rise (decreasing accumulation-accommodation ratio), and (3) regressive (highstand) carbonates deposited during late sea-level rise to early sea-level fall. These are the components for a small-scale siliciclastic-carbonate couplet as well as formation-scale cycle. The scale independent nature of the cycles is a function of the depositional system. The low-gradient, steep-edged shelf favors relative sea-level rise-dominated cycles (but with slowing rates of rise) because there is little accommodation during times of relative sea-level fall. Minor relative sea-level falls expose the shelf and regressive sand deposition is limited to just a narrow area at the shelf edge or perhaps in the deepest part of the lagoon. The updip point of the shelf margin that has appreciable accommodation even during base-level fall, marks the "accommodation hinge line" of Sonnenfeld (1991).

Because there is little space for shelf deposition during relative sea-level fall, the majority of late highstand- and lowstand-time on the shelf is represented by a surfaces of erosion or nondeposition. These surfaces in core or outcrop look remarkably similar whether at the base of a 3rd-, 4th-, or 5th-order cycle. Once again this is a function of the depositional system. An arid climate during Permian time in the Delaware Basin area would have limited syndepositional karst development. Unchannelized siliciclastic sand moved across the shelf during Yates time during even small relative sea level falls, beveling sharp planar surfaces, filling and truncating teepee structures (Borer and Harris, 1991 a and b). The surface may have been further modified (planed) during transgression. Regardless of order, bypass surfaces look quite similar at the small scale and are characterized by sharp, planar contacts of sandstone over carbonate with minor small carbonate intraclasts.

Cycle bases are sandy because during the initial sea-level rise any sand that was supplied to the shelf margin during the previous fall is trapped and reworked during the transgression (Borer and Harris, 1991 a and b). As the transgression continues the sand supply is eventually cut off and highstand carbonates are deposited as the rate of sea-level rise slows. The amount of transgressive (sand) versus regressive (carbonate) sediment in a small-scale cycle is controlled by the longer term cycles. This also imparts a sense of self-similarity to the different cycle orders. If a long term (3rd order) cycle is dominated by relative sea-level fall, then the 4th-order cycles encompassed within it, and the 5th-order cycles riding on them, will also tend to be dominated by relative sea-level-fall.

Similar scenarios occurred during each 4th- and 5th-order cycle. Progradation was a function of the carbonate factory and took place in punctuated steps during the transgressive and (early) highstand times of 4th-order cycles (Figs. 3). During the lowstands, siliciclastic-dominated shelf margin shorelines formed but could not prograde and instead bypassed sand to the basin. The thickness, internal packaging, depocenter, lateral extent, and dominant lithology of 4th-order (400-k.y.) depositional cycles is controlled by position on third-order sea-level cycles (Figs. 3 and 4). Each 4th-order sequence was built from a set of 5th-order (100-k.y.) cycles. Since these smaller stratigraphic units also have critical surfaces, siliciclastic bypass, and "system tracts", they could be considered sequences in the broadest sense.

Figure 5 illustrates additional points about stratigraphic systems with a well-developed hierarchy. This conceptual plot is based on extrapolating the Yates stratigraphic hierarchy to more

of the Upper Guadalupian section of the Permian basin and by equating the Yates and Queen Formations with long-term (4 m.y.) sea-level lowstands based on their substantial siliciclastic component. Figure 5 shows that a composite sea-level signal can produce a near continua (in both time and thickness) of depositional cycles that may prove difficult to classify into only a few discrete "orders" as is commonly done in sequence stratigraphy evaluations. Using the ordering scheme of Goldhammer and others (1991) as an example, the predicted Permian sea-level scenario exhibits cycles of two distinct "types" (magnitude and duration) within both the 3rd- and 4th-order categories. This does not even consider the fact that each cycle of a given "type" varies in magnitude and duration in concert with longer term cycles.

The classification of cycle "order" becomes even more complicated when (as in most cases) the true duration of the cycles is not known. Forcing a complicated hierarchy of cycles into three "orders" (e.g., 3rd-, 4th-, and 5th-order) may be greatly oversimplifying the case. The complexity of assigning cycle order in strongly hierarchical geologic settings is behind the serious, but somewhat tongue-in-cheek labeling of 31/2-, 41/2-, and 6th-order cycles by some workers. To further illustrate this point, consider that meter-scale (20- to 40-k.y.?) cycles which are readily apparent in Yates cores are not even considered in this discussion. Whether a complex depositional hierarchy (e.g., Yates 800?-k.y. cycle) is related to complexity in the forcing function (e.g., expanded Milankovitch series) or simply to long-term variation in the depositional response is an area that requires further work.

STRATIGRAPHIC COMPUTER MODELING

Computer models allow a geologist to visualize, test, and constrain geologic interpretations. Ideally, modeling reveals relationships that were not, or (more often) not clearly, considered. A better understanding of several topics pertinent to Yates deposition was achieved through stratigraphic modeling. These topics include: 1) cycle stacking patterns related to hierarchical sea level fluctuations; 2) the nature and timing of sediment bypass to the basin; 3) the intricacies of estimating sea-level history from stratigraphy; and 4) shelf-to-basin correlations.

The cycle analysis of Borer and Harris (1991a and b) provides a starting point for many of the input parameters needed to computer model Yates deposition. These parameters include sea-level history, depositional topography, sedimentation rates, and subsidence rates. Subsurface cross sections and the McKittrick Canyon outcrops establish stratal geometries and aggradation/progradation relationships to be matched during computer modeling. Core and outcrop descriptions provide information on paleobathymetry, facies distribution, and depositional processes that need to be adequately represented in the computer simulations.

Stratigraphic models use geodynamic algorithms from the field of basin modeling that simulate the crustal response in a basin through time to driving subsidence (thermal decay, faulting, rotation), sediment and water loading, and compaction. The simulated crustal movements are linked with dynamic sea-level and sediment accumulation algorithms that track the creation and fill of accommodation space through time. In general, stratigraphic computer forward models reconstruct the stratigraphy of a basin transect on a spatial grid using a sequence of small time steps and a prescribed set of initial conditions (Lawrence and others, 1990). The principal outputs from these "basin-fill" models are synthetic, 2-D cross sections that exhibit basin geometry, depositional sequence geometries, the temporal and spatial distribution of unconformities, and facies distribution. Additional output includes relative sea-level analysis, paleobathymetry, and chronostratigraphy. Primary input parameters include sea-level fluctuations, subsidence, sediment supply, and initial bathymetry.

The computer model used to simulate Yates deposition is PHIL (Process- and History-Influenced Layers) which was designed by Marco Polo Software, Inc. of Houston, Texas. This geometric model is based on a user-defined equilibrium profile that governs sedimentation processes in response to changes in accommodation. The model assumes that the fundamental space-filling processes (transport, deposition, and erosion of sediment) are controlled by a series of depositional interfaces whose geometries are defined by the user, based on information about modern depositional environments. The user prescribes gradients and widths of individual depositional environments. These environmental segments are linked together to define an equilibrium depositional profile that translates (progrades, aggrades, or backsteps) during each time step according to the amount of sediment available and the amount of space created by subsidence (tectonic, loading, and compaction) and eustacy.

The model simulates both carbonate and siliciclastic sediment accumulation. Siliciclastic sediments are introduced through one side of the model; whereas, carbonate sediments are produced in situ using two depth-dependent growth functions for shelf margin (reef) and platform top

(algal) carbonate factories.

Yates Model

The modeling strategy used in this study includes calibration of the model against Yates subsurface and outcrop data. The calibration step includes sensitivity tests of key input parameters which is perhaps the most important aspect of the modeling study. A "best fit" model is then used to extrapolate Yates shelf data in space and time to further our understanding of shelf-to-basin relationships. Model predictions are compared to data from a cored basinal well. This comparison provides information about the accuracy of the model, and more importantly, allows the for interpretation of additional data in light of the computer simulations. Results of this study suggest that the benefit of stratigraphic modeling is not the prediction of exact facies positions, but a better understanding of the important attributes of the depositional system which in turn promotes enhanced interpretations and predictions.

Items considered essential for a data-model "match" in our case are: (1) the correct amount of total progradation; (2) correct sediment thickness across the model; (3) reasonable paleobathymetry, including minimal exposure of the Capitan reef and minimal flooding of the shelf; (4) correct cycle stacking pattern (stratigraphic hierarchy); and (5) reasonable lithofacies prediction including the correct temporal and spatial distribution of major carbonate horizons, highstand and lowstand clastic shorelines, reef aggradation vs. progradation, and distinct seaward shifts in facies.

Figures 6 and 7 compare output from the Yates computer model to the subsurface cross section of Figure 3 drawn at a different scale. Cross sections of model-predicted lithofacies, stratal history (times lines), and bypass surfaces (3rd-, 4th-, and 5th-order cycle/sequence boundaries) are plotted at the same scale as the subsurface cross section. Although it is impossible to get a perfect data-model "match" (it is probably unrealistic to try, since multiple input scenarios can give similar output geometries/lithofacies), this "base-case" model highlights numerous important aspects of the Yates depositional system.

Attributes of the Yates model are predominantly a function of a composite sea level history (comprised of strong 4th-order cyclicity relative to 3rd-order) (Figs. 6b and 7b), operating across a distinct "accommodation profile" characterized by a very flat, low subsidence shelf, with an increased topographic/subsidence gradient towards the outer portion, and a steep shelf edge. If we add to this setting a moderately-productive, siliciclastic-resistant, deep carbonate factory, and highly variable siliciclastic-versus-carbonate shelfal accumulation rates, most of the Yates stratigraphic signature is captured.

The topography of the Yates shelf (relatively flat with a steep margin) and low subsidence sets up a distinct "accommodation profile" that results in rapid fluctuations between highstand- and lowstand-shoreline settings with only minor fluctuations in relative sea-level. This bimodal nature of the shelf has many implications for Yates stratigraphy. The model exhibits well-developed partitioning (reciprocal sedimentation) between relative sea-level rise-dominated shelf deposits and relative sea-level fall-dominated basinal deposits and predicts that alternations between shelfal and basinal deposition occurs on a much shorter time scale than appreciated by other workers. Furthermore, shelf margin deposition was relatively uninterrupted being deposited during both relative sea-level rise and fall.

The increased accommodation near the shelf edge results in a zone of greatest potential for cyclostratigraphic analysis. Updip of this zone, cycles are amalgamated (missed beats); whereas, downdip cycles cannot be readily distinguished due to steep bedding (vertical sections are too oblique to time lines/cycle boundaries) and/or a lack of water-depth-sensitive facies needed to pick cycles, i.e., subtidal missed beats. The model-predicted zone of better preserved cyclostratigraphy is consistent with outcrop and subsurface observations as discussed by Borer and Harris (1991a and b).

Figures 6 and 7 also provide insight to the nature and genesis of the "fall-in" beds that are characteristic of outer shelf equivalents of the Capitan Reef (Hurley, 1978, 1989) and are readily apparent on outcrops at McKittrick Canyon and other canyons along the trend of the Reef Escarpment of the Guadalupe Mountains. Modeling suggests that "fall-in" beds occur at the shelf margin as a natural consequence of sea-level fluctuating across an accommodation gradient. Examination of outcrops shows the progressive flattening of fall-in bed dips that is related to short-term variations of the shelf margin. Periods of "fall in" occur in the modeling during 4th-order, sea-level lowstands when accommodation space shifts seaward and off a previously deposited carbonate bank. Littoral sandstones deposited during the lowstand mark the shoreline and updip limit of accommodation. Sandstone beds inherit a strong seaward dip as they attempt to prograde over the steep carbonate margin. As the next 4th-order sea level rise slowly shifts accommodation back up the profile, there is a period of decreasing fall-in angle as the area in front of the previous carbon-

ate bank is filled in by aggradation and onlap. Onlap takes place as a series of 5th-order cycles, with each successive cycle exhibiting less of a fall in angle. During the next 4th-order fall, the shoreline jumps seaward of the aggrading margin and sets up the next "fall-in" scenario. From the modeling, the fall-in cycles correspond to 4th-order, aggradation-progradation couplets in which the progradation distance is on the order of 0.25 to 0.5 km and the aggradation approximately 30-38 m, not unlike the pattern described from the north wall of McKittrick Canyon by Hurley (1989). Periods of greatest "fall-in" coincide with long-term (3rd-order) sea-level lowstands. The downdip increase in accommodation potential also results in the basinward thickening of the Yates. Onlapping shelf strata thicken toward the basin where there is less exposure and more time represented by rock.

Figure 7 points out the fundamental importance of evaluating high-frequency cycles (normally below the limit of seismic resolution) to understand shelf evolution and siliciclastic bypass. In the Yates model, 4th-order cycles result in distinct aggradation-progradation couplets that are more distinct than any long-term (3rd-order) cycle. Furthermore, 4th-order cycle boundaries are defined by zones of concentrated 5th-order bypass surfaces as will be discussed in a subsequent section. Sediment bypass to the basin appears to be a high frequency phenomena that is only modulated by longer term cycles.

ESTIMATING THE SHAPE AND MAGNITUDE OF SEA-LEVEL FLUCTUATIONS

Insight to the complexity and nuances of estimating the magnitude and shape of sea-level fluctuations from the stratigraphic record is gained from stratigraphic computer model sensitivity studies. Investigations by several workers (e.g., Kendall and Lerche, 1989; Bond and Kominz, 1991) have pointed out the difficulty in trying to infer the shape, magnitude, and timing of eustatic sea-level fluctuations from the preserved rock record. Much of the problem lies in that the changes in accommodation that are crudely estimated from the rock record are "relative" and involve the complex interaction of topography, sediment supply, subsidence, and eustacy. Unfortunately, when one estimates the magnitude of sea-level fluctuations it is often not possible to adequately correct for topography, sedimentation rate, and subsidence. Therefore, any calculation of eustacy is a function of the values used for these other parameters (Kendall and Lerche, 1989).

Stratigraphic models explore the complexities of inferring eustacy from stratigraphy, but do not necessarily provide a unique solution (Kendall and Lerche, 1989). Instead, forward models can be used to test inferred eustacy against numerous possibilities of subsidence and sedimentation. If stratigraphic data (amount of onlap, stacking patterns, thickness, paleobathymetry) and geologic knowledge (modern sedimentation and subsidence rates) can be used to limit the possible subsidence and sedimentation models, then a more rigorous estimate of eustacy can be made.

In this section, stratigraphic computer modeling is used to investigate the relationship between inferred eustacy and the Yates stratigraphic record for different topographic, subsidence, and sedimentation scenarios. As a starting point for the modeling, a sea-level fluctuation was used with magnitudes, frequencies, and shapes based on the stratigraphic analysis of logs, cores, and outcrops described in Borer and Harris (1991 a and b). These original estimates include rough corrections for subsidence and topography. It is apparent from model sensitivity experiments that, given the geologic constraints, model resolution, and model "reality", the original estimate for Yates sea-level changes are reasonable for the 4th-order fluctuations and perhaps a bit low for the 100-k.y. fluctuations. Perhaps more important is that modeling suggests asymmetric depositional cycles of the Yates may have formed from symmetric sinusoidal sea-level fluctuations.

Shape of the Sea-Level Curve

Based on the asymmetry of Yates 4th-order (30-m, 400-k.y.) depositional cycles an asymmetric shape was inferred for the 400-k.y. sea-level fluctuations (Borer and Harris, 1991 a and b). Computer modeling illustrates how the Yates asymmetric cycles may have been produced from symmetric sea-level fluctuations. Composite sea-level fluctuations, variable facies-dependent sedimentation rates, and the flat topographic (accommodation) profile of the Yates shelf are several factors causing this phenomenon.

There are two types of asymmetry present in the Yates cycles. One type is related to the configuration of accommodation space within the depositional system. The flat topography (with a steep margin) and low subsidence results in strong partitioning between shelfal and basinal deposition. Most shelfal strata is deposited as the rate of relative sea-level rise slows, whereas most basinal strata is deposited as the rate of relative sea-level fall slows. For most of the Yates shelf (except for that portion lying depositionally down a fall-in bed), relative sea-level fall results in exposure of the shelf (minor erosion) and sediment bypass to the basin. During early relative sea-

level rise, thin (transgressive) sands are deposited across the shelf. As relative sea-level rise slows and carbonate sedimentation begins to outpace the creation of accommodation space, thick shoaling up (late transgressive to early highstand) carbonate cycles are deposited. With only small rates of relative sea-level fall (late highstand time) shelfal accommodation is quickly consumed and another bypass surface is created. Across the shoal crest some thin regressive sands may be deposited below the bypass surface; however, appreciable shelfal accommodation during relative sea-level fall is restricted to a narrow belt along the shelf margin. The resulting shelf depositional cycles are slightly asymmetric since they are dominated by sea-level fall (decreasing accommodation to accumulation ratio).

A second type of asymmetry (not entirely unrelated to the first) is the result of non uniform cycle bundling that is a byproduct of the interaction between composite sea-level fluctuations and strong, facies-dependent sedimentation rates. In the Yates composite sea-level curves (shown on Figures 6b and 7b) the amount of relative sea-level rise versus relative sea-level fall in a particular 100-k.y. cycle is a function of the cycle's position within longer term sea-level cycles. In other words, the short-term cycles are modulated by longer-term cycles. As a result, the thickness and dominant facies in each 100-k.y. cycle varies systematically. When the variation in facies type is coupled with highly variable, facies-dependent sedimentation rates, strongly asymmetric cycles are generated.

In Figures 6 and 7, extra thick shelf carbonate beds are deposited during high-frequency (100-k.y.) cycles that coincide with the rising segments of 400-k.y. eustatic cycles. The thickest of these carbonate beds also correspond with the rising limbs of even longer term cycles. Since carbonate depositional rates are fast relative to the siliciclastic rates, anomalously thick carbonate beds are deposited when only slightly more time than average (10- to 20-k.y.) is available for late-transgressive and highstand (carbonate) deposition. The extra time for carbonate deposition and the resulting asymmetric depositional cycles are a function of the slightly greater rates and magnitudes of sea level rises during positively modulated 100 k.y. cycles.

Magnitude of Sea-Level Fluctuations

Model sensitivity experiments suggest a range of possible amplitudes for the 4th- and 5th-order fluctuations that is dependent on the subsidence model used. The range is surprisingly narrow, however, since the choice of valid subsidence models is constrained by total stratigraphic thickness, cycle stacking patterns, and lithofacies (paleobathymetry). Numerous simulations were performed holding subsidence steady but varying the amplitudes of both the 4th- and 5th- order sea level perturbations (Fig. 8). In another experiment, variable subsidence models were run with the same sea level history (Fig. 9). In both cases, subsidence related to compaction and flexure loading are not considered. Instead, total subsidence is specified as a hinged model that linearly increases from left to right on each of the cross section models. The baseline subsidence model (Fig. 8 and middle column of Fig. 9) has a subsidence rate of 5 cm/k.y. at the left edge of the model which steadily increases to 7 cm/k.y. at the right edge.

Figure 8 illustrates the complex relationship between cycle stacking pattern and hierarchical (relative) sea-level fluctuations. In general, the resulting stacking pattern is controlled by the ratio between the amplitudes of the different duration cycles. When the ratio between the 400-k.y. and 100-k.y. amplitudes is high (Fig. 8, upper right), 100-k.y. cycle beats are skipped (nondeposition) and the 4th-order depositional cycles are strongly asymmetric. When the ratio between the 400-k.y. and 100-k.y. amplitudes is low (Fig. 8, lower left), all high-frequency cycles are recorded and the 4th-order cycles are more symmetric. The modeling experiment shows that the effect of amplitude ratio on cycle stacking pattern is not linear. Instead, as the amplitude of the fluctuations increase, the same amplitude ratio causes more 5th-order missed beats and 4th-order asymmetry. A comparison of the upper left plot with the lower right plot in Figure 8 illustrates this point . Both simulations have an amplitude ratio of 1, but the greater (12 m) amplitude scenario has more missed beats and asymmetric 4th-order cycles.

The two center plots of Figure 8 exhibit siliciclastic-carbonate alternations most like those found in Yates subsurface and outcrop data. These model runs suggest one (100-k.y.) cycle beat may be missed during each 400-k.y. fluctuation, resulting in the triple sandstone packages commonly observed in the Yates. The experiment suggests that (for this particular subsidence model) an 11 meter estimate for 4th-order fluctuations based on the stratigraphic analysis presented in this paper is reasonable or only slightly high; whereas, the 2 meter estimate from the stratigraphic analysis for the 100 k.y. fluctuations is less than suggested by modeling. There are several limitations in estimating the amplitude of sea-level fluctuation from simulated stacking patterns. Besides the problem of various subsidence

(discussed below) and sedimentation scenarios, model resolution and model "reality" are a consideration.

Cell spacing and the number of time slices limit model resolution. For Figures 8 and 9, cell spacing is 30 meters. There are 33 (X-dimension) grid cells for every kilometer on the cross sectional model. This is good resolution in terms of how far updip any sea-level transgression can extend. Time step resolution causes greater problems. Simulated time steps are 10,000 years. That is there are 10 time steps per 100-k.y. cycle and 100 time steps for the entire model. Due to the flat depositional profile, several kilometers of shelf may be transgressed (or prograded across) during a single time step or two. Even with the postulated low amplitude sea-level fluctuations, rapid seaward or landward facies shifts often take place in the models leaving a poorly resolved rock record. In the models, siliciclastics are often thin and discontinuous at the inner part of the outer shelf because more than a single time step or two is required to stack a resolvable transgressive sheet deposit.

In reality, the Yates depositional system probably retrograded (or prograded) more continuously and remained more in equilibrium (kept up) with relative sea-level rises (or falls). Still, the fact that models exhibit such rapid (siliciclastic versus carbonate) facies shifts related to relatively minor sea-level fluctuations indicates something important about the Yates depositional system. That is, siliciclastic-carbonate mixing on the Yates shelf is perhaps more fundamentally controlled by allocyclic base-level shifts than Waltherian facies relations.

An additional sensitivity experiment shows the effect of variable subsidence models for the same sea-level fluctuations (Fig. 9). This experiment tests whether, in terms of stacking patterns and stratigraphic thickness, a decrease in accommodation due to lower subsidence rates can be offset by higher amplitude sea-level fluctuations (and vice versa). Since carbonate systems can 'keep-up" with sea-level rises and essentially preserve (freeze) any accommodation space gains, it was hypothesized that higher-magnitude fluctuations could result in thicker sections for the same subsidence history. Results of the simple experiment illustrate that this not the case. Instead, stratigraphic thickness is a function of subsidence only. Any gains in accommodation during high-magnitude transgressions are compensated for by nondeposition during the extra-low lowstands. The carbonate factory may keep up during transgression resulting in a thick carbonate interval, however, during the subsequent sea-level fall the little excess accommodation available on a "keep-up" shelf is quickly destroyed and the platform top exposed. Since subsidence is extra low and the rate of sea-level fall extra high, more time is represented by a surface on the shelf. Furthermore, the next transgression must inundate the previous carbonate bank which remains high (and dry) as it slowly subsides.

Figure 9 suggests that stratigraphic thickness constrains the total subsidence model, whereas facies and cycle stacking patterns can be used to constrain the amplitude (ratios) and periods of the sea-level perturbations. Based on stratigraphic thickness, the subsidence rates used in the left column of Figure 9 are too low and those used in the right column are too high. Therefore, ambiguities in facies and cycle stacking related to an undetermined subsidence model is less than the variation seen across any row of the figure. Although subsidence (hinged and steady state; compaction and flexural loading effects ignored) has a first order effect on total stratigraphic thickness, it has only a second order effect on facies and cycle bundling patterns.

EXTRAPOLATION OF YATES CYCLES TO BASIN

In this section, information gained from the cyclostratigraphic analysis of Yates deposits on the shelf is extrapolated to the time-equivalent basin deposits of the Bell Canyon Formation. The detailed link between shelf and basin cyclicity is important for shelf-to-basin correlations. Basinal stratigraphy is first predicted by the model based on shelf data and then compared to that found in the Gulf PDB-03 well, a continuously cored well located near the center of the Delaware Basin.

Timing of Siliciclastic Bypass to Basin

The timing and nature of siliciclastic bypass into the Delaware Basin is poorly understood. Is sand and silt being transported to the basin across a few major surfaces, i.e. 3rd-order sequence boundaries? Or, are the numerous high-frequency exposure surfaces apparent in cores and outcrops important times of sand bypass? In light of the high-frequency stratigraphic hierarchy apparent in shelf strata of the Yates, at what level does the reciprocal sedimentation proposed by Meissner (1972) actually operate? To address these questions, the basinal stratigraphy that is predicted by the Yates computer model is used to investigate the link between shelf and basin cycles.

The amount of sediment bypass during an individual sea-level drop within a given composite sea-level curve is evaluated using the computer model. During the course of hierarchical sea-level

fluctuations (multiple events with different frequencies and magnitudes), the degree of high-frequency bypassing is modulated by the longer term sea-level signal. High-frequency sea-level falls that correspond with longer term drops (positively modulated) exhibit greater rates of relative fall and more sediment bypassing than high-frequency drops corresponding with long-term rises (negatively modulated).

Siliciclastic sediment bypass takes place in PHIL stratigraphic simulations when there is no accommodation on the shelf and relative sea level at the shelf break is falling faster than a user specified Sediment Bypass Threshold (SBT). If there is no accommodation on the shelf (a function of sediment supply, subsidence, and eustacy) but the SBT is not exceeded, a Type 2 sequence boundary is formed and progradation takes place as a shelf margin wedge without sediment bypass.

The SBT controls how fast relative sea-level has to be falling before sediment bypass occurs. The default setting is 3 cm/k.y., that is, if a eustatic fall out paces total subsidence at the shelf break by at least 3 cm/k.y., and there is no shelfal accommodation, then sediment bypass will occur. This default setting is an empirical value that has been found to be required to match most datasets (Bowman and Vail, personal communication).

Shelf topography and the competing rates of subsidence, eustatic fall, and sediment supply control whether or not siliciclastic sediments will bypass the shelf. In general, lower subsidence rates, higher amplitude sea level fluctuations, and shorter duration events (for a given amplitude) all increase the chance of sediment bypass. On the Yates shelf, low subsidence rates (4-6 cm/k.y.) and the predominance of high-frequency sea-level cycles (100 - 400 k.y.) with amplitudes of 5 to 12 meters suggests that high-frequency sediment bypass was likely.

Shelf topography, sediment supply, and the nature of the depositional system also control sediment bypass by regulating how fast shelf accommodation is filled during a relative sea level fall. Consideration of the Yates depositional system suggests that bypass may have occurred at very low relative rates of fall. Carbonate systems tend to aggrade and keep pace with sea level rises leaving little or no shelfal accommodation as relative sea-level slows then begins to fall. On a flat-topped, shallow carbonate platform such as the Yates shelf, the shoreline would quickly jump basinward to the steep shelf edge during only a minor relative rate of fall. Furthermore, siliciclastic sand that bypassed the exposed platform top could not be deposited on the steep slopes of the carbonate margin and would bypass to the basin. These points suggest a lower SBT may be appropriate for the Yates depositional system.

The SBT was adjusted in the model to test bypass sensitivity in general and to highlight the modulation of high-frequency bypass by long-term sea level fluctuations (Fig. 10). With the SBT set at -3 cm/k.y., bypass occurs during every high-frequency (5th-order) fall. With an SBT of -10 cm/k.y., only one 5th-order bypass episode is eliminated. When the SBT is increased to 18 cm/k.y., most (negatively-modulated) 5th-order falls stop bypassing sediment. At an SBT of -20 cm/k.y. only the 4th-order bypass surfaces remain. Further increase of the of the SBT can be used to evaluate the relative importance of individual 4th-order sea-level fluctuations. At an SBT of 30 cm/k.y., only the high-frequency event that has the greatest rate of fall (positively-modulated) exhibit sediment bypass. This event would be a "true" 3rd-order sequence boundary.

The fact that the SBT could be raised so (unrealistically) high and sediment bypass remain common, suggests that the Yates depositional system (low subsidence rates, low amplitude-high frequency eustacy, and flat-topped carbonate platform) readily bypassed siliciclastics, across numerous surfaces, with only minor rates of relative fall. Basinal stratigraphy should be similar to the leftmost (SBT = -3 cm/k.y.) plots of Figure 10.

Basinal Facies and Cyclicity in Gulf PDB-03

A distinct cyclicity actually exists in the basinal strata of the Delaware Mountain Group (Meissner, 1972; Kerans and others, 1992, 1993) including that portion of the Bell Canyon Formation which is time-equivalent to the Yates. Within the slope and toe-of-slope depositional setting, i.e., within the transition from Capitan to Bell Canyon Formations, Mruk and Bebout (1993) and Brown and Loucks (1993 a and b) have examined depositional cycles and siliciclastic - carbonate alternations. Cores from the Gulf PDB-03 well, as well as outcrops in the Delaware Mountains, are an opportunity to examine Yates-equivalent basinal facies.

Basinal Facies.—Three facies, distinguished by color, grain size, and sedimentary structures and reflecting "energy" of deposition, are found in the Yates-equivalent basinal deposits in the core (Fig. 11): 1) light brown sandstone, 2) dark brown siltstone, and 3) black, organic-rich lime mudstone. Subfacies occur within each of these groups.

Sandstones, comprising about 40 % of the section, are very fine- to fine-grained and well-sorted. They are massive to thin-bedded with

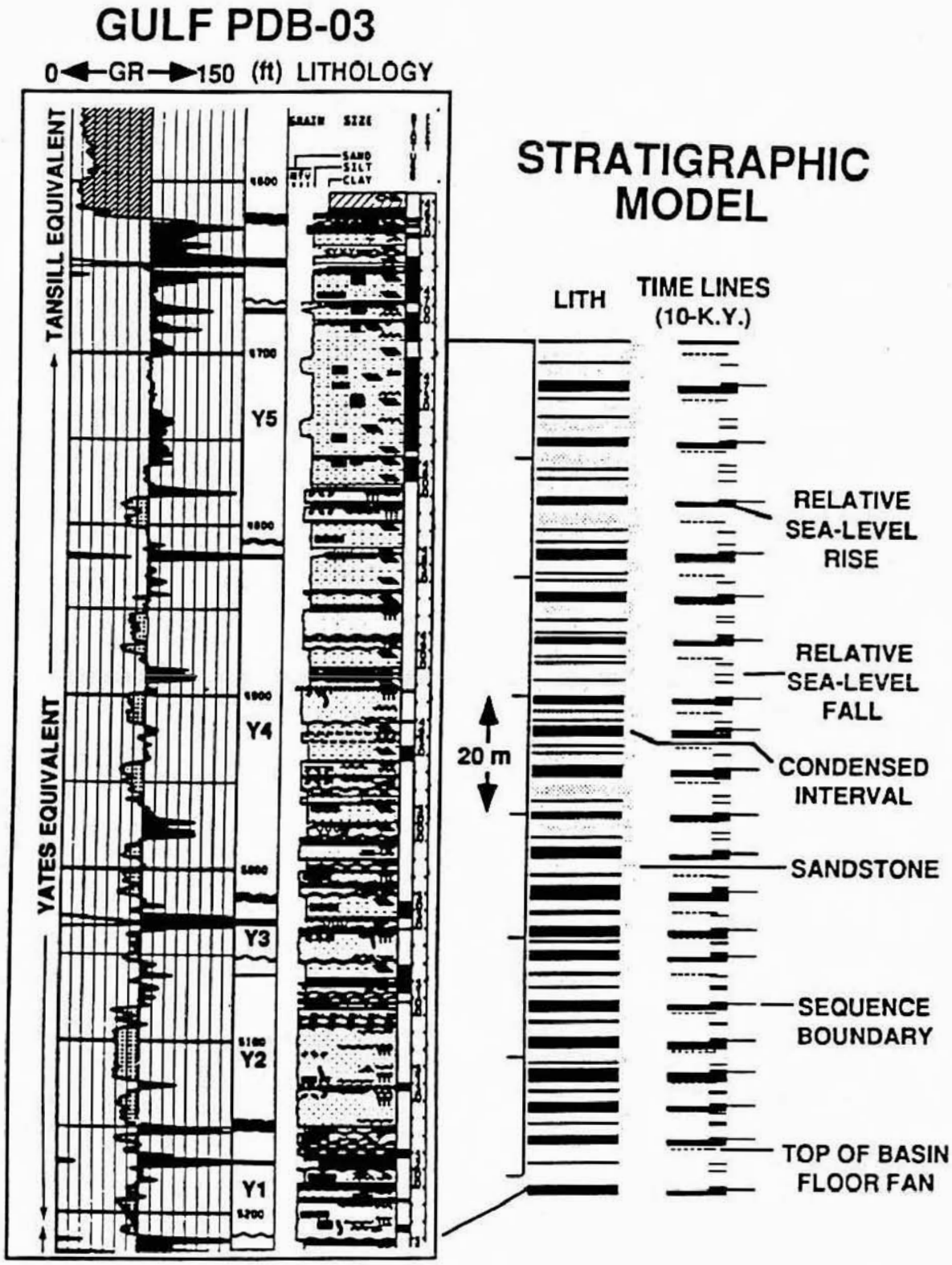

Figure 11. Comparison of model predicted basinal stratigraphy (at 12 km on Figure 6b) and Yates-equivalent basinal section from the Gulf PDB-03 well (Core description modified from M. Gardner, personal communication). Yates cycles Y1-Y5 are picked in the basin-equivalent section of the core. Sandstones are indicated by a dot pattern and lime mudstones are indicated in black on both the core decription and Gamma-Ray log. Both model and core data suggest siliciclastics bypassed the shelf and were deposited in the basin during high-frequency (5th-order) sea-level lowstands. The amount of bypass during a given 5th-order lowstand is controlled by longer-term (3rd- and 4th order) cycles. In the model, there is also a distal to proximal trend upsection.

common climbing ripple laminations. Loading/dewatering structures and contorted bedding are also common. Graded bedding is present, but subtle due to the uniform grain size. Massive (Bouma A) beds are the most prevalent but plane-bedded and rippled beds (Bouma B and C) are also common. The sandstones are interpreted as turbidites deposited during lowstands and initial transgressions of sea level. Amalgamated packages of decimeter- to meter-scale flow events form thick (3-10 m) sandstone intervals.

Dark brown, laminated and bioturbated siltstone accounts for more than 50% of the basinal section. The siltstones are organic-rich and show varve-like millimeter-scale laminations. Dark brown, organic-rich laminae alternate with light brown, silty laminae. Individual light-dark couplets are grouped into centimeter-scale bundles defined by the alternation between dominantly silt (light) and dominantly organic (dark) laminae. The organic-rich siltstones represent low energy deposition of background suspended sediment. Fischer and Sarnthien (1988) suggested eolian transport as a possible source for such suspended silt deposits in the Delaware Basin. Other possible sources for the silt include storms or distal turbidite plumes. Although the exact source of the suspended silt is not known, it is clear there were rhythmic alterations between organic-rich versus silt-rich times. Alternatively, the bundled-varve cycles could be a function of dilution with either component remaining constant and only one component fluctuating. Locally, the laminated subfacies is replaced by a bioturbated fabric. Ghost laminations are often visible through the bioturbation. Burrows are predominantly wispy, horizontal feeding traces of an unknown affinity. Alternation between laminated and bioturbated intervals probably record changes in bottom water salinity or oxygen content.

The remaining 10% of the section is comprised of black, organic-rich lime mudstone. The mudstone is laminated to massive and contains thin (mm-to cm-scale) bentonites and micritic intervals. Distinct spikes on the gamma-ray logs coincide with mudstones; values range from 90 to 200 API. The mudstones are interpreted as condensed intervals deposited as pelagic rain during times of maximum flooding of the shelf when siliciclastics were trapped far updip. During these times the basin floor may have become anoxic.

Basinal Cyclicity.—The core description and gamma-ray logs of Figure 11 indicate a distinct depositional cyclicity in the basinal deposits as has also been demonstrated by Kerans and others (1992, 1993). Cycle boundaries are marked by condensed intervals of organic-rich lime mudstone. A strong stratigraphic hierarchy exists with three scales of cyclicity clearly present and a fourth probable.

The dominant (easiest to pick) cycles, from 15 - 60 m thick, are considered to be genetically related to the 4th-order (30-m, 400-k.y.) cycles on the shelf and are labeled as such on Figure 11. As suggested by the computer modeling, thickness variation between the 400-k.y. cycles is a function of facies dependent depositional rates and strong facies partitioning controlled by longer-term cycles. The thickness of a given 400-k.y. cycle varies according to position on longer-term cycles. Thick, sand-dominated cycles were deposited in the basin during long-term lowstands; whereas, thin, organic-rich mudstone-dominated cycles were deposited during long-term highstands.

The large-scale basinal cycles are slightly more symmetrical than their shelf counterparts; typically showing a gradual increase in clean sandstone and decrease in siltstone and organic-rich mudstone away from a condensed interval, and the converse towards the next condensed interval. This symmetry is considered to represent bypass deposition during first an increase (sea-level fall) and then decrease (sea-level rise) in the rates of relative sea-level fall.

Small-scale (100-k.y.) cycles are delineated by the individual organic-rich mudstones (gamma-ray spikes) within major condensed intervals or small, poorly developed lime mudstones within sandstone intervals (e.g., Y4 and Y5). There are typically three to five of the 5th-order cycles within a 4th-order cycle. Missed beats probably occurred during long-term lowstands where high-frequency condensed intervals were not deposited or were thin and/or eroded by later turbidites.

The 100-k.y. cycles display a complicated variable thickness pattern that is expected since non-uniform cycle bundling is operating on an additional level. Fifth-order cycle thickness is nearly a continuum, ranging from less than 3 m for the most condensed (5th-order rise on 4th-order rise on 3rd-order rise) to 15 m for the thickest (5th-order fall on 4th-order fall on 3rd-order fall). Cycles with intermediate thickness correspond to the other possible hierarchical sea-level (rise-fall) scenarios (i.e., rrf,rff,rfr,frr,frf,and ffr). The relative order, in terms of thickness, of these other scenarios is poorly understood, though there is probably much overlap.

Long-term (3rd-order) cycles are present based on the presence of major condensed intervals and changes in the character (thickness, dominant lithology, symmetry, etc.) of bundled 4th-order cycles. Major condensed intervals occur from 4680-4720 ft and 5150-5235 ft in the core and con-

sist of the organic-rich mudstone-dominated portions of two 4th-order cycles. Third-order flooding surfaces are picked at the maximum gamma-ray excursion (organic-rich lime mudstones) within a major condensed interval. The organic mudstones typically exhibit several extreme spikes on the gamma-ray log.

Depositional Cycles As A Shelf-To-Basin Correlation Tool

Little detail is actually known about shelf-to-basin relations in the Delaware Basin due to limited biostratigraphic control and the inability to trace beds or time lines from the cyclic shelf deposits, through the massive reef and foreslope, and into basinal siliciclastics. The presence of a strong hierarchy of depositional cycles on the shelf and also in the basin suggests that the cycles may be useful as a correlation tool. In order to use cycles for correlation, the link between shelf and basinal sedimentation needs to be well established, as was investigated by Brown and Loucks (1993 a and b) for the Tansill and toe-of-slope equivalent Lamar deposits in McKittrick Canyon, and periods of potential missed cycle beats need to be recognized.

The current shelf-to-basin correlation scheme for the Capitan shelf margin is based largely on a series of five carbonate members of the Bell Canyon Formation, in ascending order, the Hegler, Pinery, Rader, McCombs and Lamar (Fig. 1), that prograded part way into the basin at discrete times (King, 1948; Newell and others, 1953). The genetic implications of these carbonate wedges are not well understood. Are they highstand deposits, lowstand deposits, or both? Certainly, they do not all have the same character and the detailed geology within an individual wedge suggests they consist of several genetic packages (Reekman, 1986; Lawson, 1989; Brown and Loucks, 1993 a and b). Also, the carbonate tongues are only easily recognizable proximal to the toe of slope so they cannot be used as correlation tools further into the basin, and they are difficult to recognize (particularly in cores and logs) within the slope proximal to the reef as was discussed by Garber and others (1989).

A shelf-to-basin (and outcrop to subsurface) correlation scheme is proposed on Figure 11 based on matching 3rd- and 4th-order cycles from Figures 3 to the basinal core data. The correlation scheme hinges on equating the 3rd-order condensed intervals described above with the thick carbonate "banks" deposited at the upper Seven Rivers - Yates Y1 and Yates Y5 - lower Tansill boundaries. Within this tentative large-scale framework, there is a reasonably good match between 4th-order cycles on the shelf and in the basin. Some ambiguity remains, however, due to the possibility of missed cycle beats in both the shelf (thin or no cycles, erosion) and basin (no or minor condensed mudstones resulting in sand on sand, erosion) during long-term lowstands.

Comparison Between Core Data And Model

The hierarchy or stacking pattern observed in one depositional environment (e.g., shelf) can be extrapolated to another environment (e.g., basin) provided that the genetic link is understood. The computer simulations described previously help to investigate the link between Yates shelf and basinal cyclicity. These simulations suggest siliciclastics bypassed the Yates shelf and were delivered to the basin during high-frequency (5th-order) lowstands. The record of high-frequency bypass is evident in slope equivalents to the youngest portion of the Yates and to the Tansill Formation in the McKittrick Canyon outcrops (Brown and Loucks, 1993 a and b; Mruk and Bebout, 1993). Furthermore, the amount of bypass during any 5th-order lowstand was controlled by longer-term cycles. In Figures 6 and 7, 4th-order cycles have more of a control on the amount of bypass than 3rd-order cycles because the stratigraphic computer model did not include the major transgressions at the top of the Seven Rivers and base of Tansill.

The stratigraphy of the Yates equivalent basinal section in the Gulf PDB-03 well is in general agreement with model predictions. Figure 11 compares the basinal section from the core with a columnar section (at 12 km) from the Yates "best fit" model of Figure 6B. Although a perfect fit is not expected, several significant attributes of the model compare well against the basinal data. Foremost is the importance of high-frequency (5th-order) bypass and condensation. Fourth-order (400-k.y.) "condensed intervals" are somewhat expanded since they contain multiple calcareous mudstones separated by turbidite sandstones deposited during 5th-order (100-k.y.) lowstands. Stratigraphically above (shown on Figure 11) and below (not shown) the Yates equivalent interval, long-term highstands limit high-frequency bypassing and result in stacked mudstones that represent major (3rd- and 4th-order) condensed intervals. The computer model predicts a basinal sand to shale ratio of approximately 2:1; whereas, the sand to shale ratio calculated from the well using a gamma-ray cutoff of 70 API is slightly lower at 1.3:1.

Another interesting attribute of the model is how time is partitioned in the basinal section. The difference in accumulation rates for the turbidite

sandstones and the condensed mudstones is striking and well-illustrated by the variable spacing of the time lines adjacent to the columnar section (Fig. 11). In the model, accumulation rates for the condensed muddy intervals are 4 to 10 times slower than for the sandstones.

CONCLUSIONS

High-resolution stratigraphic analyses (i.e., the evaluation of the changes in the packaging of depositional cycles through time and at different positions on the shelf) shows that at least three orders of cyclicity produced the stratigraphy of the Yates Formation on the shelf as well as the time-equivalent basinal deposits. Evidence suggests that orbitally-forced, 400- and 100-k.y. (4th- and 5th-order, respectively) duration (eustatic?) sea-level cycles (Milankovitch, long and short eccentricity cycles) were predominant events. Several, long-term (3rd-order) accommodation (sea-level) cycles with durations of 0.8 to 2 m.y. are also apparent in the Yates stratigraphy and controlled the nature (thickness, facies, symmetry) of the 4th- and 5th-order depositional cycles. The third-order cycles may be related to climate (low-frequency orbital forcing?) or tectonics. The hierarchical sea-level fluctuations resulted in depositional cycles that exhibit regional and local variability.

Stratigraphic computer modeling illustrates how the distinct Yates accommodation profile, hierarchical sea level history, and the interaction of carbonate and siliciclastic systems were fundamental controls on Yates stratigraphy. Simulations show how the Yates topography (flat platform with a steep margin), low subsidence, and "keep up" carbonate factory provided a distinct accommodation profile that resulted in rapid fluctuations between highstand- and lowstand-shoreline settings with only minor fluctuations in relative sea-level. Modeling suggests strong reciprocation between shelfal deposition during (decreasing rates of) relative sea-level rise and basinal deposition during (increasing and then decreasing rates of) relative sea-level fall occurred on a much shorter time scale (5th-order, 100-k.y.) than appreciated by previous workers (e.g., Meissner, 1972).

Modeling and outcrop stratal geometries show how increased accommodation near the shelf edge resulted in a zone of greatest potential for cyclostratigraphic analysis and suggests that "fall-in" beds were the byproduct of a hierarchical sea-level operating across an outer shelf accommodation gradient. Periods of "fall in" occurred during 4th-order, sea-level lowstands when accommodation space shifted seaward and off a previously deposited carbonate bank. Progradation was limited because the carbonate factory was decreased and lowstand siliciclastics could not prograde across the steep carbonate margin. During the subsequent 4th-order relative sea-level rise, accommodation slowly shifted back up the profile and there was a period of decreasing fall-in angle as the bank margin filled in by aggradation and onlap. Onlap took place as a series of 5th-order cycles, with each successive cycle exhibiting less of a fall in angle.

Modeling results point out the fundamental importance of evaluating high-frequency cycles (normally below the limit of seismic resolution) to understand shelf evolution and siliciclastic bypass. In our Yates model, sediment bypass to the basin is a high frequency phenomena that is varied by longer term cycles. Furthermore, 4th-order cycle (sequence) boundaries are defined by zones of closely spaced 5th-order bypass surfaces and 3rd-order sequence boundaries are, in turn, defined by zones of low-accommodation, 4th-order cycles.

Modeling experiments (sensitivity studies) provide insight to the complexity of the Yates stratigraphic hierarchy and potential problems of inferring the shape and magnitude of eustatic fluctuations from the stratigraphic record. Simulations suggest a range of possible amplitudes for the Yates 4th- and 5th-order fluctuations depending on the subsidence model used. The range is reasonably narrow, however, since the choice of valid subsidence models is constrained by total stratigraphic thickness, cycle stacking patterns, and facies (paleobathymetry). Modeling suggests 4th-order eustatic fluctuations ranged from 8-12 m; whereas, 5th-order fluctuations ranged from 4-8 m. Modeling also illustrates how asymmetric Yates depositional cycles may have formed from symmetric (sinusoidal) sea-level fluctuations due to nonuniform cycle bundling.

As a test of the stratigraphic model, basinal stratigraphy was predicted based on a "best fit" model for the Yates shelf and then compared to basinal stratigraphy in a cored well. Although a perfect stratigraphic match was not acquired (or expected), several attributes of the model stratigraphy compare well against the basinal data. These include the degree of vertical heterogeneity, the distribution of condensed (sealing) mudstones, the ratio of sand to shale, and thickness of individual sands. The model provides valuable information about the genetic link between shelf and basinal depositional cycles.

The sequence stratigraphic interpretation presented in this paper for the Yates is substantially different than the classic "Vail" model and includes: (1) dominant transgressive and highstand

progradation related to carbonate productivity; (2) high-frequency (4th- and 5th-order) sand bypass to basin; (3) relatively little missing time at 3rd-order sequence boundaries (lots of missing time in high-frequency increments throughout entire shelf section); (4) rapid seaward-shift in (siliciclastic) facies with only minor (not maximum) relative sea-level fall; and (5) 3rd-order critical surfaces (sequence boundary, flooding surface) comprised of zones of multiple higher-frequency surfaces.

This study suggests, that within a basin-margin context, erosion and bypassing (as well as flooding, condensation, aggradation, and progradation) should be considered high-frequency processes. Stratigraphic modeling experiments illustrate how the efficiency of these processes vary with position in a 3rd-order cycle (e.g., 4th-order bypassing and flooding are more efficient during the 3rd-order fall and rise, respectively). At some critical threshold a surface is generated that is considered to be a 3rd-order surface (sequence boundary or flooding surface); however, the surface is actually generated during a 4th- or 5th-order event when the rate of base-level change is maximized. Prior or subsequent high-frequency surfaces may be genetically just as important.

Modeling suggests that amalgamated sequence boundaries split into multiple high-frequency surfaces downdip, whereas, flooding surfaces split updip. Picking a single third order sequence boundary or flooding surface, particularly at shelf margin, may be difficult and misleading. In some cases it is more appropriate to pick critical zones rather than surfaces (shown also by Montanez and Osleger, 1993), such as the zone of closely spaced (low accommodation) 4th- and 5th-order cycles (corresponding to Y2 and Y3) on Figure 3. However, even this may be misleading since other 4th-order lowstands are also important times of bypass.

Whether 4th-order surfaces are amalgamated (to form true 3rd-order surfaces) or separate entities is a function of (a) the shape, magnitude, and duration of the 3rd- and 4th-order sea-level events, (b) the rates of sedimentation and subsidence, and (c) the topographic profile of the shelf-to-basin transect. In other words, these fundamental parameters control how good a given depositional system is at recording an input sea-level signal. The Yates depositional system was apparently a very good signal recorder. Stratigraphic models illustrate how each parameter varies the genetic importance of 5th-order cycles, relative to 4th-order cycles, relative to 3rd-order cycles.

ACKNOWLEDGMENTS

This paper is based on a M.S. Thesis completed in May 1993 by J. M. Borer at the University of Southern California. In addition to P. M. Harris, committee members were D. Bottjer, A. Fischer and D. Gorsline. We are grateful to the committee members for their suggestions. We also thank Chevron Petroleum Technology Company for their support of our subsurface and outcrop studies of the Yates Formation.

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YATES DATA - MODEL CONVERGENCE

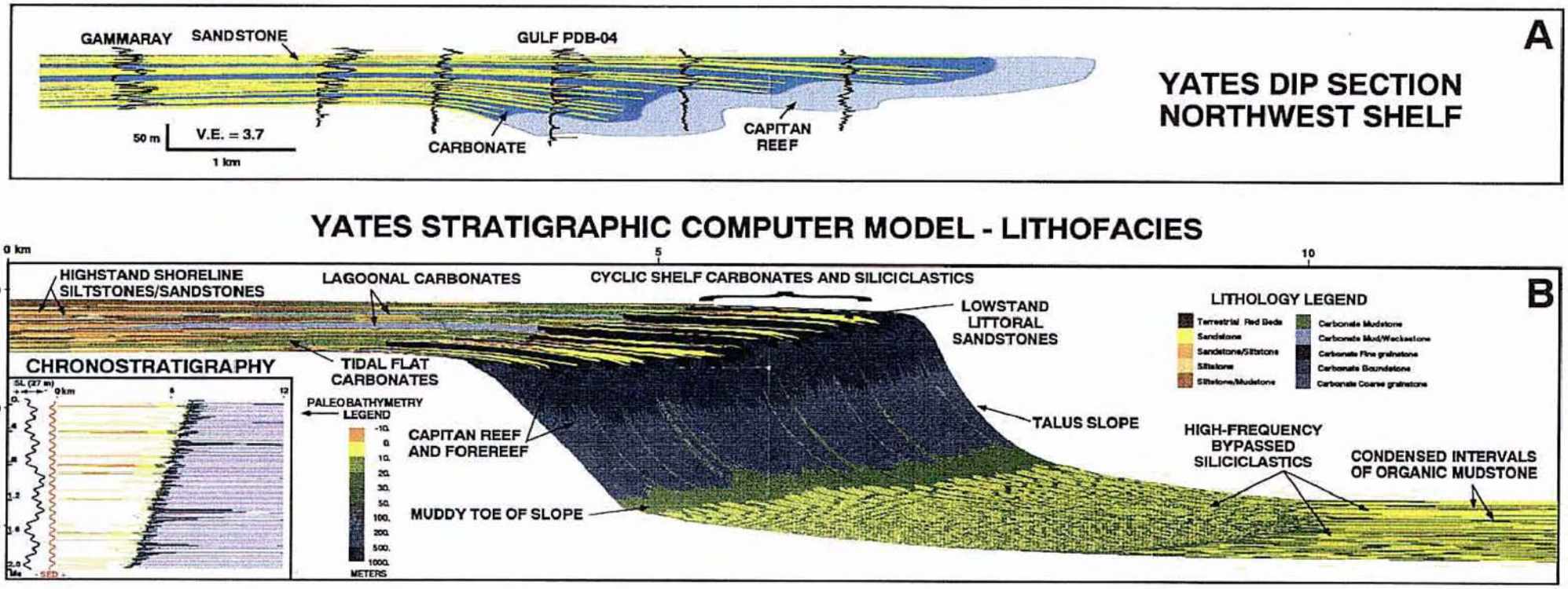

Figure 6. Comparison between (A) Yates subsurface dip cross section for the Northwest Shelf of the Permian Basin from Borer and Harris (1991 a) and (B) model-predicted lithofacies. Model parameters are derived by progressively tuning a set of initial parameters formulated from a cyclostratigraphic analysis. Parameters were tuned until the model "matched" subsurface and outcrop data in terms of: (1) the correct amount of total progradation, (2) correct sediment thickness across the panel, (3) reasonable paleobathymetry, including no exposure of the Capitan reef and only shallow flooding of the shelf, (4) correct cycle stacking pattern (stratigraphic hierarchy), and (5) reasonable lithofacies prediction including the correct temporal and spatial distribution of major carbonate horizons, highstand and lowstand clastic shorelines, patterns in reef aggradation and progradation, and distinct seaward shifts in facies. The model illustrates many important attributes of the Yates stratigraphy, particularly the genetic importance of high-frequency cycles in regard to shelf construction, siliciclastic sediment bypass, and shelf reservoir heterogeneity (highstand siliciclastics). The Yates stratigraphic signature or style is largely a function of a composite sea-level history, with a strong 4th-order cycle relative to 3rd-order, operating across a unique accommodation profile.

(Borer & Harris)

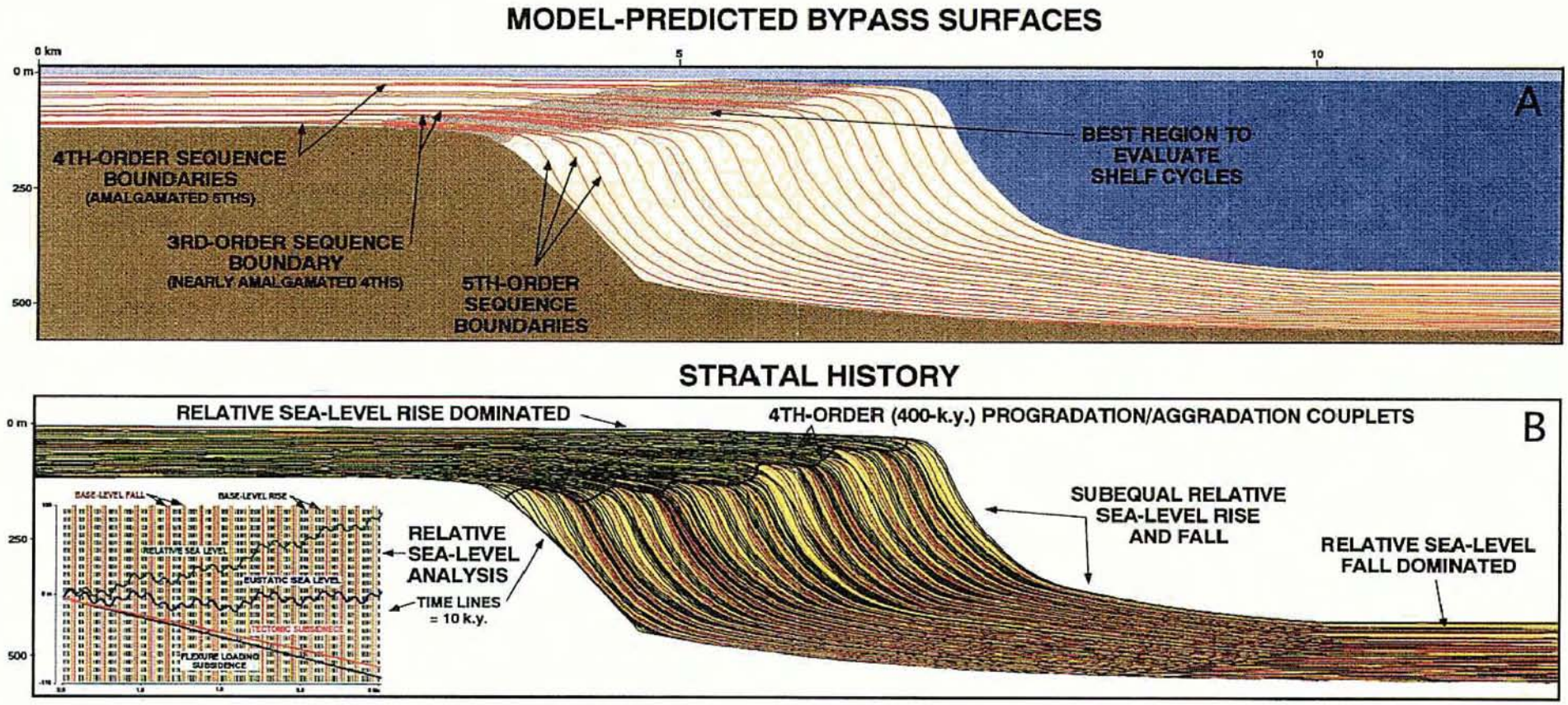

Figure 7. Output from the computer model of Figure 6b to show bypass surfaces and stratal history plot. (A) The model suggests that siliciclastics bypassed the shelf during numerous high-frequency events. Fifth-order bypass surfaces are concentrated into distinct zones that define 4th-order cycles. Two, nearly amalgamated, 4th-order cycles in turn define a 3rd-order sequence boundary zone. The model illustrates why the outer shelf has the greatest potential for cyclostratigraphic analysis (gray shaded area). Cycles are amalgamated (missed beats) updip of this zone, whereas downdip cycles cannot be readily distinguished due to steep bedding (vertical sections are too oblique to time lines/cycle boundaries) and/or a lack of depth-dependent facies. (B) Time lines in cross section correspond to those in the relative sea-level analysis inset. Green lines represent time of relative sea-level rise, orange lines sequence boundaries, red lines times of relative sea-level fall, and yellow lines end of bypass (top of basin floor fans). The Yates accommodation profile and sea-level history resulted in a strong high-frequency reciprocation between shelfal and basinal deposits, whereas shelf margin deposition was nearly continuous. Fourth-order cycles are the dominant constructional elements of the Yates shelf and seem to be genetically more important than the longer term cycles.

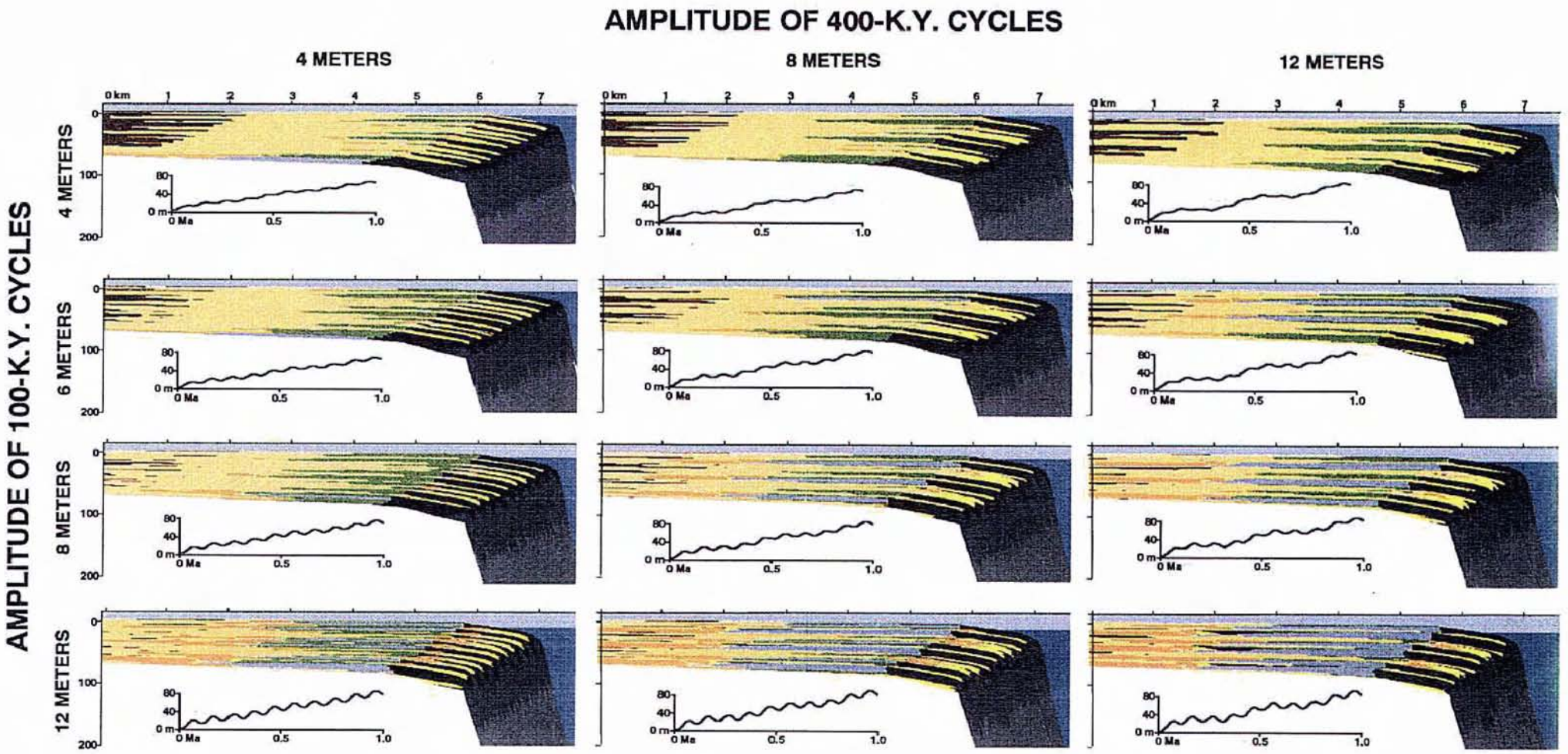

Figure 8. Model output indicating sensitivity of cycle stacking patterns to various amplitude combinations of uniform duration 4th- and 5th-order sea-level fluctuations. Inset sea-level curves are relative, i.e. include subsidence. The two center plots exhibit carbonate-siliciclastic alternations most like those found in Yates cores, logs, and outcrops. These model runs suggest one (100-k.y.) cycle beat may be missed during each 400-k.y. fluctuation, resulting in the common triple sandstone intervals seen in the Yates. The experiment also suggests that for this particular subsidence model (hinged, 5 cm/k.y. on the left and 7 cm/k.y. on the right) the 11 meter estimate for amplitude of the 4th-order fluctuations of Borer and Harris (1991 a and b) based on stratigraphic analysis is reasonable; however, their 2 m estimate for the 100-k.y. amplitudes is less than predicted by modeling. Also note the asymmetric cycles caused by nonuniform cycle bundling. Extra thick "400-k.y." carbonate beds occur when 100-k.y. transgressions are positively modulated by 400-k.y. transgressions. The slightly greater amount of time for highstand carbonate deposition combined with rapid sedimentation to form thick cycles.

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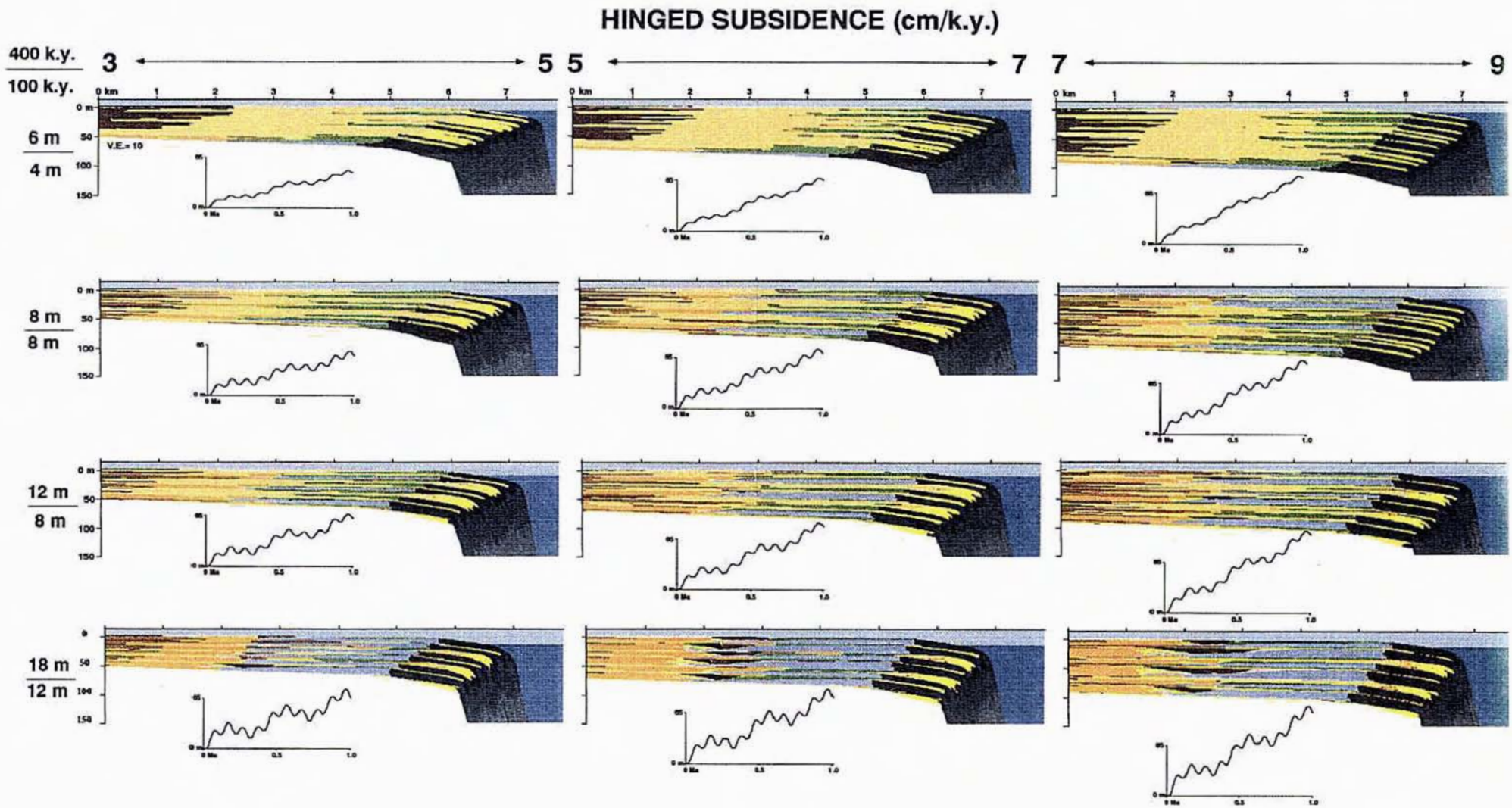

Figure 9. Model output indicating sensitivity of cycle stacking patterns to uniform sea-level fluctuations but different subsidence scenarios. The input relative sea-level curves are shown. Each row has uniform sea-level amplitudes for both 4-k.y. and 100-k.y. oscillations. Each column corresponds to a different hinged subsidence model. Total subsidence has been specified; compaction and flexural loading are not operative. In terms of stacking patterns and stratigraphic thicknes decrease in accommodation related to lower subsidence is not offset by greater sea-level fluctuations and vice-versa. Total stratigraphic thickness is controlled by subsidence; larger short-term transgressions do not result in thicker stratigrap sections. Subsidence has only a second order effect on facies and cycle stacking patterns.

(Borer & Harris)

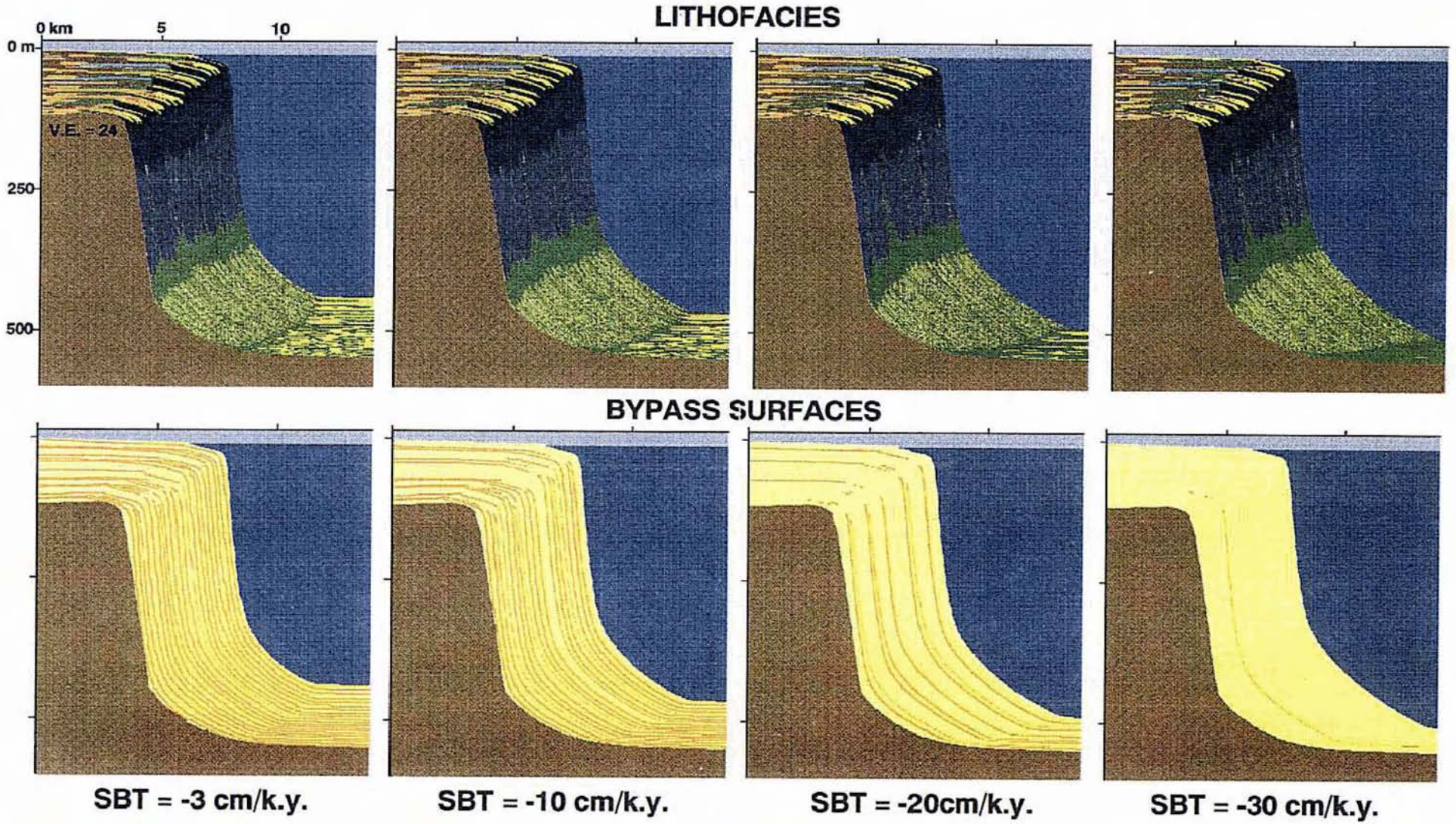

Figure 10. Model output illustrating sensitivity to sediment bypassing. In the computer model, sediment bypasses to the basin when there is no accommodation on the shelf and relative sea-level is falling at the shelf break at a rate greater than that specified by the user. The default rate for this Sediment Bypass Threshold (SBT) is -3 cm/k.y.. Unreasonably high SBT values are required before episodes of high-frequency (5th-order) bypass are eliminated. Running the model with high values illustrates which 4th-order fluctuations are the most important in terms of bypass. Orange lines depict model-predicted bypass surfaces, and yellow lines mark end of bypass (top of basin floor fans). The experiment strongly suggests siliciclastic bypass to the basin was a high-frequency phenomenon and that the plot furthest to the left should most closely approximate basinal stratigraphy. The amount of bypass on any given high-frequency surface was modulated by the longer-term sea-level cycles.

rer & Harris)