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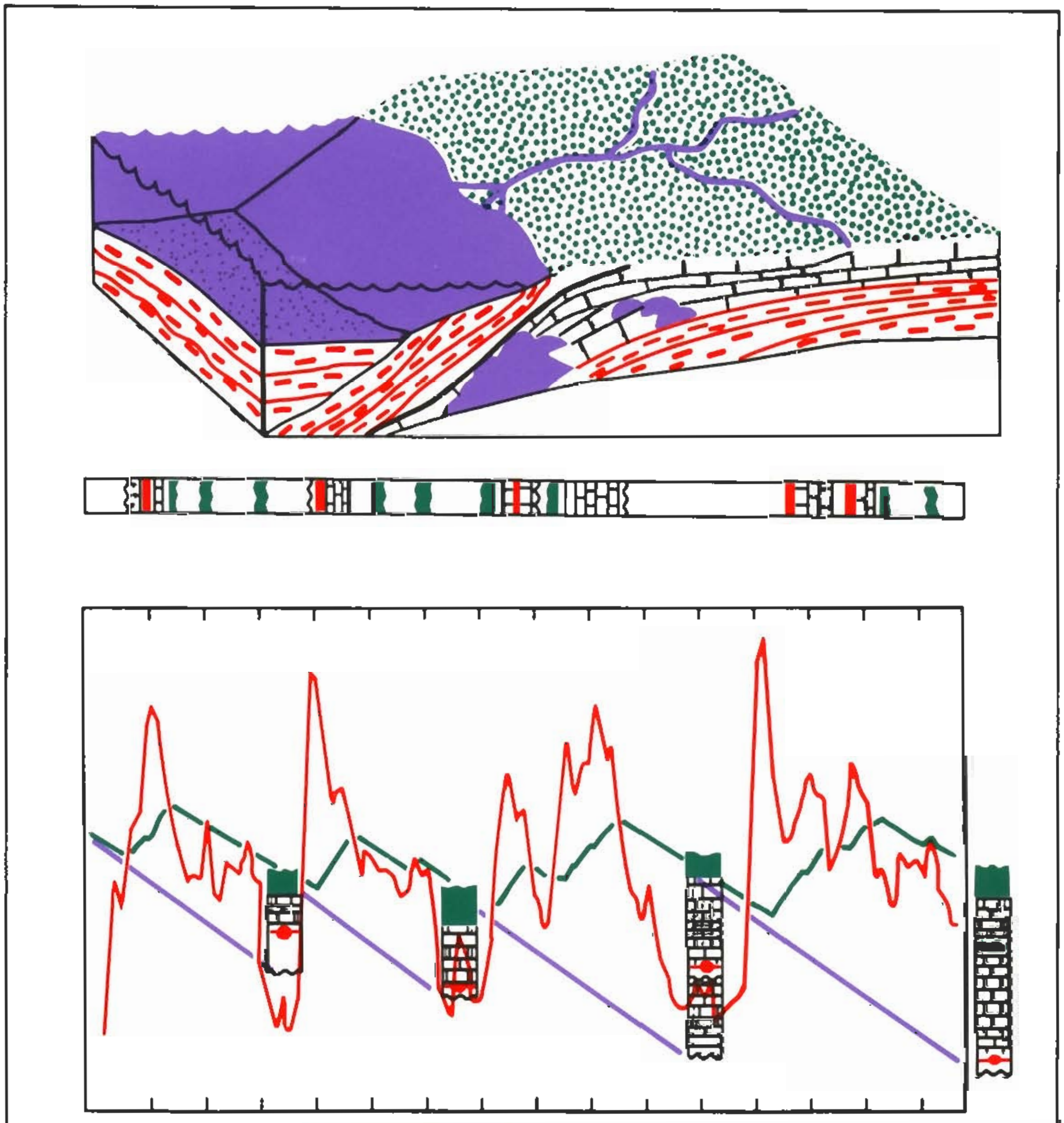
Sedimentary Modeling:

Computer Simulation of Depositional Sequences

Evan K. Franseen and W. Lynn Watney, editors



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ON THE COVER: *Upper*—Block-diagram interpretation of the Hertha and Swope sequences in a shelf to basin setting, eastern Kansas. *Lower*—Example of a forward computer simulation of a Pennsylvanian carbonate-dominated depositional sequence. *Cover design by Jennifer Sims*.

Contents

Introduction

This volume contains a collection of summary papers from presentations made at the conference on "Sedimentary Modeling: Computer Simulation of Depositional Sequences" held at the Kansas Geological Survey in Lawrence, Kansas, on October 13, 1989. The idea to hold a conference was initiated in recognition of 100 years of continuous service by the Survey and of the recent advances in sedimentology that incorporate sequence-stratigraphic concepts, computer modeling, and related methods that help refine our interpretations of the stratigraphic record. We are at the threshold of a new era in geology where various field, laboratory, and conceptual relationships can be interpreted through computer simulations. Although the scales of space and time dealt with in modeling are immense and the parameters are complex, systematic collection of data followed by simulation modeling may reap significant rewards for geologic predictions. It was our goal to incorporate into one meeting a group of sedimentologists, paleontologists, and modelers to address the following themes: 1) current computer models of sedimentary rocks, 2) applicability of models to the rock record, 3) limitations and assumptions of models, and 4) where the future leads for modeling. The objectives of the meeting are not to reach a consensus, but to present and discuss current ideas and approaches, facilitate further communication, and heighten awareness on subjects we believe will become increasingly important in sedimentologic studies.

This conference volume contains 32 papers on a variety of subjects that are important, either directly or indirectly, in sedimentary modeling. Several papers focus on the current use of simulation models, including forward, inverse, and basin-analysis modeling. Some other papers are concerned with the controlling parameters important to modeling, such as estimating sea-level changes and subsidence patterns and their effects on sedimentation, accumulation rates, effects of global or stratigraphic forcing, periodicity in cyclic sediments, and lag time or breaks in sedimentation. Other papers illustrate the importance and usefulness of diagenesis, paleotectonic considerations, subsurface techniques (high-resolution seismic, wireline logs), and paleontology/paleoecology in sedimentary modeling. Several papers concentrate on various aspects of the midcontinent Pennsylvanian strata or "cyclothems." These midcontinent-focused papers provide a springboard in carrying the conference themes to the post-conference field trip that will examine the Pennsylvanian-age Lansing and Kansas City groups in a shelf-to-basin setting between Kansas City, Kansas, and Chanute, Kansas. The field trip will focus on the application of sequence-stratigraphic concepts to these outcropping strata and to analogous near-subsurface strata. By incorporating these concepts and other new methodologies in the study of cratonic strata, we may be able to develop, test, and refine computer-simulation models of depositional and diagenetic features that will be useful for locating natural resources in Kansas.

The Kansas Geological Survey is celebrating its centennial of *continuous* service to the state of Kansas in 1989 with this conference, much the same as the Survey celebrated its "other" centennial in 1964 (the KGS was initially started in 1864, but was closed from 1866 to 1889). The 1964 "Symposium on Cyclic Sedimentation" resulted in a benchmark symposium volume edited by D. F. Merriam (1964). The 1964 symposium volume included an insightful introduction by W. W. Hambleton (then Associate Director of the KGS); many of his comments are still valid for our conference, some 25 years later. The following are two excerpts from that introduction (Hambleton, 1964, p. v.):

> Since the beginnings of the science of geology, geologists have generated models to explain observable phenomena. Often, the model was based upon an experience factor, and one could look for and recognize a pattern in information that could be related to previously encountered models. However, the generation of a model is not always simple because problems are rarely simple, and one may be faced with the evaluation of many interacting parameters.
>
> Our notions about the tectonic and stratigraphic boundary conditions of sedimentary environments, for example, have long been controlled by models that may have outlived their usefulness and only by imaginative and systematic studies can we look to new models.

The fact that 25 years later the same statements are appropriate for our conference on sedimentary modeling underscores the extreme complexity of interpreting the rock record and understanding the interplay of the many variables that interact to create the sedimentary rock record. We can not yet duplicate exactly what is observed from the rock record in an experiment, in large part due to the vast amount of time required for geologic processes to occur. We can only approximate geological processes. An incomplete rock record allows only limited observable features available to describe a depositional system. The interaction of large- and small-scale events (time and space) was likely important in creating the rock record, yet the large-scale nature of the rock record limits the ability to sample, recognize, and describe small-scale features. Sedimentation rates, accumulation rates, and duration of hiatal surfaces are relatively poorly understood variables today, but with more rigorous studies they will likely form the foundation for more realistic models.

Despite the seemingly overwhelming problems that face sedimentary geologists, progress has been made over the last 25 years toward quantification of process-response relationships. The approaches and concepts used in collecting and interpreting data on sedimentation and stratigraphy are becoming increasingly more accurate and precise due to advances in biostratigraphy, paleoecology, subsurface studies, and seismic- and sequence-stratigraphic concepts. Other methods and new technological advances are providing increased resolution of both small- and large-scale features of the stratigraphic record (e.g., seismic-reflection profiling, wireline logging, chemical stratigraphy). The demand for greatly improved geologic prediction (e.g., reservoir characterization to predict bypassed oil and gas in existing fields) is resulting in interdisciplinary studies that provide independent data, useful in modeling, to test and verify stratigraphic and sedimentologic interpretations. Computing facilities are becoming more available and accepted for sophisticated computing tailored to managing larger data sets in shorter time periods, solving geologic problems, and for simulation modeling of the sedimentary record.

Computer-simulation modeling, a theme of this conference, holds exciting possibilities in helping resolve long-outstanding geologic problems. For example, modeling provides the means to 1) empirically test interactions of causal mechanisms of sedimentary sequences, 2) test and improve accuracy and precision of data collection and interpretation, 3) encourage interdisciplinary study and independent verification of data, 4) identify new areas of problem-oriented research, and 5) eventually permit prediction of sedimentary sequences. Computer-simulation models in use today include forward models (process-response), inverse models (rock to process, in time), simulations of sedimentary processes, simulations of stratigraphic units, and geometric models (concerning stratal elements). However, computer models are only as useful as the parameters used to define the models. There is good reason to believe that sedimentary modeling will be greatly improved as more problem-oriented interdisciplinary studies are conducted to acquire independently verifiable parameters that are accurate and precise, thereby providing improved constraints to models.

The challenge today in sedimentary geology and modeling is to extend the lower limit of resolution through improved problem development and more systematic and sophisticated quantitative data collection and analysis. Integrated or collaborative investigations using current concepts and technologies may be the best means to address these problems. Moreover, interdisciplinary studies can provide a means to corroborate results and improve interpretations. We hope that this conference provides a means to stimulate thought on the problems and potential of quantitative sedimentary analysis and simulation.

Acknowledgments—The planning and organization of a successful conference and field trip requires the combined efforts of many individuals and institutions. We thank the Kansas Geological Survey for administrative and logistic services. Conference and field-trip expenses were offset by generous contributions from the Kansas Geological Survey, Continuing Education and Academic Affairs Divisions of the University of Kansas, the Kansas Geological Foundation, and Arco Oil and Gas Company.

We are grateful to K. Kappleman and the Division of Continuing Education for handling much of the budgeting, planning, and logistical details before and during the conference and field trip. R. Buchanan's help with initial conference planning and publication procedures is greatly appreciated. We give our sincere thanks to the reviewers for their time and expertise on early versions of the summary papers in this volume. Members of the Petroleum Research Section of the Kansas Geological Survey, in particular C. G. Maples, D. L. Baars, and K. D. Newell were helpful in numerous ways throughout the development of the conference and field trip. We wish to thank L. A. Davidson for secretarial and word-processing services, J. Charlton for processing photographs, and S. Larson for preparing rock samples and thin sections. We thank M. D. Adkins–Heljeson, J. Sims, and R. Hensiek for timely drafting, technical editing, and arrangement of the manuscripts into the final format of this volume. The willing and able help of Kansas Geological Survey and University of Kansas graduate students, S. Roth, R. Fillmore, M. Lambert, D. Lehrmann, R. Abeg, J. Johnson, and J. Youle helped make for a more smoothly run conference and field trip.

Evan K. Franseen
W. Lynn Watney
Kansas Geological Survey
September 1989

Simulation of the sedimentary fill of basins

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Introduction

Use of SEDPAK is illustrated with examples from the Permian basin of west Texas and New Mexico, the Permian of the Sichaun basin, the Upper Devonian of western Canada, and the Cretaceous and Tertiary of the Bahamas. The interactive computer simulation program SEDPAK tracks cross sections of clastic and carbonate sedimentary bodies as a basin fills from both sides. Data entered to run SEDPAK include the initial basin configuration, local tectonic behavior, sea-level curves, the amount and source direction of clastic sediment, and the growth rates of carbonates as a function of water depth. SEDPAK is implemented in C (Kernighan and Rittchie, 1978), uses the X-window system for graphical-plotting functions, and is operated on a UNIX-based work station, such as DEC 3100, SUN, and/or APOLLO.

SEDPAK represents a system that can test seismic interpretations based on sea-level curves. These curves can be input parameters to the program. The program responds to tectonic movement, eustasy, and sedimentation, modeling sedimentary bypass and erosion. It reproduces lacustrian, alluvial, and coastal plains; marine shelf, basin slope, and basin floor; clastic settings and progradation; the development of hardgrounds, downslope aprons, keep-up, catch-up, back-step, and drowned reef facies; and lagoonal and epeiric sea facies in carbonate settings. It simulates extensional vertical faulting of the basin, sediment compaction, and isostatic response to sediment loading. Sediment geometries can be viewed immediately on a graphics terminal as they are computed. Based on the observed geometric patterns, parameters can be repeatedly changed and the program rerun until the user is satisfied with the resultant geometry.

SEDPAK is a stochastic computer model that tracks evolving sedimentary geometry as a basin is filled by clastic sediments, and by the production and transport of in situ carbonates responding to sea-level changes. Clastic depositional phenomena incorporated include clastic infilling of topographic depressions, creation of sediment wedges or fans, draped fill over topography, procedures to ensure that clastic sediments penetrate a minimum distance into the basin, and devices to monitor the volume and areal distribution of the sediments being deposited. The effects of eustatic changes upon clastic-sediment deposition also are modeled. Important carbonate phenomena modeled include the influence of eustasy upon the accumulation rate and the rates of progradation or retreat of carbonates.

Additional influences upon sediment geometries include faulting of the basin, water depth, erosion of previously deposited sediments, submarine slumping, compaction of sediments, and isostatic subsidence of the basin. For a complete description of the SEDPAK algorithm, see Strobel et al. (1987), Helland–Hansen et al. (1988, 1989), Nakayama and Kendall (1989), Kendall, Tang, et al. (in press), and Strobel et al. (in press).

Clastic deposition

The "volume" of clastic sediment deposited from either side of the basin at each time step is simulated by the use of two right-angle triangles, one each for sand and shale. The area of the triangles represents the volume of sand or shale available, respectively, for deposition at that time step, and the base of the triangle represents the maximum distance that the respective sediment penetrates into the basin from that margin at that time step. The triangles are a device to model the distance the sediments are transported into the basin and simplify the simulation of depositional processes.

Deposition occurs as follows: 1) If the slope does not exceed the angle of maximum stability, sediment is deposited on that column up to a height controlled by the maximum stability angle. Then the simulation deposits sediments from the current column away from the center of the basin up to a maximum stability slope. If it is above sea level, this slope defines the surface of the alluvial plain or if it is below sea level, it defines the surface of a submarine slope. Sediment fans terminate upslope at the point at which the present surface of the basin exceeds the stable slope. 2) If the combined sediment heights of the triangles do not reach the maximum deposition height possible, then the simulation deposits the sediments that are available from the area of the sediment triangle.

Carbonate model

The main influence upon the amount of carbonate to be deposited in each column is the depth of water for that column mimicking the response of carbonate-producing organisms to photosynthesis. The amount of carbonate accumulation in each column is influenced by 1) wave energy damping rates of carbonate accumulation on build-ups or reef margins; 2) the presence of "reefs" or build-ups on the margins of lagoons that limit aerating waves or nutrient supply into the lagoons and within epeiric seas, so reducing accumulation rates; and 3) the amount of clastic material deposited in the column, which damps carbonate growth and mimics the oversupply of nutrients to the area. Transported carbonate talus is modeled by assuming that talus deposition follows rules similar to those for clastic materials.

Examples and results

The block (fig. 1) output shows how SEDPAK handles offshore topographic relief and models drape when clastic sediments encounter some offshore topographic relief. The tolerance level for offshore topographic relief is a user-supplied input. Fig. 1 shows how SEDPAK first fills in the offshore topographic relief and then proceeds to deposit sediments past the relief once it has been topped. The salt data set (fig. 2) shows that features such as salt ridges can be incorporated into the simulation. In addition, the user can model varying density uplift for the salt ridges.

To demonstrate how the SEDPAK algorithm works, we used several geologic examples including the Permian sediments of west Texas and New Mexico (Kendall, Strobel, et al., 1989; Kendall, Harris, et al, 1989; Kendall, Tang, et al., in press; fig. 3), and the sedimentary fill of the Sichuan Basin of China by Upper Permian coals and carbonate sequences (Tang et al., 1989; fig. 4).

The sediments of the west Texas Upper Permian are composed of carbonate and clastics (Kendall, Strobel, et al., 1989; Kendall, Harris, et al, 1989; Kendall, Tang, et al., in press). We used as the geometries that we were trying to duplicate, cross sections of the Upper Permian Capitan margin of the northern Delaware basin made by King (1942) and Harris and Grover (1989). These cross sections show a mixed carbonate/clastic sequence prograding from 4 to 19 km (2–11 mi) into a basin, at least 400 m (1,320 ft) deep, over a period of 2.5 m.y. Locally, the Seven Rivers Formation carbonate margin aggrades some 140 m (462 ft) with little progradation, then it moves seaward over its debris some 3 to 7 km (2–4 mi), aggrading about 10 m (33 ft). The carbonate margin of the Yates and Tansill Formations aggrades 140 m (462 ft) with a progradation of about 3 km (2 mi).

Using SEDPAK, the present geometries of the sediments of the Permian basin Capitan shelf margin were reproduced by having a rapid third-order sea-level rise upon which 3–10-m (10–33-ft) fourth-order sea-level fluctuations were superimposed.

Most of the carbonate sediment was modeled as forming in less than 20 m (66 ft) of water at the basin margin with most of the carbonate that is produced being transported downslope to form the prograding clinoforms of the margin. The margin was allowed to develop a stable carbonate slope of up to 20° (a response to active cementation) and a siliciclastic slope of 1.6°. The siliciclastics were modeled by trapping them updip during sea-level high stands and having them bypass the margin at low stands to collect in the basin. The models developed with SEDPAK suggest that the Permian basin was being rapidly filled by the prograding carbonate margin and clastic bypass.

Data on the Upper Permian Sichuan basin were provided by a visiting scholar from China (Tang et al., 1989). The Upper Permian Sichuan basin is underlain by basaltic lava flows. Over these basaltic lava beds a transgressive, aggrading clastic sequence was deposited. As the clastic sediments onlapped shelfward, deep-water carbonates began deposition in the distal basin where clastic sediment was starved. As the sea-level rise continued, clastic sedimentation in the basin decreased and the deep-water carbonates began shoaling upwards, finally reaching sea level to prograde into the basin. Our simulation was able to capture the geometries and the sense of the Sichuan Upper Permian (fig. 4).

Other examples include the modeling of the accumulation of carbonates in the Upper Devonian in western Canada (Scaturo et al., 1989) and the Upper Cretaceous and Tertiary of the Bahamas as interpreted by Eberli and Ginsburg (1989).

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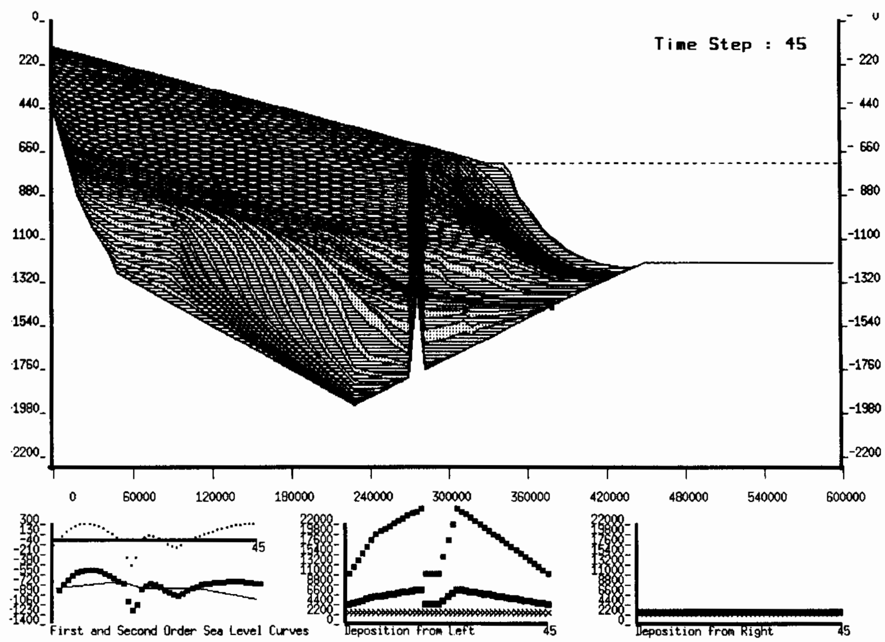

FIGURE 1—OUTPUT OF THE BLOCK DATA SET SHOWING HOW SEDPAK CAN MODEL OFFSHORE TOPOGRAPHIC RELIEF. Sand is represented by dots and shale is represented with horizontal lines.

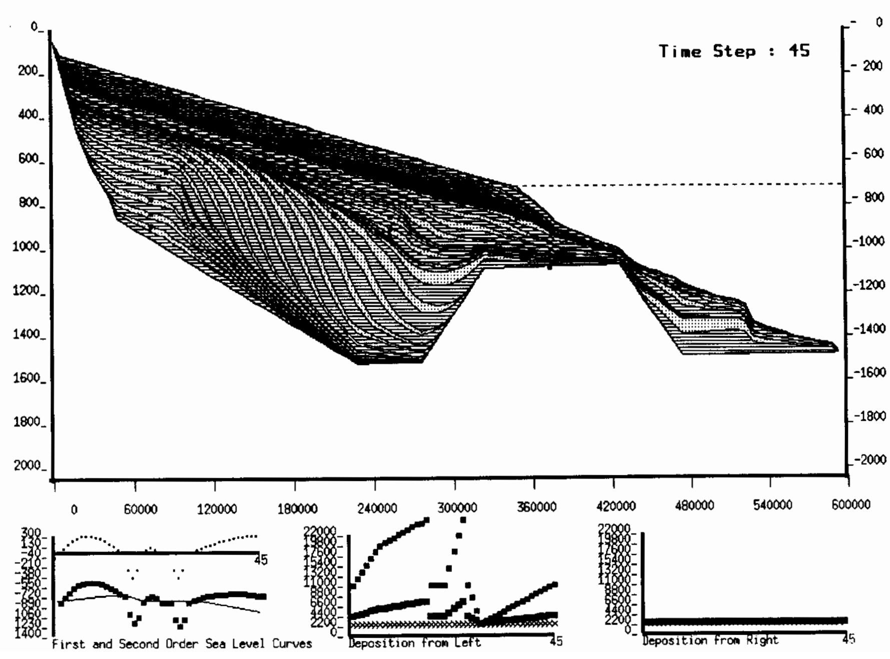

FIGURE 2—OUTPUT OF THE SALT DATA SET SHOWING HOW SEDPAK CAN MODEL SALT RIDGELIKE FEATURES WITHIN A BASINAL ENVIRONMENT. Sand is represented by dots and shale is represented with horizontal lines.

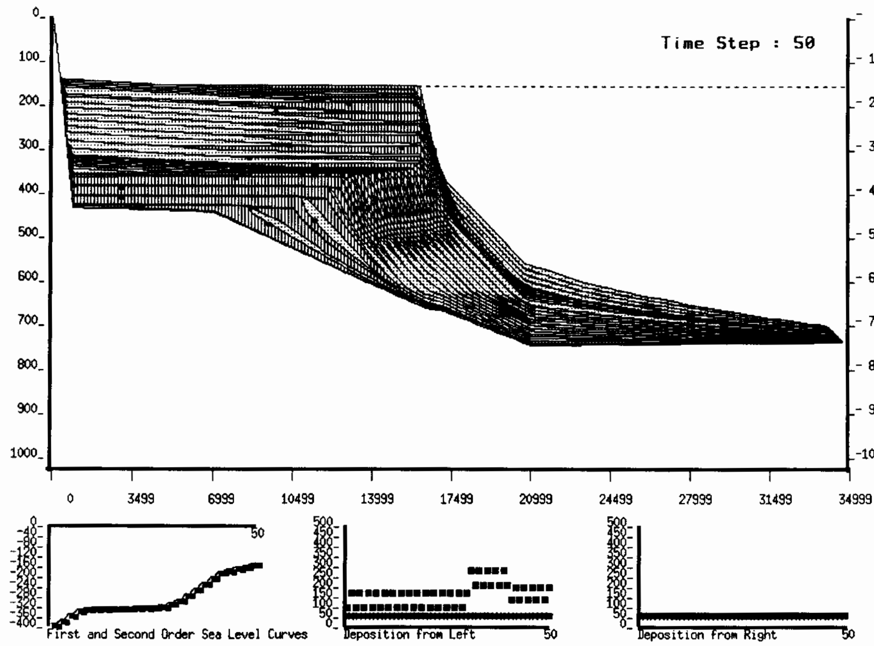

FIGURE 3—Output of the Permian data set showing SEDPAK reproducing the geometries of the Upper Permian of the west Texas Permian basin. Sand is represented by dots, shale is represented with horizontal lines, and carbonates are represented with vertical lines.

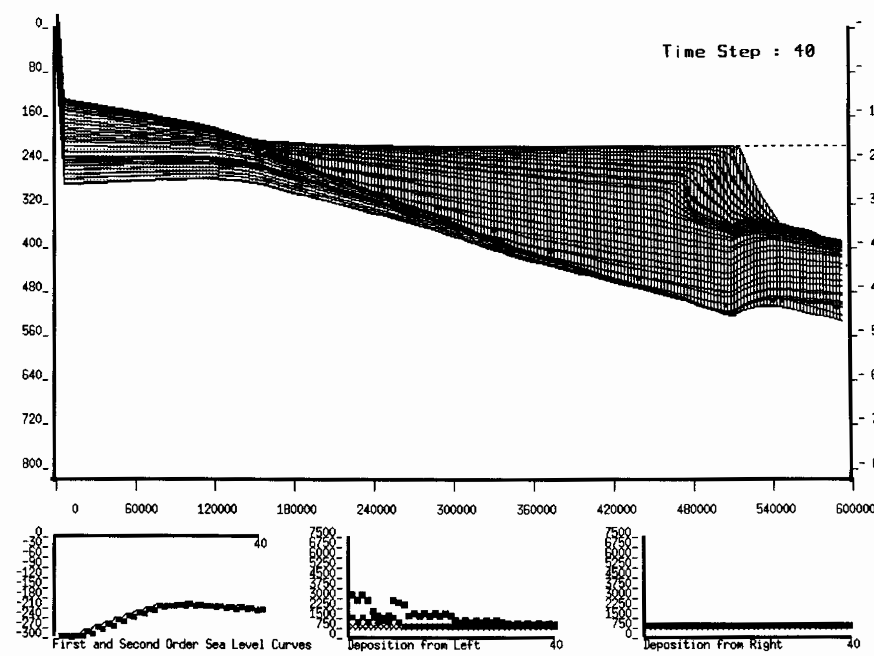

FIGURE 4—Output of the Sichuan data set showing SEDPAK reproducing the geometries of the Upper Permian of the Sichuan basin. Sand is represented by dots, shale is represented with horizontal lines, and carbonates are represented with vertical lines.

The stratigraphic record as a constraint on quantitative stratigraphic modeling

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Quantitative stratigraphic modeling is emerging as a new tool in stratigraphic analysis. By systematically varying the major controls on depositional-sequence development (e.g., sea level, subsidence, and sediment supply), quantitative stratigraphic modeling provides new insights into the relative contribution of each variable. When tied into a basinal data base, this technology offers a means for predicting lithologic associations away from existing control. Geologic-data sets play a critical role in constraining both the model design and the range of possible solutions in a modeling exercise.

Stratigraphic-modeling packages consist of an assemblage of mathematical algorithms that are simplified representations of complex geologic processes. The choices of which processes to include in the model and descriptions of their interdependence constitute hypotheses for how natural systems operate. The process of evaluating these hypotheses is accomplished by running the model repeatedly, with different input variables, and comparing the results with a chosen geologic-data set. Alterations to the algorithms or input parameters are made until a satisfactory match is achieved. No illusion is held that the model is the uniquely "correct" solution to reproducing a geologic section. Rather, a "successful" model solution is defined as one where the output adequately matches a geologic-data set. The more geologic data the model can reproduce, the more rigorous or useful the model, and the greater the likelihood that the model will produce reliable predictions in areas of no control.

Therefore, for quantitative models to gain our confidence as tools for stratigraphic analysis and prediction, they must be tested, i.e. compared to and calibrated with large, high-quality geologic-data sets. Unfortunately, the level of stratigraphic detail available in most geologic-data sets is relatively poor and this limits the level of detail at which model-to-data comparisons can be made. As a result, model output that is more detailed than the data base available for comparison cannot be verified. Along with the geologic-data base limitations, there is a desire to keep the number of model- input parameters to a minimum in order to limit the number of possible model solutions. Consequently, a model design strategy has been formulated that matches the complexity of the model output to the level of data quality available in the chosen data sets. To test the model, we devised strategies for 1) describing the geologic record for the purpose of model-data comparisons, 2) statistically analyzing the data to determine the sources of variance, and 3) assigning a measure of uncertainty to model predictions based on repeated model runs (using random sampling of probabilistic variable distributions).

We have utilized two data sets thus far to constrain both model design and model solutions: a series of measured sections along a dip-oriented outcrop belt of the Book Cliffs, eastern Utah, and a subsurface-data set from the Washakie/Red Desert basin, south-central Wyoming. The relative strengths and weaknesses of the outcrop and subsurface data sets provide "ground truth" for different portions of a clastic depositional system. The closely spaced (<2 miles [3.2 km]) sections of the Book Cliffs provide detailed correlation and facies information in the transition between coastal plain and shallow-marine shoreface environments. The description of and relationships between the shoreline sub-environments (foreshore, upper and lower shoreface, and transition zone) also provide constraints on wave-process and storm-current modeling. The subsurface-data set provides a basin-scale view of depositional systems where chronostratigraphic units can be correlated from topset to bottomset environments and where regional relationships between turbidite and shoreline sand systems can be defined. Although lacking in detailed facies, the basinal correlation framework provides information on three-dimensional sequence geometries, gross lithologies, and total sediment supply through time.

Strategies for describing the data sets involve the correlation and digitization of time lines, facies boundaries, and individual lithologies from each section. For the purpose of model-to-data comparison, the stratigraphic data are decompacted to reconstruct depositional geometries. Decompacted, restored sections prove invaluable in resolving correlation problems, such as those resulting from differential compaction between coaly coastal-plain environments and sandy shoreface systems.

The process of comparing model results to the reconstructed data set involves numerous iterations of the modeling program utilizing different combinations of model-input parameters. To limit the number of variables included in the deterministic-model design, an analysis of variance is performed on the reconstructed data set(s). This procedure evaluates the number and relative importance of the variables (or their proxies) that control the distribution of lithologies. Armed with this information, the relative complexity of the deterministic-model design (i.e. the number of variables) can be adjusted.

Finally, we attempt to define the uncertainties in the deterministic-model predictions that are associated with the uncertainties contained in the model-input variables. To the extent that the basinal-data set constrains the ranges of these variables (e.g., base-level change = topset thicknesses), the level of uncertainty can be reduced. Ranges of variables that cannot be constrained by the data set (e.g., rates of sediment supply, rates of sea-level change) must be estimated or guessed based on information or experience from other basin studies. Given a frequency distribution of possible variable values, the stratigraphic model can be run repeatedly utilizing a random sampling scheme of the unconstrained variable ranges. This procedure produces a solution set that can be used to estimate the uncertainty in predicted lithologies at each location in a basin or along a cross section.

Thus, to best evaluate the results of a stratigraphic-modeling package, we must have detailed knowledge of the geology we are trying to match. In most cases the complexity of the model result exceeds our knowledge of the geologic system. Advances in stratigraphic-modeling technology must also be paralleled by the collection and description of high-quality data sets (i.e. with detailed correlation and facies interpretations) which can constrain both the model design and the range of possible model solutions.

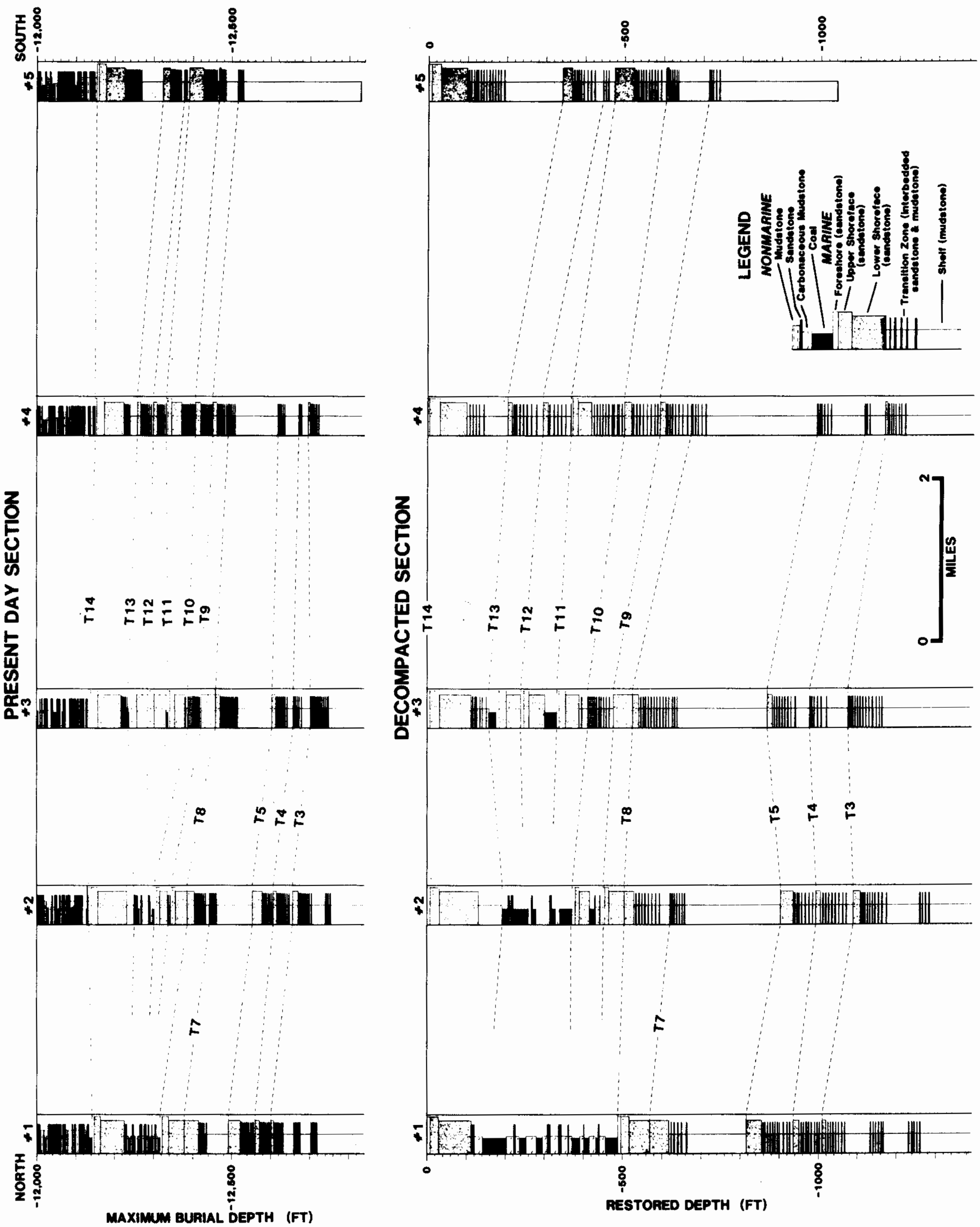

FIGURE 1—Present-day and decompacted stratigraphic cross sections along the Book Cliffs illustrating the effect of differential compaction on marine to nonmarine correlations. The decompaction exercise demonstrates the time equivalence of vertically stacked shoreface sandstones, T9 through T13, to coaly coastal-plain facies.

Observational foundation for and scaling limitation to sequence modeling

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Observational foundation

The design of useful models for predicting sequences and facies patterns of sedimentary cycles depends on an adequate observational foundation. Six facets must be met: 1) adequate documentation of sequence character; 2) characterization of spatial and directional variability and continuity of facies; 3) adequate data base on influence of primary and secondary controls on sedimentation; 4) understanding interaction of controls on sedimentation; 5) understanding limits of physical, biogenic, and chemical influences; and 6) understanding early- to late-stage diagenetic modifications to sequence nature and thickness. Examples from each category illustrate the necessity for meeting each facet.

1) *Sequence characterization* must include a) proper definition of fundamental depositional sequence; b) adequate statistical characterization of vertical sequence; c) proper definition of sequence boundaries; d) definition of lateral-facies continuity and boundaries; e) clear differentiation of transgressive, regressive, and still-stand facies; and f) differentiation of sheet deposition vs. bank/mound/ridge accumulation of facies.

2) *Spatial and directional variability* includes intracycle and intercycle variations in facies type, morphology, and growth habit with orientation of platform margin or coastline; intercycle variations in lateral facies shifts with variations in orientation; variations in early diagenesis with orientation; and variations in emergent topography with orientation.

3) *Primary controls* include a) sea-level dynamics; b) sediment supply; c) topography and physiographic setting; d) relative importance of prevailing energy, winter storms, hurricanes, ocean swells, and tides; e) tectonic pulses, flexures, and hinges; and f) climate (especially rainfall and temperature). These primary controls define a variety of *secondary controls* including organism communities, biogenic sediment production, and water circulation and renewal. Lack of proper consideration of any one primary control can negate the validity of resulting models. In this regard, it is unwise to apply recognized controls on clastic sedimentation to carbonates and vice versa. Clastic and carbonate processes are commonly out of phase with respect to sea level.

4) *Interaction of primary controls on sedimentation* commonly generates new processes and facies characteristics that would not be formed independently. For example, sediment accumulation/loss rates and sediment texture are defined by the interaction of a) rate of sediment dispersal by events *and* platform width; b) potential sediment circulation *and* windward and leeward margin openness; c) rate of sediment production/supply *and* shallow-water bioerosion (loss of coarse) or dissolution (loss of fines); d) potential sediment transport *and* stabilization by vegetation or cementation; and e) surficial sediment accumulation *and* subsurface replacement by sediment infills of burrow excavations.

5) *Physical, biogenic, and chemical controls* have discrete but subtle temporal and spatial boundaries to their influence. For example, winter storms, hurricanes, and other physical controls occur only over certain geographic ranges, and this range changes with geologic time. Subtle changes in water chemistry, temperature, and renewal time define limits for various types of carbonate sedimentation and diagenesis (e.g., ooid production, bioerosion, intragranular and intergranular cementation).

6) *Diagenetic modifications* include syndepositional biogenic facies modification through repetitive burrow excavations and infillings causing a) transformation to new sediment composition and permeability in old sediment-body geometries, b) loss of transgressive facies, c) misrepresentation of timing and rates of sedimentation, and d) amalgamation of sedimentary cycles, and later stage compaction and pressure dissolution reducing depositional thickness of sequences.

Scaling

One must be careful in drawing on influences, patterns, and rates from one scale of sedimentation for application to another. Many fundamental controls on sedimentation will have very different effects on different scales of sedimentary cycles. The finer scales of sedimentation may not be conducive to predictive modeling, especially if the driving forces are episodic.

Holocene analogues represent sedimentary cycles in various stages of incompleteness. Integration with Pleistocene sequences are a first step towards assessing the duration necessary for generation of complete cycles and assessing usefulness of Holocene/Pleistocene as analogues to times of dampened eustatic driving forces.

Inverse modeling of early to middle Paleozoic sea-level changes from craton to passive margins of North America

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We have applied inverse-modeling procedures to lower and middle Paleozoic strata of the craton and passive margins of North America. The procedures correct cumulative-thickness curves for sediment loads and for compaction as a function of grain size and facies. Tectonic subsidence, controlled mainly by cooling, is removed by subtracting an exponential curve with a decay constant of 62.8 m.y. from the corrected thickness curves. The residual curve reflects "external" events superimposed on the tectonic component of subsidence and is a composite record of local tectonic events, climatically induced changes, and eustatic sea-level changes (Bond et al., 1989).

We have found evidence of several orders of cycles in the shallow-marine carbonate-platform strata of Middle Cambrian to Middle Devonian age in the passive margins. The longest wavelength cycle has a duration of about 70–100 m.y. These cycles do not correlate well with the Sloss sequences, but they appear to closely match global-extinction patterns of shallow-marine invertebrates. Field work on Middle and Upper Cambrian platform strata in the Cordilleran and Appalachian regions reveals two smaller scale cycles with wavelengths of about 2 and 6 m.y. (Bond et al., 1989; fig. 1). Error analysis indicates that these cycles are not caused by changes in sedimentation rates or by changes in water depths. The 2–6-m.y. cycles occur in widely separated localities within the lower Paleozoic passive margins, including the southern Canadian Rockies, Utah–Nevada, and the Virginia–Tennessee Appalachians (fig. 1). Such widespread distribution argues strongly against a local tectonic origin of the cycles. Our data also indicate that the 2–6-m.y. cycles are not caused by variations in magnitude of intraplate stresses, a mechanism that has been proposed recently by Cloetingh (1988) to account for some sea-level events on the Vail–Haq global sea-level chart (Vail et al., 1977; Haq et al., 1987). For example, we have identified all the Cambrian cycles in sections on the craton edge of Montana. This area lies well beyond the limit of the Cordilleran passive margin, where the intraplate-stress model predicts that the cycles should not occur. All of the Cambrian cycles remain in phase (correlative) across the hinge zone of the passive margin in the southern Canadian Rockies. According to intraplate-stress models, the cycles outboard of the hinge zone should be out of phase with those in the passive margin. Finally, the falling segments of several of the cycles correlate temporally with craton-wide unconformities, which also is inconsistent with the intraplate-stress model. This leaves a multi-ordered eustatic mechanism as the most likely explanation for the sea-level cycles. Limited data from the Middle Cambrian platform in Utah suggest that precessional and eccentricity cycles of the Milankovitch band (~20 Ka and 100 Ka) also are present in the carbonate-platform sequences (Kominz and Bond, this volume). It is not clear if these shallow-marine Milankovitch cycles record eustatic sea-level changes, however. The evidence for large-scale multi-ordered eustatic cycles, together with small-scale cycles with periodicities in the Milankovitch band, is intriguing in view of the lack of evidence for Cambrian glaciation.

The amplitudes of the sea-level changes are difficult to quantify. Based on modeling in both the passive margin and on the craton, the 70–100-m.y. wavelength cycles have amplitudes of about 100 to 200 m (330–660 ft) and the 2–6-m.y. cycles have amplitudes of 20 to 60 m (66–198 ft). The most important sources of error in the estimate of amplitudes are uncertainties in compaction corrections and in the correct decay constant for thermal subsidence. The error resulting from these uncertainties is probably on the order of ± 50%. The error in amplitudes resulting from ignoring flexure in construction of the subsidence curves is only about ± 7%.

The inverse methods we use produce results that are generally similar to those of sequence analysis. In some cases the inversion method is more reliable on outcrop because it is sensitive to subtle trends in facies, grain size, and to changes in subsidence rates. In Cambrian strata, for example, the inversion method reveals sea-level falls where physical evidence for unconformities is obscure and where criteria for locating the major regressive facies are confusing (e.g., "A" in fig. 1). The procedure also reveals sea-level rises where facies indicate regression and shoaling (e.g., "B" in fig. 1). The inversion method has the additional advantage of providing a quantitative basis for recognizing multi-ordered sea-level changes and for assessing the error in the sea-level signal.

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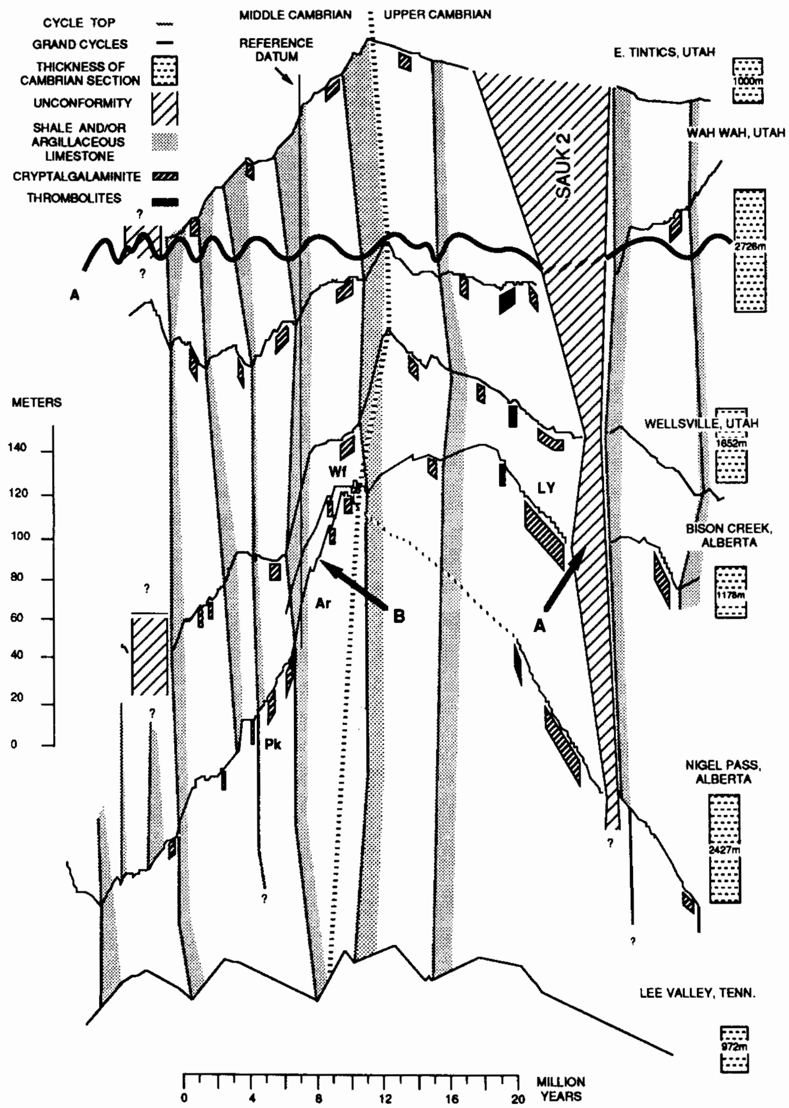

FIGURE 1—Diagram of our correlation of R2 curves from the Great Basin, the southern Canadian Rockies, and the Appalachians, produced by inverse modeling of measured stratigraphic sections (modified from Bond et al., 1989). The R2 curves from Canada were matched with those in the Great Basin using a distinctive shaly interval as a datum (marked "reference datum" in the figure). Most trilobite zones are not distorted between sections indicating that the correlation is essentially correct (Bond et al., 1989). The solid curve "A" is an approximation of the average short-term eustatic curve derived by eye from the R2 curves. Rising segments or those with lower slopes correspond to rising eustatic sea level, and the sequence boundary (either the unconformity or the correlative conformity) lies within these segments, close to the inflection point.

The bold arrow labeled "A" locates the position of a major unconformity within the Lyell Formation (LY) in the Bison Creek section in Alberta. The unconformity is defined by fossils (Palmer, 1981) and has essentially no physical expression on an outcrop scale. It probably would be missed using conventional sequence-stratigraphic techniques. Similarly, the rising segment labeled with the bold arrow "B" is an evaporitic tidal flat to lagoonal facies, the Arctomys Formation (Ar) that is much shallower than the overlying Waterfowl Formation (Wf) and underlying Pika Formation (Pk) that produce flatter segments. Sequence analyses would probably identify this interval as a low stand or sea-level fall, but its thickness clearly required a rising sea level. We interpret the formation of a shoaling, regressive facies during rising sea level as a result of a very high sedimentation rate.

Modeling carbonate-progradation geometry and sediment-accumulation rates—a comparison of "MARGIN" results with field data

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The geometries of carbonate-buildup margins vary widely but are commonly well exposed and clearly definable. Because carbonate buildups are, to a first approximation, relatively simple shapes, their geometries are readily amenable to quantitative computer modeling. This report considers the effects and constraints of different margin geometries and patterns of sediment accumulation on the progradation geometry of a carbonate buildup. This examination uses a simple sediment-accumulation model.

In most general terms, progradation of the margin requires sediment accumulation to fill in the edge of a basin, allowing a shallow-water platform to build over and bury the former basin and foreslope. In terms of sedimentation rates, progradation requires that foreslope accumulation exceed platform accumulation while escarpment formation implies the reverse. Thus, the large-scale pattern of buildup-progradation geometry reflects long-term patterns of sediment accumulation.

Models of prograding carbonate systems have typically focused on shallow-water, meter-scale, shallowing-upward packages (Read et al., 1986; Dunn et al., 1986; Spencer and Demicco, 1989). Some have attempted to model stratal patterns by modeling depositional processes (Lerche et al., 1987), or by using a sediment-budget model (Bice, 1988). The sediment-budget approach is adopted here because the consequences of different accumulation rates could be directly investigated.

A sediment-accumulation model

To examine margin geometries, "MARGIN" (a simple sediment-accumulation model of a carbonate buildup) was written in Pascal for an IBM PC. This model allows the comparison and evaluation of the significance of sediment-accumulation patterns and three-dimensional geometric factors in controlling the evolution of buildup geometries. The recognition of the more significant factors focused the consideration of actual field examples, here chosen from the Middle Triassic of the Dolomites.

The model uses a generalized buildup-margin profile consisting of a shallow-water flat-lying platform, a foreslope with a constant dip, and a deep-water flat-lying basin (fig. 1). The basic idea is similar to the model of Bice (1988): a series of iterations is run until a predetermined buildup thickness is reached. During each iteration, sediment is produced on the platform and is deposited on the platform up to sea level (filling any space created by subsidence), and any excess is added to the foreslope. However, two additional factors are added: 1) the three-dimensional geometry may be taken as a circular buildup or as a linear margin, and 2) a sediment-accumulation rate for basinal sedimentation. In addition, no attempt is made to duplicate the actual details of sediment transport or deposition but only the resulting sediment-accumulation patterns. Further details and the program code are presented in Harris (1988).

The three-dimensional shape (linear or circular), platform width (or radius), buildup relief, and foreslope angle define the initial buildup geometry. The subsidence history, sediment-production rate, and basinal sediment-accumulation rate control the addition of sediment during any simulation. A simulation terminates when the basin fills, the buildup drowns, or a preselected platform thickness is reached. The program calculates the principle geometric dimensions and the relative rates of sediment accumulation, and the results may be output as a scaled cross section of the buildup (fig.2).

Changes in sediment-accumulation patterns during a simulation are the result of changes in the buildup geometry, subsidence rate, or sediment-production rate. Variations in the initial buildup geometry may also result in very different geometries at the end of a simulation.

Enhanced progradation results from various modeling conditions: 1) low buildup relief, 2) high foreslope angle, 3) slow subsidence, 4) high sediment production, 5) linear margin geometry, and/or 6) high rates of basin deposition (fig. 3). The first two factors reflect the smaller sediment volume required to fill in the edge of a low-relief, steep-sided basin. Factors 3 and 4 from above both increase the rate of foreslope deposition (and thus increase progradation). A linear margin progrades farther than a circular buildup because sediment production is proportional to the platform area, and a linear margin has a greater platform area for foreslope volume. A higher rate of basin deposition (factor 6) lessens the relief as the simulation proceeds.

During a modeling run, a decrease in subsidence rate will shift the maximum rate of deposition from the platform to the foreslope due to reduced sediment accommodation in the platform area. Increasing sediment productivity during a simulation has a similar effect. These effects may mimic changes in sediment-accumulation patterns during tectonic pulses or eustatic sea-level changes on a scale of a few million years or less.

On a long-term perspective (several million years, or many hundred of meters of thickness), the extent of progradation into basins depends upon the rate of basin filling. Starved basins ultimately become too deep for foreslope infilling in all simulations. Increasing foreslope deposition by factors of 2-3 will not maintain progradational geometries as the relief increases from tens to several hundred meters. This geometric relation suggests that the processes, thickness, and timing of basin sedimentation (which commonly may be siliciclastics or evaporites) is a controlling factor on the geometries of carbonate-margin progradation.

Comparison to ancient buildups

Despite the simplicity of the "MARGIN" model, the results provide insights for interpretation of ancient buildup geometries. Examples of two circular buildup geometries are briefly considered below.

Various circular Triassic buildups of the Dolomites provide marked contrasts in buildup geometry (Bosellini, 1984; Harris, 1988; fig. 3). The Upper Anisian–Ladinian Latemar buildup has a vertical platform margin throughout most of its evolution (Goldhammer and Harris, 1989; Harris, 1988). Low rates of basinal sedimentation resulted in increasing depositional relief which prevented progradation despite an increasing rate of foreslope-sediment accumulation. In contrast, the Carnian Sella buildup exhibits increasing progradation throughout its deposition (Bosellini, 1984). This pattern probably results from the rapid deposition of basinal sediments which decreased syndepositional relief.

Conclusion

Carbonate-margin progradation geometries reflect long-term sediment-accumulation patterns. While many factors combine to produce any ancient example, the ultimate extent of buildup progradation is directly dependent upon basinal deposition.

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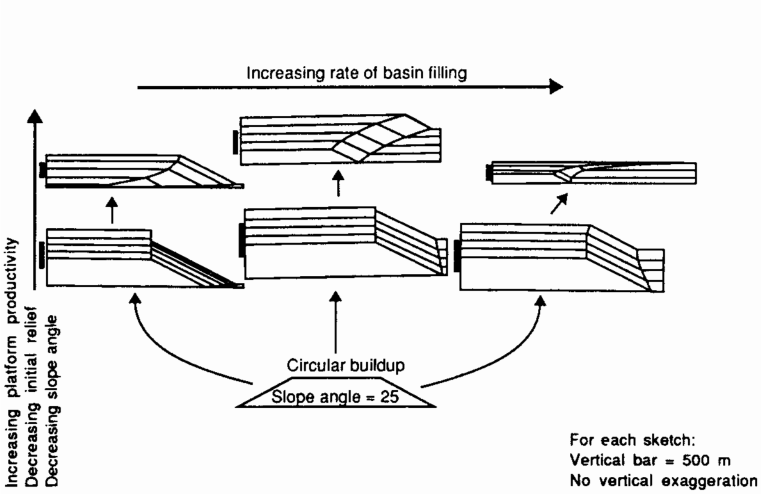

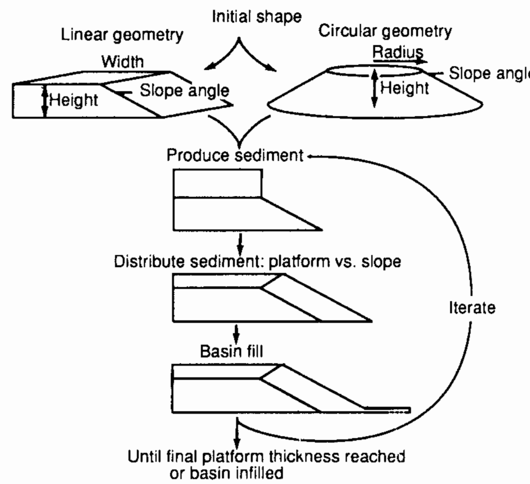

FIGURE 1—Basic modeling steps.

FIGURE 2—Buildup cross sections generated by the program "MARGIN" under conditions of constant subsidence Factors leo variatios in buildup geometry are indicated.

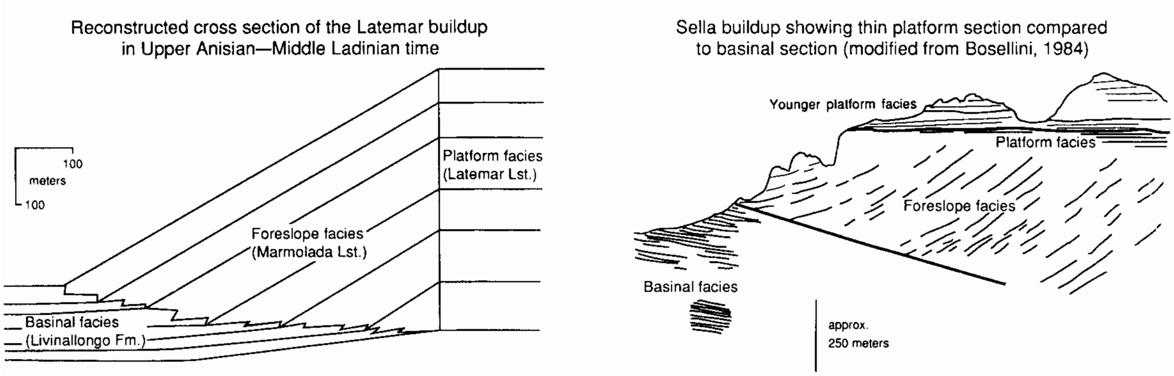

FIGURE 3—Geometries of Middle Triassic buildups of the central Dolomites, Italy.

Orbital forcing of glacioeustasy—requirement of a realistic two-dimensional forward model

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Orbital forcing of climate change at key latitudes has long been recognized as a probable cause of variation in continental ice budget and thereby sea level. The precision cycle, variation in tilt of the earth's axis relative to the sun, and variation in the eccentricity of the earth's orbit about the sun all effect seasonal solar insolation. The seasonal solar insolation signal at any particular latitude is complex, with periods ranging upwards from 20,000 years to hundreds of thousands of years. Further, non-linear responses of the earth system (e.g., slow buildup and rapid destruction of continental ice sheets) can convert modulation of short-period signals into long-period signals of up to two (perhaps five?) million-year periods.

This complexity of expected glacioeustatic sea-level signal places important requirements on two-dimensional forward-model construct. First, sea-level changes of a few meters can send the shoreline migrating hundreds of kilometers. Given the prospect of periods as short as 20,000 years to as long as 5 m.y., we are talking perhaps 500 reversals of sea level just to model one stratigraphic sequence (taken as nominally 5 m.y. long). Second, rapid changes in sea level can have a profound effect on a related alluvial system which is constantly linked to the marine depositional system by sea level.. Source/sink relations, which might be overlooked if sea level were slowly moving in one direction for long periods, can drastically modify availability of clastic sediment to the marine environment.

We are currently constructing a two-dimensional forward model specifically designed to quantitatively study these and similar consequences of orbital forcing of glacioeustasy throughout the Phanerozoic. Fig. 1 presents an example of output. Further examples of reasonable, synthetic sea-level input curves and examples of model-sensitivity tests will be available at the conference.

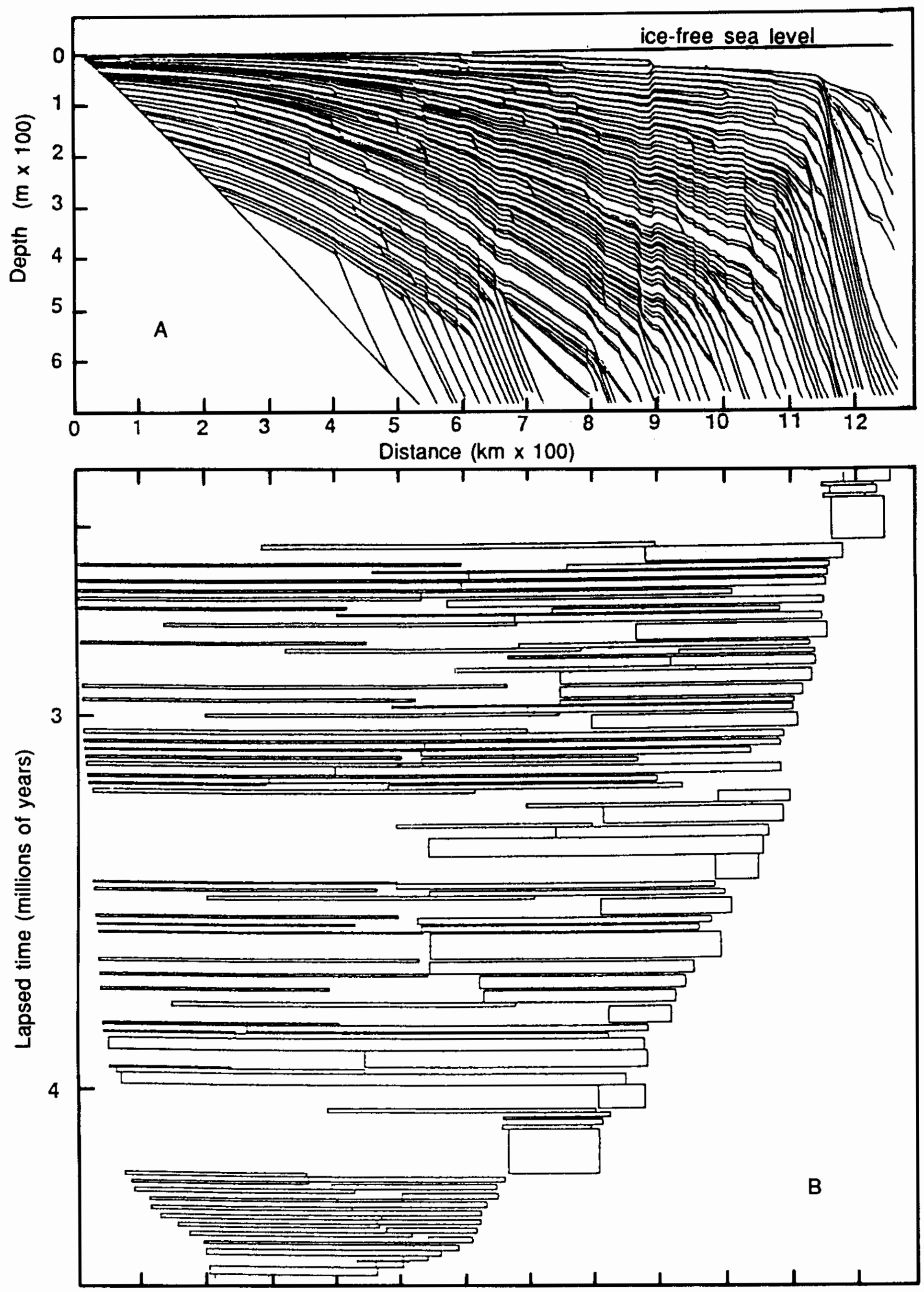

FIGURE 1—STRATIGRAPHIC CROSS SECTION (A) AND CHRONOSTRATIGRAPHIC CHART (B) depicting output of a forward model which interacts a 2.15-m.y. interval of calculated (quite preliminary, highly artibrary) orbitally forced glacioeustatic signal with a submarine shelf having an initial slope of 1 m/km. Topset units are taken to be sand and arbitrarily 10 m (33 ft) thick; these are the units depicted in (B). Note the stratigraphic complexity that is to be anticipated to result from a scant 2 m.y. of orbitally forced glacioeustatic sea-level fluctuation.

A theoretical model for sequence geometry—simulation of the U.S. Western Interior Cretaceous foreland

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A two-dimensional numerical model of basin formation and sedimentation is developed to simulate the characteristic sequence geometry of sediment fill in a foreland-basin setting. We describe a simple model for sediment dispersion on a wave-dominated shelf. In this approximation, waves and bottom currents are treated as random variables, producing dominantly longshore transport and a net offshore diffusive transport dependent on water depth and grain size.

The model is used to investigate the controlling factors on sequence geometry of the U.S. Western Interior Cretaceous basin. Initial results show that the sedimentation history of the Cretaceous basin has developed in response to 1) major thrusting events at 110, 100, and 90 Ma and 2) basement movements relating to the start of Laramide tectonics at 80 Ma. Each thrust-related sequence can be described by two stages of sedimentation. In the first, alluvial-fan conglomerates and sandstones grade rapidly seaward into dominantly shaly, relatively deep-water, strike-fed deposits. In the second stage, progradation of a low-relief shelf edge forms a thickening sandy clastic wedge. In contrast, the response of sedimentation to vertical tectonics is illustrated by a sequence of prograding clinoforms developed during the Campanian. As simulated by the model (fig. 1), changes in progradational style develop in response to relative changes in sea level associated with the regional rate of subsidence/uplift in the Wyoming area.

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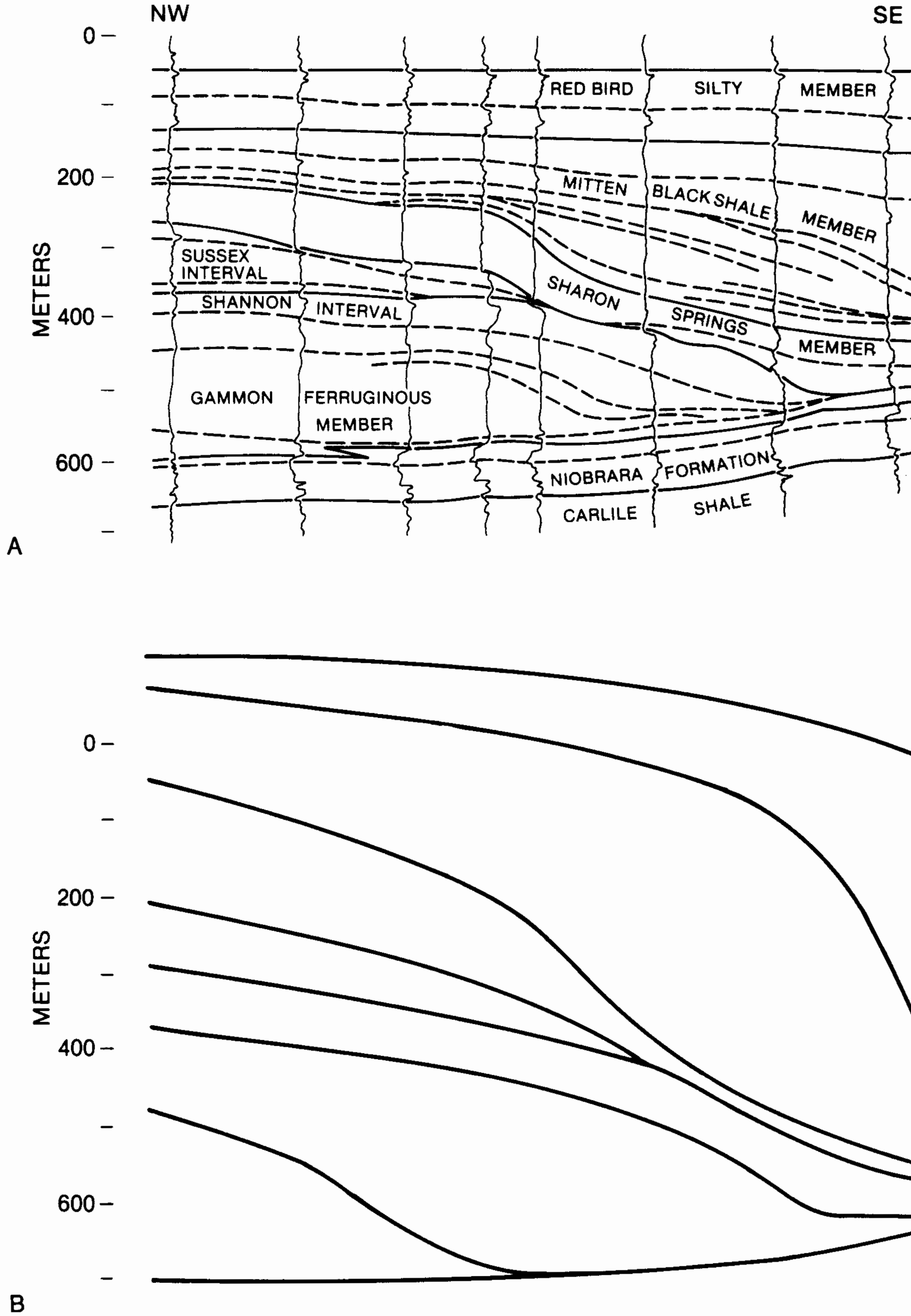

FIGURE 1—The predicted pattern of progradation in response to Late Cretaceous vertical tectonics in the Powder River basin matches the observed E-log cross section from Asquith (1970); A) Powder River well-log section and B) simulated model.

The effect of long-term sea-level changes on shelf sedimentation—the concept of sediment regime

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The shelf surface can be viewed as a surface of dynamic equilibrium controlled by such variables as sea-level change, sediment input, oceanographic conditions, and basin subsidence which, taken together, define the *sedimentary regime*. Sediment accumulating on a continental margin, given sufficient time, builds up towards a steady-state topographic profile which is a function of sedimentary regime. The role of such a topographic profile in controlling the external geometry of sedimentary rocks depends on its type: 1) *graded*, 2) *isostatic equilibrium*, 3) *equilibrium shoreline*, 4) *steady-state advective*, and 5) *steady-state diffusive*.

Changes of sea level relative to the surface of the shelf and coastal plain have profound effects on the sedimentary regime, by controlling the ability of sediment to pass through the shoreline. Shoaling and breaking waves on oceanic coasts create a mean landward-directed bottom stress which tends to drive sand towards the shore, resulting in a "littoral energy fence." Sediment passes through this fence in one of two ways. During regressions or slow transgressions, *river-mouth bypassing* transports sediment to the shoreface via the flood-stage jet of a deltaic river mouth. It is then transported along the coast and offshore by coastal-storm currents. During transgressions, river mouths become sediment-trapping estuaries. The entire shoreface may become a direct sediment source as a consequence of erosional shoreface retreat (*shoreface bypassing*).

Shelf sedimentary regimes, operating through time in response to shifting process variables, create in this fashion the depositional sequences of the rock record. Three examples of regime sedimentation are illustrated. The first, from the modern, discusses the sedimentation regime of inshore areas of the Mississippi delta. It is shown that the topographic profile of these areas maintains its shape as it progrades. The form of this regime profile is uniquely determined by the Gulf of Mexico wave climate and the input of sediment by Mississippi river-mouth bypassing.

In the second example, the regime approach is used to integrate measurements of storm-deposited bed thicknesses into a sequence-stratigraphic interpretation of prograding-shoreface deposits of the Mesaverde Formation of the Big Horn basin, Wyoming.

The third example applies a simplification of regime sedimentation to the modeling and interpretation of large-scale sequence geometries as are typically observed on seismic profiles of passive continental margins. Regime models of this type serve as a basis for the depositional-sequence model of Vail (1987) and Haq et al. (1987), which are used to interpret the geohistory of sea level, subsidence, and sediment supply, on the basis of observed patterns of stratal geometries.

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Field and modeling studies of cyclic carbonates—a predictive tool for petroleum exploration

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Stratigraphic modeling done by the Virginia Tech group has concentrated on understanding how 1–30-m (3–99-ft)-thick (4th and 5th order) carbonate cycles are arranged to make up Vail-sequences (3rd order) of carbonate platforms. In carbonate sequences containing large numbers of 1–10-m (3–33-ft) carbonate cycles, lack of well-defined marker beds generally prevents construction of detailed stratigraphic cross sections showing complex facies changes. Fischer plots that graph cumulative cycle thickness, corrected for linear subsidence using average cycle period, can be used to correlate sections and show relation of individual cycle-types to 3rd-order sea levels. Interaction between simple or complex sea-level curves defined by various frequencies and amplitudes, the sediment-surface, water-depth-dependent sedimentation rate, lag-time, and subsidence through time can be shown using one-dimensional models. Isostatically balanced two-dimensional models that incorporate the above variables, plus initial platform slope and antecedent topography, thermotectonic subsidence (divided into rotational and regional components), sediment- and water-loading using an elastic-beam model, and erosion, can be used to construct synthetic cyclic-facies cross sections of carbonate platforms. These can be used to define regional relations between cycles, likely vertical- and lateral-facies changes, distribution of disconformities/conformities and tidal-flat caps, and relative water depths of facies likely to be developed on the platform, as well as likely location of early diagenesis. The integration of field and modeling studies (e.g., Koerschner et al., 1989; Read et al., 1986) provides a rigorous analysis of cycle deposition that could be of great predictive value in the exploration and development of petroleum reservoirs.

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Estimating sea level from stratigraphic data offshore New Jersey and Alabama Tertiary

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Eustatic sea-level positions for the Middle-Late Miocene and Early Pliocene have been estimated through analysis of prograding siliciclastic sediments from the Baltimore Canyon trough and the northeastern Gulf of Mexico. Here we describe the Neogene stratigraphy of these areas, the methodology used to derive sea-level estimates, and the results obtained. A companion paper by Schroeder and Greenlee (this volume) discusses basin-modeling techniques that were used to model the observed stratigraphy of the area and test sea-level estimates.

The Middle and Upper Miocene and Lower Pliocene strata in both study areas consist of a series of lobate, progradational depositional sequences. Each sequence is composed of strata which onlap below the preexisting shelf margin, interpreted as low-stand deposits, and more areally extensive high-stand deposits. These sequences have been correlated, using available biostratigraphy from exploratory wells, to third-order eustatic cycles noted on the chart of Haq et al. (1987).

Sea level was calculated at each high-stand shelf edge using the formula

$$1.446SL = SEDLOAD + UNCOMP + SUB + PWD - Z$$
(Hardenbol et al., 1981)

where
- SL = estimated sea level for a given horizon and 1.446 is the correction factor for the isostatic load of any change in sea level
- SEDLOAD = amount of subsidence caused by the isostatic load of sediments overlying the horizon
- UNCOMP = the decrease in thickness of the underlying horizon caused by compaction effects
- SUB = the amount of subsidence caused by tectonic and thermal effects
- PWD = the paleo water-depth of the horizon at the time of deposition
- Z = the depth of the horizon below present sea level

Using this formula, we are tracking sediment-accommodation potential through time and compensating for the effects of isostatic and tectonic subsidence. Tectonic subsidence is calculated using a method based on angular-rotation rates of the subsiding margin shown in fig. 1. This method is preferable to geohistory analysis in this case as no assumption of eustasy is incorporated. Our primary uncertainty in calculated sea levels, apart from the reliability of the stratigraphic-age determinations, relates to estimating the paleo water-depth at the shelf margin. Paleo water-depth estimates of benthic foraminifera and facies analysis have been used to constrain these factors. In addition, due to erosion during sea level or nondeposition during the highest portions of the third-order cycles, we may not be measuring the highest stands of sea level. We attempted to measure third-order sea-level falls by measuring the downward shifts in onlapping shallow-marine sediments from high-stand to low-stand positions.

Our estimates of specific sea-level highs and lows are consistent to within about 20 m (66 ft) in the two study areas. High-stand sea-level estimates are lower than most previous studies. The amount of long-term sea-level fall during the Middle to Late Miocene calculated here is 24–42 m (79–139 ft). Third-order sea-level fluctuations of 12–116 m (40–383 ft) were estimated. The long-term sea-level fall is similar to that calculated by estimates of changes in oceanic ridge volume (Kominz, 1984) but lower than that depicted on the curve of Haq et al. (1987). Estimates of the magnitude of third-order fluctuations are similar to those represented on the Haq et al. (1987) curve.

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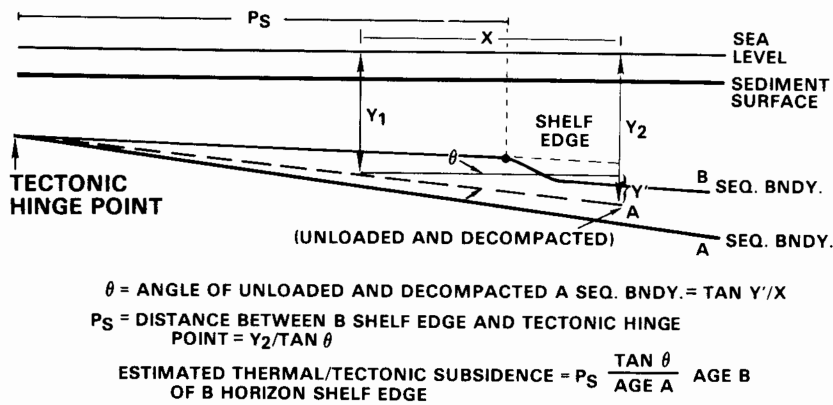

FIGURE 1—METHOD USED TO CALCULATE TECTONIC SUBSIDENCE RATE OF CONTINENTAL MARGIN (from Moore et al., 1987). An average angular-rotation rate from a calculated hinge point is determined based on basinward thickening of sediments. This rate is then used to derive a value of tectonic subsidence at the paleo-shelf edge relative to present sea level.

Modeling the effects of subsidence and eustatic changes on depositional sequences—an example from the Baltimore Canyon, offshore New Jersey

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In a companion paper, Greenlee and Moore (this volume) describes the characteristics of the Middle and Upper Miocene depositional sequences within the Baltimore Canyon trough. This paper presents some basin-modeling results using a key, dip-oriented seismic section from this area. Our objectives were to evaluate several published sea-level curves and document that the sequence characteristics are attributable to the combined effects of slow basin subsidence and long-term eustatic fall.

Fig. 1 shows the procedure we use in performing a basin-modeling study. We begin with an interpreted cross section derived from well and/or seismic data. The geohistory technique is used to model basin subsidence and fill at individual locations. We ensure temporal consistency by displaying the basin's history as a function of time at each location. By combining the results of the one-dimensional analyses, we display restored cross sections for each correlated horizon. We use temporal and spatial consistency as constraints to refine the paleobathymetric interpretation and determine the thermotectonic component of subsidence. The final step is to simulate the development of one or more depositional sequences. Basin simulation allows us to investigate the way in which subsidence, sediment supply, and eustasy have interacted to produce the preserved stratigraphy.

We modeled the Neogene sediments within the Baltimore Canyon trough because this area had a simple tectonic history during the Neogene and the available well and seismic data provide sufficient stratigraphic and paleontologic control. Thirteen sites and 22 horizons were modeled. Geohistory analyses ensured that our interpretation is both spatially and temporally consistent with the known geology. Simulated cross sections were generated using sea-level curves published by Haq et al. (1988), Greenlee and Moore (1988), Watts and Steckler (1979), and Kominz (1984). Each simulation covers the interval from the Early Miocene (18 Ma) to the present, using a time step of 0.2 m.y. Each simulation was evaluated as to how well it was able to replicate the interpreted stratigraphy (fig. 2).

We developed three major conclusions from this study. First, the spectacular Neogene progradational sequences deposited within the Baltimore Canyon trough are attributable to a relatively low rate of thermotectonic subsidence coupled with a long-term sea-level fall. These two conditions led to the development of a small amount of shelfal accommodation relative to the volume of incoming sediment. Progradation rapidly moved the position of the shelf margin basinward.

The second conclusion is that a component of sea-level change with a period on the order of 1 m.y. is necessary to explain the Neogene stratigraphy within the Baltimore Canyon trough. Without this component, the simulations suggest extremely gradational facies changes which are contrary to observations. The third conclusion is that the sea-level curve proposed by Greenlee and Moore (1988) is better able to replicate the interpreted cross section than the Haq et al. (1988) curve.

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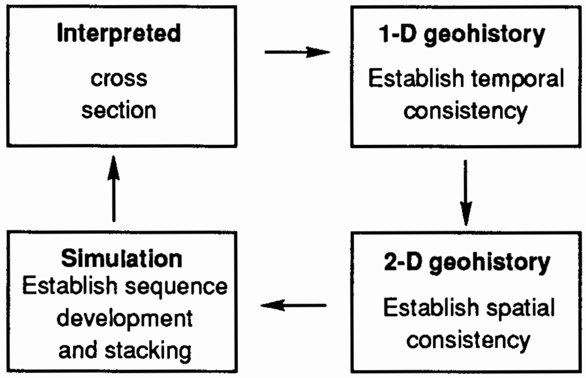

FIGURE 1—DIAGRAM OF BASIC APPROACH TO BASIN MODELING.

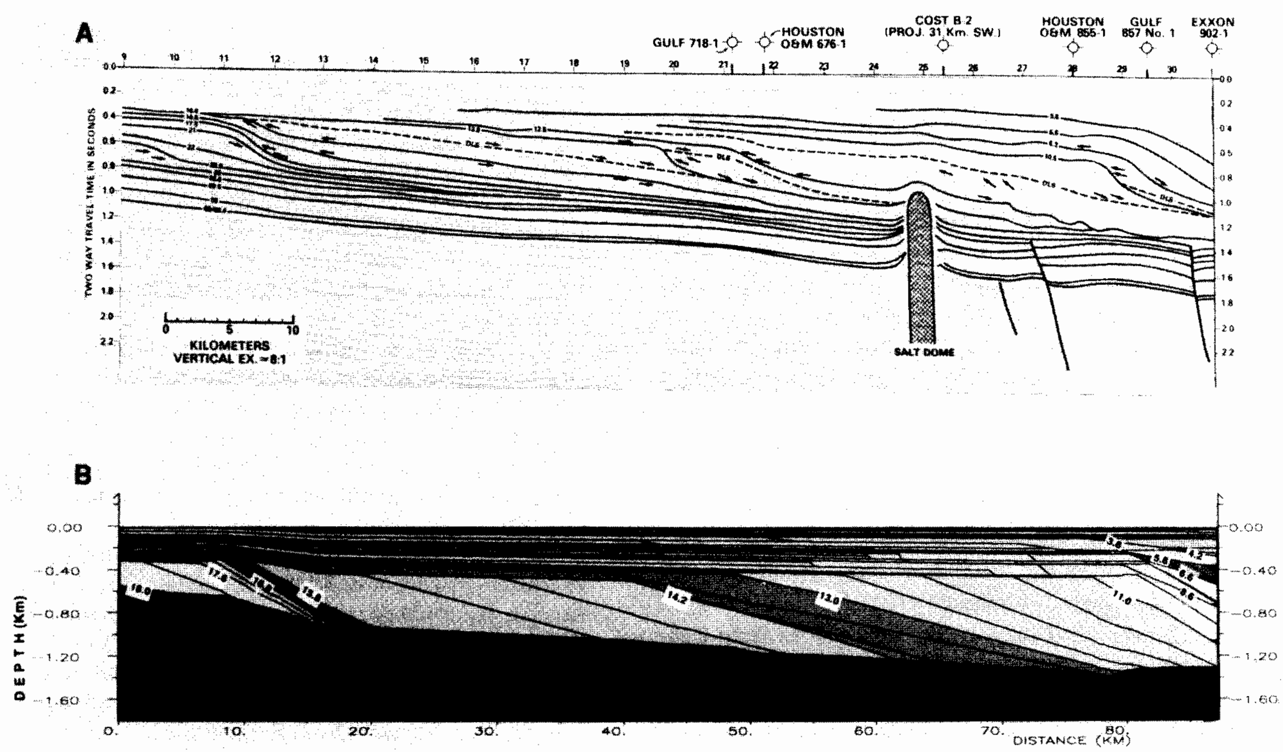

FIGURE 2—A) INTERPRETED SEISMIC LINE FROM GREENLEE ET AL. (1988). Ages correspond to inflection points during sea-level falls. B) SIMULATED CROSS SECTION USING THE SEA-LEVEL CURVE OF GREENLEE AND MOORE (1988). The simulation began at 18 Ma and ran to the present using a time step of 0.2 Ma; ages correspond to changes from high-stand to low-stand deposition.

The hierarchy of stratigraphic forcing—an example from Middle Pennsylvanian (Desmoinesian) shelf carbonates of the southwestern Paradox basin, Honaker Trail, Utah

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Middle Pennsylvanian (Desmoinesian) shelf carbonates in the southwest Paradox basin display three superimposed orders of stratigraphic cyclicity, in which long-term forcing of higher frequency eustatic cycles by lower frequency eustatic rhythms (at two overlapping scales) has resulted in a systematic succession of cycle-stacking patterns and facies-stacking patterns, as well as predictable vertical diagenetic trends. Fifth-order cycles (34 cycles in 645-ft section at the Honaker Trail; avg. 20 ft (6 m) thick, c. 40 ky duration) are grouped into fourth-order sequences (avg. 100 ft [30 m] thick, c. 400 ky duration), which vertically stack to define a third-order accommodation cycle (650+ ft [195 m] thick, c. 2.4 m.y. duration). A shelfal section at the Honaker Trail spans six fourth-order sequences and correlates in the subsurface 100–120 km (60–72 mi) across the southwest Paradox shelf east and southeast into basinal settings. The outcrop facies and cyclic stratigraphy of one of the fourth-order sequences (the Desert Creek interval of the Paradox Formation) have been tied to the equivalent subsurface productive interval at McElmo Creek (Aneth field) through a detailed core study. This example yields a two-dimensional shelf-to-basin transect where both cycle-stacking patterns and lateral continuity of cycles can be studied.

Fifth-order cycles are composed of shallowing-upward packages of dominantly subtidal shelf carbonates with sharp cycle boundaries, either a subaerial exposure surface (exposure cycles) or a flooding surface (subtidal cycles). From base to top an idealized, complete shoaling cycle consists of the following elements: 1) Basal exposure or flooding surface; 2) *Transgressive marine sandstone*—TMS: trough crossbedded, calcareous sandstone and laminated, mudcracked siltstone; shallow marine to tidal flat, probable reworked eolian siliciclastics; 3) *Black laminated mudstone*—BLM: nonfossiliferous, black, shaly mudstones; low-energy, anerobic conditions, >35-m (116-ft) water depth; 4) *Sponge facies*—SF: silty, argillaceous, cherty carbonate mudstone with abundant sponge spicules and rare phosphatic debris; low-energy, dysaerobic conditions (25–35-m [83–116 ft] water depth); 5) *Intermediate facies*—IF: thin-bedded, silty, mixed skeletal wackestone-packstone full of normal marine fossils (crinoids, brachiopods, bryozoa, etc.) and burrows; moderate-energy, normal marine subtidal, 5–25-m (17–83-ft) water depth; 6) *Algal facies*—AF: phylloid-algal mound and mound-flank wackestone-packstone; normal-marine, subtidal phylloid-algal bioherms, 5–25-m [17–83-ft] water depth); 7) *Skeletal-cap facies*—SC: well-sorted, abraded, mixed skeletal packstone-grainstone; shoaling subtidal, 0–5-m (0–17 ft) water depth; 8) *Nonskeletal cap facies*—NSC: trough crossbedded and ripple cross-laminated oolitic-peloidal grainstone; high-energy shoaling subtidal; 0–5-m (0–17 ft) water depth; 9) exposure or flooding surface.

Fifth-order cycles are packaged into fourth-order depositional sequences bounded by type 1 (subaerial) sequence boundaries. Criteria for the recognition of sequence boundaries are as follows: a) boundaries are regionally correlative subaerial-exposure surfaces marked by laminar caliches or evidenced by early-developed, meteoric diagenesis in upper parts of fifth-order cycles (solution porosity and meteoric recrystallization in skeletal/nonskeletal cap and phylloid-algal facies); boundaries correlate from outcrop to subsurface (shelf to basin) for 100–120 km (60–72 mi); b) sequence boundaries in shelf-margin to basinal settings are onlapped by basinally restricted evaporite (anhydrite) wedges interpreted as low-stand deposits associated with fourth-order sea-level drops below the Paradox shelf; c) sequence boundaries in a shelfal position are overlain by BLM facies interpreted as the fourth-order condensed section superimposed atop thin, shelfal low-stand transgressive deposits; d) fifth-order cycle-stacking patterns—subtidal cycles characterize the lower portion and exposure cycles occur in the upper part of fourth-order sequences and, additionally, cycles tend to thin upward within individual fourth-order sequences, reflecting fourth-order accommodation changes. Significantly, the occurrence of siliciclastics (TMS facies) in the section is equivocal with respect to identification of fourth-order sequence boundaries in a shelfal position.

Fourth-order sequences can be subdivided into systems tracts, recognizable on the basis of fifth-order cycle-stacking patterns, vertical and lateral facies associations, and the regional shelf to basin correlation of the top of the BLM facies, interpreted as the fourth-order maximum-flooding surface. Subsurface data demonstrate that the sequences contain a basinally restricted low-stand wedge of evaporites and quartz clastics (20–60 ft [6–18 m] thick) in a downdip position. In detail, onlapping low-stand wedges actually contain higher frequency, mixed clastic-carbonate, fifth-order shoaling cycles that either pinch out below the previous shelf edge or thin updip by onlap. These low-stand, fifth-order cycles are expressed as lengthy subaerial-exposure surfaces high on the shelf. In some of the sequences, on the shelf a thin (<1–3-ft [.3–3 m]) drape of siliciclastics (TMS facies) sits atop the exposure boundary depicting a thin shelfal low stand reflecting siliciclastic bypass. The transgressive systems tract is represented primarily by black, sapropelic shales and shaly carbonate mudstones (BLM facies) which mark the condensed section of the fourth-order sequences. These shaly intervals thicken into the basin (up to 30–40 ft [9–12 m] thick) and thin updip onto the shelf (<3–10 ft [.9–3 m]), essentially superimposed upon the underlying sequence boundary. The high-stand systems tract is characterized by an aggradational stack of shelfal fifth-order cycles and a thinner basinal section composed of deeper water foreslope and basinal facies. The high-stand systems tract comprises the bulk of the sequence in terms of thickness.

Systematic variation in the thickness of the fourth-order sequences (progressive thinning-upward followed by progressive thickening-upward), as well as the number of fifth-order cycles/sequences (decreasing followed by increasing number), as revealed by graphical time-space analysis ("Fischer Plots"), define a third-order accommodation trend which is also regionally correlative. Fifth-order cycles and fourth-order sequences are interpreted as aggradational allocycles generated in response to glacioeustatic sea-level fluctuations driven by Milankovitch climatic forcing. The fifth-order cycles record the earth's obliquity cycle (mean period of 41 k.y.), and the fourth-order sequences result from the long eccentricity cycle (mean period of 413 k.y.). The hierarchy of these two superimposed orders of eustasy is reflected in the approximate 10:1 ratio of fifth-order to fourth-order cyclicity observed in complete sequences. Additionally, in complete sequences, quartz clastics are observed every third fifth-order cycle, suggesting still another level of cyclicity, approximately 120 k.y. in duration, intriguingly close to the earth's short eccentricity cycle. The style of cyclicity (internal-facies architecture and early diagenetic patterns), the hierarchy, and the periodicity of cyclicity observed in the Paradox shelf cycles all are directly analogous to coeval midcontinent shelf cycles (Kansas–Iowa), strongly supporting the existence of Milankovitch-induced glacioeustasy in the Middle Pennsylvanian. Significantly, the short eccentricity cycle (approximately 100 k.y.) and the earth's precessional cycle (approximately 20 k.y.) apparently had minimal amplitudes and minor effect on stratigraphic cyclicity.

The observed stratigraphy has been replicated by computer (Mr. Sediment, figs. 1 and 2), using the following parameters: 1) Eustasy—40 k.y. (sinusoidal, 9-m [30-ft] amplitude), 120 k.y. (sinusoidal, 2-m [7-ft] amplitude), 400 k.y. (asymmetric, 28-m [92-ft] amplitude), 2.4 m.y. (sinuform, 15-m [50-ft] amplitude); 2) Sedimentation—depth-dependent with maximum efficiency at 0–5 m (0–17 ft; 0.40 m [1.3 ft]/1,000 yr.); depth-dependent facies with water depths as defined above; 3) Subsidence—linear and total (0.15 m [0.5 ft]/1,000 yr.); 4) Lag depth—1 m (3.3 ft); 5) Caliche rate—0.01 m (0.03)/1,000 yr. Eustatic amplitudes, as well as depth estimates for facies, are constrained by two-dimensional facies and stratal geometries (corrected for compaction) displayed on shelf-to-basin well-log cross sections.

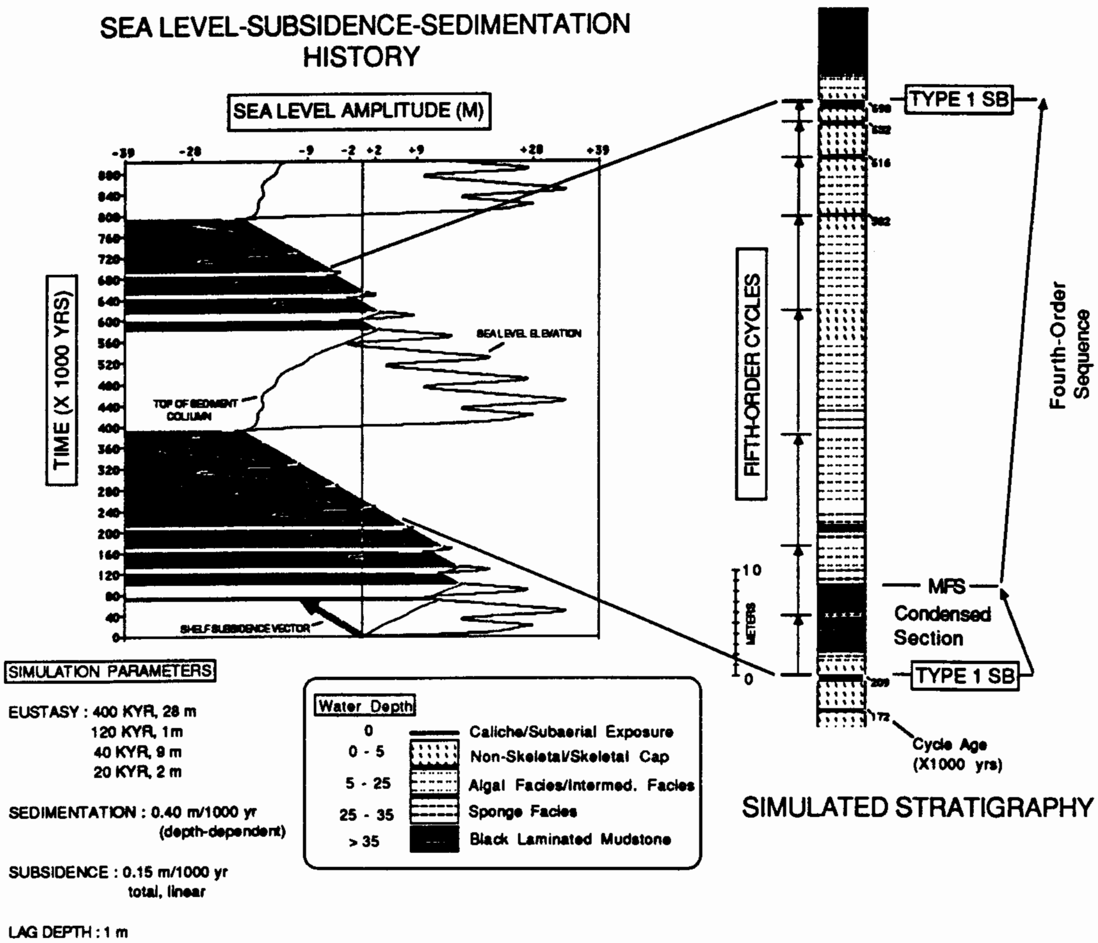

FIGURE 1—Simulation stratigraphy using Mr. Sediment.

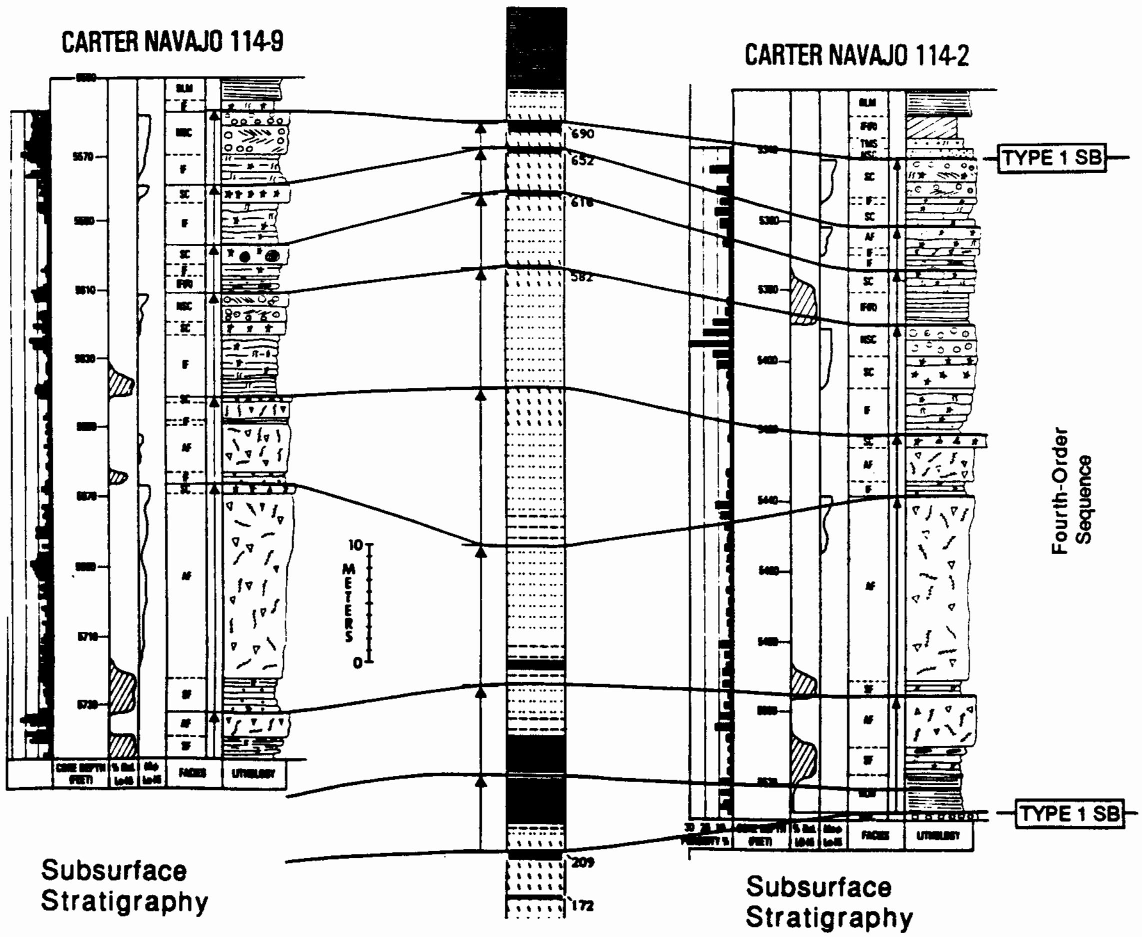

FIGURE 2—Simulated stratigraphy using Mr. Sediment.

Reef architecture—a base for reef modeling and porosity prediction

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Modeling of carbonates requires detailed understanding of sediment-generation processes as well as sediment-distributive processes. Organic-generation and multiple-degradation processes operate to form carbonate-sediment bodies. This approach to modeling in reef carbonates was initiated with qualitative constructs of modern and ancient reef environments. Reefs have economic significance and are geographically distinct, although they derive from a complex environmental "mix" of processes.

Fortunately, there is a relatively good modern sedimentation-data base from which to work. Reefs are sensitive indicators of prevailing oceanographic conditions at the time of generation. The sequence of rock fabrics developed (architecture) constrains models. Processes and paragenesis of reef formation can be interpreted from rock architecture; once the sequence of processes has been interpreted, a detailed interpretation of sea-level history is possible.

Qualitative modeling indicates that architectural properties of reefs could provide a genetic classification, which in turn permits certain characteristics of the reef fabric to be predictable, including sediment sorting, early diagenesis, and relative effective porosity (Gerhard and Burke, 1986; Burke and Gerhard, 1987; Gerhard and Burke, in review). The qualitative model, still undergoing field testing in ancient reefs, is used as the basis from which to construct a quantitative model. Quantitative models may develop useful predictions of porosity and permeability. Initial attempts to develop polynomial descriptors of reef-sedimentation history and sea-level rise have been apparently successful. Work towards a more complete quantitative model of reef architecture continues; this paper summarizes progress to date.

Theoretical premise

It is our (Gerhard and Burke, in review) thesis that all three-dimensionally discrete bodies of organically derived carbonate rocks are "reefs," that they result from the interplay of definable major sedimentary processes, and that their depositional and diagenetic settings can be interpreted from observing their vertical sequence of fabrics. Reef fabrics and internal architecture evolve in response to changing rates of sea-level-rise. Availability of organisms within a specific reef setting and interruptions in this evolution may determine final architecture.

Part of the thesis is that the *rates* at which the processes of reef generation operate will determine the fabric of any reefs formed. As a corollary, fabrics of sediment (rocks) generated at a reef site can be interpreted with respect to the rates and balances of processes that operated.

We have deciphered a continuum of fabrics and architectural styles which are controlled more by sedimentary processes than by biotic evolution or community succession. Fabrics thus result from the interplay of organic growth, dynamic processes, and depositional topography.

It is a deliberate choice to use the term "reef" as a general term with appropriate architectural modifiers rather than "bank" or "bioherm" in order to stress the inherent continuum of fabrics and processes interpreted from reef studies.

Carbonate sediment is a product of growth of carbonate skeletons which are modified by biologic and mechanical degradation, providing sediment of varying size and shape. Sediment so generated is either incorporated into the reef or transported out of it. The balance between skeletal growth and degradation and transportation processes determines the reef-body fabric and architecture, and ultimately, the type and degree of diagenesis. The degree of transportation of detritus out of a reef system is a function of wave energy and depositional slope. Transportation of detritus from a reef system creates the opportunity for framework to develop and for syngenetic cementation. Lack of sediment removal provides smaller pore space and inhibits skeletal growth and syngenetic cementation. Production of carbonate sediment within an active reef system is so rapid that frameworks cannot develop unless the sediment is removed; frameworks can literally drown in their own detritus. In the opposite extreme, a hydromechanic pile of loose sediment will be the result of transportation or sweeping of carbonate sediment into a wave-induced bar-form.

Effects of the three major reef-construction processes, skeletal generation, degradation, and transportation, can be graphically represented on a ternary diagram (fig. 1). A corresponding reef-classification terminology, framework, biodetrital, and hydromechanical, is derived from the processes (fig. 2).

Eustasy is the remaining dynamic process that must be considered as controlling reef fabric. Neumann and Macintyre (1985) have interpreted part of this relationship in their "catch-up, keep-up, or give-up" view of succession. However, while addressing organism response to sea-level changes, they did not consider the sequence of fabrics which is coincident with a normal cycle. Normal cycles, characterized as sine curves, have rapidly changing rates of rise, which, in conjunction with relatively stable organism-growth rates, provide large variations in absolute water depth. We have not considered whether sea-level changes are true global eustasy or of local origin.

Qualitative model

Three major processes appear to control the development of reefs. Generation of carbonate though biologic deposition provides the carbonate material from which the reef is constructed. Most of the carbonate is subjected to biologic and mechanical degradation, which reduces the size of primary particles and produces detritus. Finally, transportation of the carbonate (or lack thereof) determines the sorting and geometry of the reef-pile. The relative importance of each of these processes to an individual reef determines its architecture, easily displayed on a ternary diagram (fig. 1).

End-member reef classes which correspond to the stated major processes can be graphically displayed on a similar ternary diagram (fig. 2). The three end-member reef classes are *framework* (generation process is dominant), *biodetrital* (degradation process is dominant), and *hydromechanical* (transporation process is dominant).

Characteristics of the framework-reef setting and resultant reef architecture are moderately steep depositional slope, high mechanical energy, framework development, and syngenetic cementation. Porosity tends to be occluded by early cementation and relatively uniform primary mineral assemblage (mostly aragonite in modern reefs).

Characteristics of the biodetrital-reef setting and resultant reef architecture are moderate depositional slope and moderate mechanical energy; the resulting reef is a biodetrital sediment-laden mass and has little or no framework and virtually no cementation. Porosity tends to be well-developed in fossil examples because the sediment-mineral assemblege is composed of well-mixed calcite, mg-calcite, and aragonite with differing susceptibility to dissolution and replacement. Early diagenetic-porosity development appears to be common through subaerial exposure or exposure to freshwater wedges in a submarine setting.

Characteristics of the hydromechanical-reef setting and resultant reef architecture are very low depositional slope, variable but frequently low mechanical energy, hydromechanical accumulation of reef grains, and little or no syngenetic cementation. Algal and other skeletal grains appear to be partly autochthonous to the accumulations. High flotation potential of the algal plates common in hydromechanical reefs obviates the need for high mechanical energy during reef construction. Little seismic evidence exists for current-bedded internal structure, likely because there is constant turnover by burrowing infauna as well as autochthonous particle contribution. Porosity may be high due to the susceptibility of aragonitic algal plates to early diagenetic cementation and dissolution; open spaces may be early cemented with calcite or aragonite and muds in the reef matrix appear to be less permeable than algal plate masses and thus less susceptible to dissolution or replacement.

From many field observations, and from the above discussion, as reefs of any framework percentage grow, a certain amount of detritus is generated and accumulates within the reef. If this detritus is not removed from the reef, it will to some degree inhibit organic skeletal growth. If detrital generation is high and transportation is low, the accumulation of detritus (bioclasts) will be high and will provide a significant or major part of the reef mass in comparison with the amount of interlocking framework. In the extreme, the reef will develop as a three-dimensionally discrete body of organic detritus (hydromechanical or biodetrital reefs).

In contrast, if the reef setting is such that waves and currents winnow the degradation products (biodetritus) from the reef, then the reef will be characterized by organic skeletons and open space, encouraging the establishment of well-developed framework. From this, one can infer that fast-growing reef organisms in a sediment-sweeping setting will most likely produce framework (framework reefs).

Early diagenesis of reefs and other shallow-water carbonate deposits is commonly characterized by submarine cementation, as in the example of ancient framework reefs where adequate open space and water flushing occurred. For most other reefs, cessation of sea-level rise or elevation of the reef and exposure to meteoric waters provide a significant early diagenetic paragenesis that can influence the reef's potential for future petroleum trapping.

From this qualitative model, compared to sea-level-change rates, derives the basis for quantitive modeling (fig. 3). As modern reef-growth rates are compared to modern sea-level-change rates (Adey and Burke, 1976), a numerical basis for predicting architecture evolves (fig. 4). Current work is focusing on the development of polynomial equations to describe modern sea-level changes and comparative sedimentation (reef-growth) rates. The relationship of reef-growth rates and species diversity to water depth has been contrasted to abundance of detritus. Future work will develop these concepts towards prediction of reef occurence and porosity based upon geophysical log-interpreted sea-level changes.

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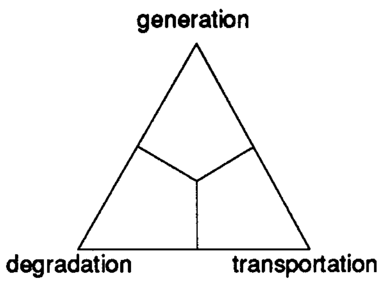

FIGURE 1—Ternary diagram showing the three major carbonate processes that determine reef architecture. Connecting plotted points representing individual samples can trace the evolution of process influence on the reef.

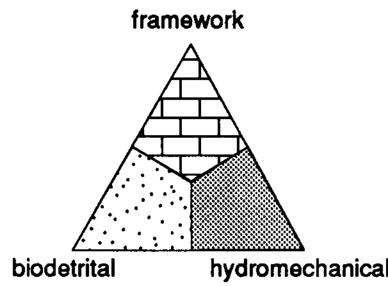

FIGURE 2—Ternary diagram of three major reef classes based on architecture developed by processes shown in fig. 1. There is a correspondence between points of the two ternary diagrams, that is, framework reefs are dominated by generation processes, biodetrital reefs by degradation, and hydromechanical reefs by transportation.

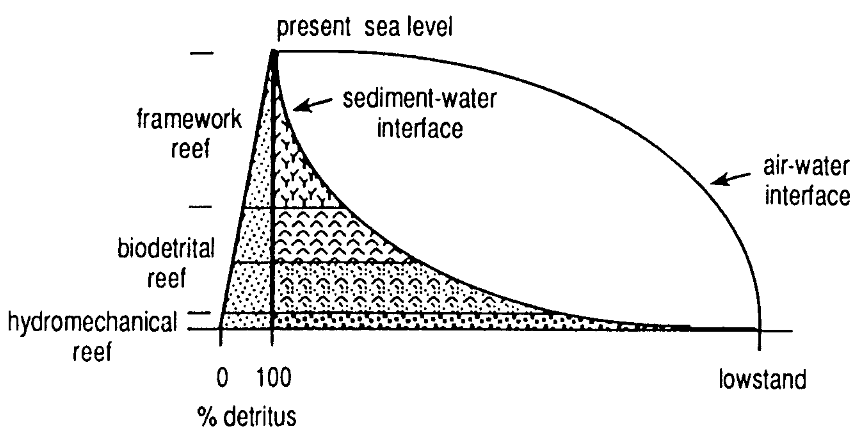

FIGURE 3—Schematic diagram showing the relationships of sea-level change to absolute water depth, detritus generation, sedimentation, and reef architecture.

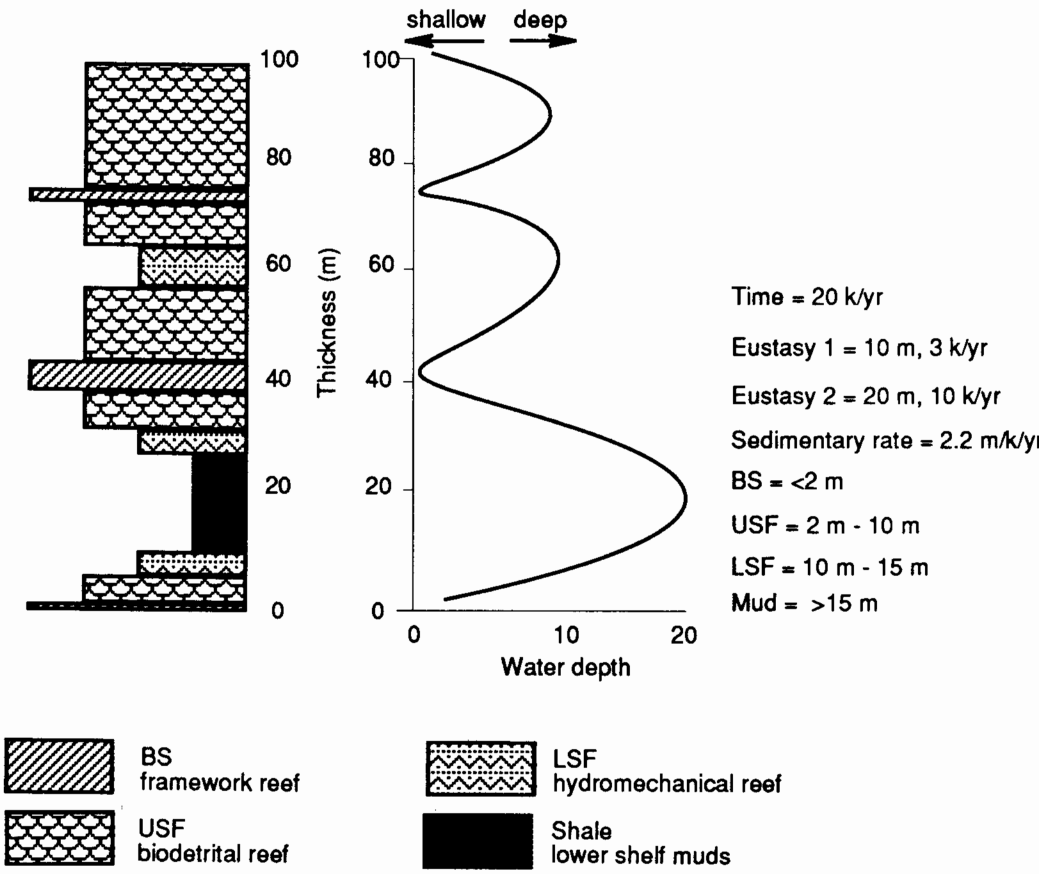

FIGURE 4—Application of the Cross and Lessenger (unpublished) one-dimensional stratigraphic model to a reef squence.

Are cyclic sediments periodic?

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A new technique, gamma analysis (where gamma is defined as time/unit thickness), tests for constant period in cyclic sediments even in the absence of age control. The method utilizes the individual cycles themselves and their facies distribution to determine if the cycles represent constant time and/or that accumulation rates are constant within facies. Since sedimentation rates are conventionally assumed to be constant in order to assign time to strata, it is important to test whether this is true even within a specified facies. Because sedimentary cycles are often assumed to be constant period in order to assess what that period is, it is also crucial to test if cycles have a constant period. Both sets of information are extremely difficult to obtain using conventional methods but can be derived from gamma analysis.

Results from the Middle Cambrian Trippe Formation from the Wah Wah Range of central Utah indicate that shoaling-upward, shallow-marine strata there have essentially constant gamma values and were probably deposited in response to a periodic process. The results of gamma analysis are consistent with field observations of lack of evidence of hiatuses within this section. Abundant hiatuses would be likely to result in calculation of highly variable facies-accumulation rates and gamma values.

When Fourier analysis of the Middle Cambrian cyclic interval in the Wah Wah Range was performed using the conventional assumption of constant accumulation rates in all facies, the spectral pattern, although composed of distinct peaks, was not diagnostic of any known climatically induced mechanisms and showed no periodicity at the scale of the measured cycles. However, Fourier analysis of the sections, in conjunction with time corrections derived from the gamma analysis, produced a spectral pattern that is strikingly similar to that predicted by the orbital or Milankovitch model of climate forcing. Specifically, the gamma-corrected time series strongly indicates that the primary cycles have precessional periods (19/23 Ka) and that significant periodic components are also present at both 100 Ka and 400 Ka, the periods of eccentricity. The 41-Ka period, or tilt component of orbital forcing, is weak or absent, however. This pattern of Milankovitch signals, precessional cycles modulated by eccentricity, is thought to be characteristic of low-latitude, monsoon-dominated climate. Although Middle Cambrian time was not a time of glacial climate, the sequences of interest were deposited in low latitudes which are most likely to be affected by monsoonal climate. Thus, studies of the periodicity of strata incorporating gamma analyses have the potential to increase our understanding of the controls of climate in these ancient environments.

Relative accumulation rates derived from the results of gamma analysis indicate that, on average, cryptalgalaminites and parted limestones had the highest accumulation rates, while calcareous grainstones had the lowest accumulation rates. Assigning relative time based on the assumption that the cycles are precessional results in average accumulation rates of 20 cm/Ka for the cryptalgalaminites and parted limestones and 8 cm/Ka for the calcareous grainstones.

Carbonate-sediment accumulation rates

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Studies of carbonate sediments suggest that the most important factors controlling the growth of platforms are eustatic sea-level variations, thermal and flexural subsidence, and changes in sediment-accumulation rates. These factors are interdependent, and they combine in a complex manner to determine the platform geometry. Computer simulation integrating these three factors is very helpful to understand the interplay of the different processes and the resulting geometry. One of the constraints of computer simulation is that the independent variables of eustasy, subsidence, and accumulation rates are not well known in the geologic record. In many cases the variables are synthetic or are calibrated after Holocene case studies. Carbonate-sediment accumulation rates are probably the most difficult parameter to measure, in part because the Holocene accumulation rates are one order of magnitude higher than ancient rocks (Wilson, 1975). Independent measurements of eustasy and subsidence for a given example are obtained using standard facies analysis (flooded in contrast to subaerially exposed platform top) and backstripping techniques. The objective of this paper is to describe a method to quantify two-dimensional sediment-accumulation rates on carbonate platforms, and to tabulate measurement for different ancient platforms. The method integrates vertical aggradation and lateral progradation of carbonate platforms, and the results can be applied to constrain the magnitude of sediment-accumulation rates used in computer simulation. This is a progress report, and refinement of the method and acquisition of data are needed.

Carbonate platforms, when under favorable conditions, aggrade vertically and prograde basinward, filling some or most of the accommodation space available. In general these two directions of platform growth are expressed in Bubnoff units (m/Ma or mm/ka) by two linear measurements: sediment-accumulation rates (a vertical measurement—length of section by the time required for it to accumulate), and progradation rates (a horizontal measurement—distance from an older shelf edge to a younger shelf edge by the time needed for it to prograde). Sediment accumulation and progradation rates are different from sedimentation rates because they include times of deposition and nondeposition (see discussion of stratigraphy completeness, Dott, 1988). Difficulties in quantifying sediment accumulation and progradation rates come from uncertainties in the biostratigraphic time scale, and in the amount of compaction and diagenetic changes. The basic idea in this paper is to combine the vertical and horizontal linear measurements and obtain a cross sectional area of a platform for a given time interval. The measurement of the area can be attained using different techniques (planimeter, image analysis) directly from reconstructed stratigraphic cross section or seismic lines. The cross sectional area can be converted to an average sediment thickness if the progradation is known, and vice versa. The selection of the time interval is highly dependent of each individual cross section and basin geometry. I suggest the use of unconformities, sequence boundaries, or regional sharp-facies changes to delineate the different sedimentary packages to be measured. Sediment-accumulation rates in this paper are defined as the cross sectional area divided by the time interval required for it to accumulate. This two-dimensional sediment-accumulation rate method averages the sediment-accumulation rates of different depositional facies existing on the platform and averages the effects of preexisting topography. The two-dimensional accumulation rates obtained by this method are different from the carbonate platform growth-potential concept (Schlager, 1981). The platform-growth potential (at least 400-500 Bubnoffs; Schlager, 1989, personal communication) centers on the potential of platform rims to growth at "full speed" at certain times to "catch up" with an increasing vertical accommodation space. The major problem with this areal method is to quantify offbank-sediment dispersal. In the examples studied, I excluded detrital and pelagic sedimentary wedges (few meters thick), but I did not exclude cases where small amounts of detrital and pelagic grains are well mixed with carbonate sediments. Particular care was taken in confining the boundary between foreslope and basin facies. Foreslope facies includes all the rocks with "in situ" relatively shallow-water sediments and deeper sediment with boulder- to sand-size carbonate clasts and grains derived from shallow water.

Preliminary data (fig. 1, table 1) suggest variations of areal-accumulation rates of 2–10 km^2 (0.8–4 mi^2)/Ma. Higher accumulation rates occur when the carbonate platforms show high progradation but slow aggradation rates. Lower accumulation rates occur when carbonate platforms show high aggradation but slow progradational rates. A crossplot of linear- and areal-accumulation rates (fig. 1) shows three fields characterized by A) low linear-accumulation rates (under 200 m [660 ft]/Ma) and low areal-accumulation rates (under 5 km^2 [2 mi^2]/Ma), B) high linear-accumulation rates (200–600 m [660–19,800 ft]/Ma) and low areal-accumulation rates (under 5 km^2 [2 mi^2]/Ma), and C) low linear-accumulation rates (under 200 m/Ma) and high areal-accumulation rates (5–10 km^2 [2–4 mi^2]/Ma). Linear-accumulation rates were measured in the thickest part of the platform. Errors incorporated in the calculations include biostratigraphic uncertainties, compaction, diagenesis, and accuracy of each cross section analyzed.

This preliminary data suggest that the accommodation space (e.g., relative sea-level changes, inherited topographic relief, water depth) is a very important factor in controlling carbonate-platform geometry (fig. 1), assuming an optimal biota-growth potential. However, environmental factors such as inimical bank water, nutrients, climate, and waves are also critical in controlling the type (fig. 1) and geometry of the carbonate platforms.

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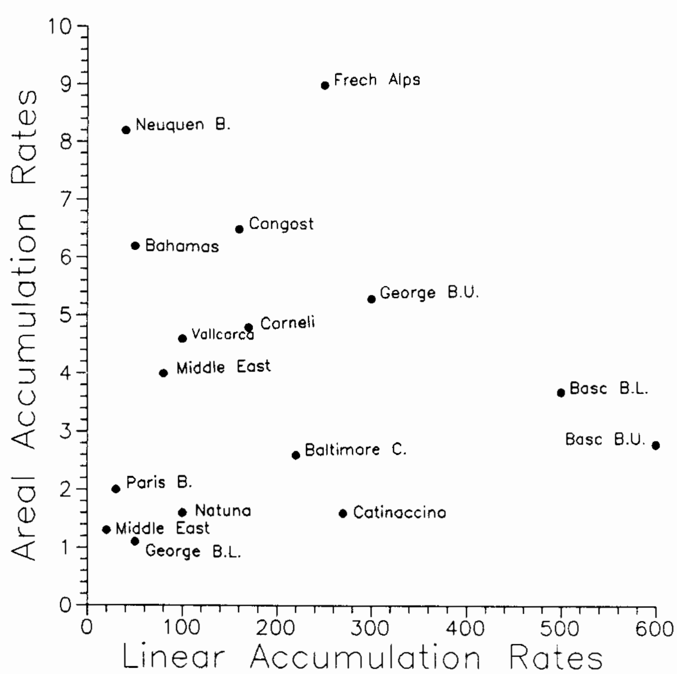

FIGURE 1—CROSS PLOT OF LINEAR VERSUS AREAL ACCUMULATION RATES; DATA FROM TABLE 1.

TABLE 1—Accumulation rates of Cenozoic and Mesozoic carbonate platforms.

Time	Platform	Linear Rate mm/Ka	Areal Rate sq Km/Ma	Observation	Source
Upper Miocene–Pliocene	Bahamas	50	6.2	prograding rimmed platform	Eberli & Ginsburg (1989)
Middle–Upper Miocene	Natuna platform, South China Sea	100	1.6	backstepping isolated platform	Rudolph & Lehmann (1989)
Campanian	Vallcarca, Southern Pyrenees	100	4.6	prograding skeletal-rich platform	Simo (1989)
Santonian	Sant Corneli, Southern Pyrenees	170	4.8	prograding skeletal-rich platform	Simo (1989)
Coniacian Turonian	Congost, Southern Pyrenees	160	6.5	prograding skeltal -rich platform	Simo (1989)
Lower Albian	Basc basin Upper platform	600	2.8	isolated platform, with deep lagoon	Fernandez–Mendiola (1987)
	Lower platform	500	3.7	isolated platform ramp	
Barremian–Bedoulian	French Alps	250	9	prograding platform with outer-shelf	Arnaud (1984)
Barremian	Middle East	20	1.3	low-energy ramp	Morris (1980)
Tithonian–Valanginian	Neuquen basin	40	8.2	prograding platform with delta-plain facies	Mitchum & Uliana (1985)
Tithonian	Middle East	80	4	rimmed prograding platform, with evaporitic lagoon	Morris (1980)
Tithonian	Baltimore Canyon U.S. Atlantic coast	220	2.6	rimmed prograding platform with delta-plain facies	Earlich et al. (1988)
Bathonian	Paris basin	30	2	oolitic platform	Dubois & Yapaudjian (1985)
Upper Jurassic	George Bank, U.S. Atlantic coast	300	5.3	prograding rimmed platform with delta plain	Poag (1982)
Lower–Middle Jurassic	George Bank, U.S. Atlantic coast	50	1	prograding rimmed platform with delta plain	Poag (1982)
Ladinian, Triassic	Catinaccino platform, Southern Alps	270	1.6	isolated prograding platform	Bosellini & Doglioni (1988)

Lag time—is it simply storm-wave base?

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Inundation of a carbonate platform during transgression apparently does not lead to an immediate onset of rapid production of carbonate sediment. Stated another way, carbonate-sediment production does not reach its full potential for a finite period (Schlager, 1981). Thus carbonate-sediment accumulation tends to lag behind the relative rate of sea-level rise, producing a deepening sequence (Read et al., 1986). The time between initial inundation and onset of rapid sediment accumulation is "lag time." This interval is critical in our understanding of shoaling-upward platform cycles. Without lag time, carbonate sedimentation would either remain at sea level or, if accumulation rate is less than the relative rate of sea-level rise, a continuously deepening sequence would result. Lag time is also essential to Ginsburg's (1971) autogenic cycles; when carbonate sediment has built to sea level across a platform, thereby destroying its source of sediment, there follows a finite period of transgression before rapid sediment accumulation begins progradation.

Despite lag time's profound effect on the character of shoaling-upward cycles (cf. Read et al., 1986, p. 108), the causative processes are poorly understood. In modeling of cycles, the duration of lag time is typically assigned by trial and error to produce reasonable cycles.

Experience with modern shallow-water carbonate sedimentation in south Florida suggests that lag time is caused by extensive winnowing of sediments deposited above local storm-wave base. Regardless of in situ rates of production, the geologic record of sediment depends on net accumulation, that is, production at a rate in excess of removal. When rise in sea level places the bottom below the reach of storm waves, rapid sedimentation can occur. The accumulation rate will be rapid if the bottom remains within the euphotic zone, a common case where terrigenous input is not excessive. Alternatively, construction of barriers may dampen storm waves below the threshold of erosion, permitting carbonate accumulation in quite shallow water.

In the south Florida shelf margin, seaward of the Florida Keys, the inshore zone is dominated by rock bottoms or veneers of skeletal sediment too thin to support sea grass and infauna. Sediment does not accumulate in this zone despite significant populations of sediment-producing organisms. Depths at the outer edge of this zone, where it becomes covered with sediment, are uniformly 3 m (10 ft) along the entire length of the Florida Keys. This depth apparently represents the limit of winnowing by local waves, developed behind the shoals at the platform edge (Enos, 1977). In this setting, then, lag time is the interval from initial flooding until water depth reaches 3 m (10 ft), about 4,000 yrs in the present transgression (Scholl et al., 1969; Robbin, 1984). Obviously lag time has several controls; the most prominent are rate of sea-level rise and local hydrographic setting, primarily fetch, which determines storm-wave base.

In Florida Bay, a shelf lagoon restricted by the Florida Keys and muddy shoals, sediment accumulation in shallow basins is restricted to depths greater than about 1.8 m (6 ft). Wave base is controlled by fetch within sub-basins between the restricting mud banks. Fetch is of the same order of magnitude throughout the bay, thus significant sediment accumulation begins at about the same depth. The last 1.8 m (6 ft) of the Holocene rise of sea level required about 3,600 yrs (Scholl et al., 1969) lag time in Florida Bay.

In this concept of lag time, a key element is the control of substrate on ecologic community and thereby on production of carbonate sediment (Enos, 1977). Hard substrates restrict the fauna essentially to encrusting and boring organisms. Mobile, coarse-grained substrates also have impoverished faunas. A soft substrate of lime mud, such as accumulates below storm-wave base, supports a burrowing infauna, calcareous algae, and a sea-grass community with profuse epibionts. Thus the accumulation of mud initiates a quantum jump in sediment production (Stockman et al., 1967; Bosence et al., 1985; Nelson and Ginsburg, 1986; Bosence, 1989). This is not a "chicken and egg" dilemma; a stable substrate is a prerequisite to colonization by green algae and especially grass. A shelly substrate that is not reworked for long periods may be stabilized and support sediment-producing populations.

The sedimentary record of the delay mechanism is the familiar "basal lag" of reworked shells and pebbles overlain by finer-grained sediment. This deepening interval is followed by a shallowing sequence as carbonate production exerts its ability to outstrip most rates of sea-level rise.

Recognition of the cause of lag time does not immediately produce numbers for modeling of carbonate cycles. It does allow intelligent estimates and should lead to better quantitative models where the hydrographic setting and relative rates of sea-level rise can be approximated.

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Field recognition of small-scale genetic surfaces

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Application of computer simulation of genetic units in stratigraphic sequences requires meaningful field testing. Small-scale (i.e. 5th and 6th order: Busch and Rollins, 1984; Busch and West, 1987) genetic units may be either autogenic or allogenic. Autogenic genetic units are the depositional results of such events as delta switching, storm scour, or local tectonism and thus are not geographically widespread. Allogenic genetic units result from sea-level or climatic changes and therefore are correlative over wider geographic areas. The practical differentiation of autogenic and allogenic units is scale-dependent and has to be assessed prior to any specific stratigraphic analysis. Intrabasinal studies, for example, may define allogenic genetic units in terms of tectonostratigraphic dynamics constrained to a single basin, whereas these same genetic units might be autogenic in an interbasinal study concerned with global sea-level changes. However, in order to ascertain whether a unit is autogenic or allogenic, the stratigrapher must attempt to trace each genetic unit to its geographic limits.

The field testing of computer-modeled late Paleozoic sequences generally involves precise recognition of paleobathymetric changes, usually expressed as rather sharp contacts (genetic surfaces) of autogenic or allogenic origin. Typical allogenic surfaces are the results of either marine transgression or climate-change (Busch et al., 1989). Transgressive surfaces are recognized where 1) a marine facies abruptly overlies a nonmarine facies, 2) a "more normal marine" facies abruptly overlies a "restricted" facies, or 3) a relatively deeper marine facies abruptly overlies a shallower facies. Determination of "more normal marine" and "relatively deeper" will often rely upon detailed assessment of faunal paleoenvironmental tolerances and paleobathymetry. Such surfaces may be cryptic in the interiors of depositional basins, perhaps discernible only as abrupt changes in time-averaged taxonomic diversity, extensive epibiont infestation, crevice faunas, abrupt biofacies boundaries, or condensed sections displaying complex shell beds. Transgressive surfaces are more easily recognizable, and typically less numerous, near basin margins where they may be associated with heterochronous deposition (exhumation and redeposition into time-averaged condensed sections), erosion or ravinemant, nondeposition (firmgrounds, hardgrounds, palimpsested surfaces, *Trypanites* and *Glossifunqites* ichnofacies), or any combination of the above. Climate-change surfaces may be indicated by 1) subaqueous-nonmarine facies abruptly overlying subaerial-nonmarine facies, 2) deeper subaqueous-nonmarine facies abruptly overlying shallower (relatively) subaqueous-nonmarine facies, 3) a relatively less restricted subaqueous-nonmarine facies abruptly overlying a relatively restricted subaqueous-nonmarine facies, and 4) a relatively more humid subaerial-nonmarine facies abruptly overlying a relatively less humid subaerial-nonmarine facies.

St. Catherines Island, in the shallow Georgia embayment, provides a modern analog for detailed field study of many basin-margin features noted in late Paleozoic stratigraphic sequences (West et al., in press; Morris and Rollins, 1977; Pemberton and Frey, 1985). The relict marsh muds exhumed along the seaward edge of the island record minor shoreline fluctuations (both allogenic and autogenic) in the form of palimpsested surfaces, *Trypanites* and *Glossifunqites* ichnofacies, transgressive shell lags, etc. Many of these features have analogs in the Pennsylvanian strata of the Appalachian basin and the midcontinent United States.

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Modeling of Carboniferous tidal rhythmites based upon modern tidal data

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Detailed analyses of millimeter-scale laminations within tidal rhythmites from Carboniferous strata of Indiana, Illinois, Iowa, Kansas, and Colorado reveal a hierarchy of recognizable periodicities (Kvale et al., 1989). These periodicities are manifested by systematic changes in laminae thickness. Cycles contained within rhythmites, which occur in carbonate mudstones and siliciclastic shales, siltstones, and sandstones, can be related to an ordering of tidal periodicities. Consistency of these patterns through as much as 6 m of vertically continuous section in one example indicates a strong extrinsic control on sedimentation. The significance of the patterns can be explained by using modern tidal data to model a sedimentologic regime in which tidal rhythmites can be formed. Spectral analyses of modern data aid in recognizing and predicting tidal events which, from smallest to largest scale, include: 1) diurnal to semidiurnal tides related to the earth's rotation, 2) neap-spring patterns related to the lunar orbit, 3) tropical-equatorial tides related to lunar declination and distance, 4) solstitial-equinoctial tidal patterns related to the earth's orbit and axial tilt, and 5) yearly patterns related to seasonal parameters. Thus, such cyclic patterns represent the highest frequency oscillations of sea level observable within the rock record (fig. 1). Vertical continuity of the patterns indicates that sedimentation rates exceeding 1 m (3.3 ft)/year were attained during deposition of these laminated sediments and that such sections exhibit a very high degree of stratigraphic completeness (Archer and Kvale, 1988).

Factors controlling modern tides are exceedingly complex but are related ultimately to the gravitational effects of the moon and sun upon the oceans of the earth. Each order of tidal periodicity in turn can be related to the earth's rotation, lunar orbit and declination (angle of lunar orbit to earth's equatorial plane), distance of the moon from the earth (apogean-perigean effects), and earth's orbit and solar declination (position of sun relative to earth's equatorial plane). Because these periodicities are not completely in phase, their interaction results in a recognizable hierarchy of patterns.

The smallest-scale (first-order) tidal patterns are produced by the earth's daily rotation relative to the gravitational effects of the moon and sun. A tidal bulge forms within the oceans and sweeps around the earth with a periodicity consisting of a stronger 12.42-hour component (lunar effects) and a weaker 12-hour component (solar effects). Thus, this bulge ideally has a twice daily, or semidiurnal, affect on the oceans of the earth.

Second-order patterns can be compared to cycles produced by tidal effects created by the periodicity of the lunar orbit, which is completed every 29.5 days. The earth, moon, and sun are aligned when the moon is either in a new or full phase. During these times, the gravitational effects of the moon and sun are combined and the highest, or spring, tides occur. Conversely, during the half-moon phases, the secondary gravitational effects of the sun offset lunar effects to produce the lowest, or neap, tides. Neap-spring cycles occur every 14.75 days and two such cycles occur during one lunar orbit (lunar month).

Third-order tidal patterns are related to the moon's declination, which is the angle of the lunar orbit to the earth's equatorial plane, and also by the distance of the moon from the earth. For example, the time required for the moon to change declination from zero (over the earth's equator) to the maximum of 28° (over the tropics) and then back to zero is 13.66 days. During the time when the moon crosses the equator, or "crossover," the semidiurnal inequality is minimized. Therefore the two semidiurnal tides produced during a crossover are approximately equal in height. Conversely, when the moon is at its maximum declination, the semidiurnal inequality is maximized. Because the crossover period is less than the interval between spring tides (14.75 days) described above, crossovers will occur about one day earlier within each successive neap-spring cycle.

The yearly cycle of seasons on the earth is related to the earth's axial tilt of 23.5°. Fourth-order patterns can be related to solstitial and equinoctial tides. In modern environments tidal ranges are maximized during the solstices (June and December), which is also the time of maximal semidiurnal inequality of the tides. An opposite effect occurs during the equinoxes (March and September) when the semidiurnal inequality is at a minimum. During the equinoxes, dominant tides are approximately equal to subordinate tides.

Yearly sea-level variations also occur across most of the oceans. Direct astronomical effects are in part responsible for yearly sea-level change; however, the fluctuation is equated more directly to seasonally varying parameters such as temperature, salinity, and air pressure. Maximum yearly sea level occurs in different parts of the world during different seasons. Thus tidal patterns in such areas will exhibit yearly fluctuations in tidal heights superimposed upon all the previously discussed, smaller scale patterns.

Tidal cyclicity preserved in the rock record can be used to estimate sedimentation rates. Estimates of deposition rates of about 1 m (3.3 ft)/year within Carboniferous tidalites are based upon thicknesses of semidiurnally emplaced laminae, occurrence and thickness of neap-spring cycles, and interpretation of larger scale yearly cycles. These high rates of sedimentation are supported by other observations, such as occurrence of upright lycopod trunks.

The nearly continuous record of semidiurnal deposition for several years bears greatly on concepts of "stratigraphic completeness" (Sadler, 1981). Not only has a detailed, multi-yearly record of daily sedimentation been preserved, but also extremely high rates of sedimentation have been documented. Although such rates probably were achieved only locally and may be related to compaction of underlying sediments, the recognition of such rates poses some potential problems with the delineation and correlation of longer term (10,000–100,000-yr) cycles on either a local or regional scale. Rates of sedimentation based upon detailed laminae measurements are orders of magnitude more rapid than rates derived by dividing formational thickness by formational time. For example, tidalites within the Mansfield Formation of Indiana have determinable rates of accumulation as high as 1 m (3.3 ft)/year; however, dividing formational time (about 15 Ma) by formational thickness (about 90 m [297 ft]) yields rates of about 1 m (3.3 ft) per 160,000 years. At least within these localized tidal deposits, formational time divided by formational thickness will yield depositional rates that are many orders of magnitude slower than those indicated by detailed sedimentological analyses (fig. 2). Such comparisons support a view of the rock record in which short-term episodes of rapid sedimentation are punctuated by long periods of nondeposition. Thus delineation of short- and long-term cycle durations becomes extremely problematic without reasonable sedimentological constraints.

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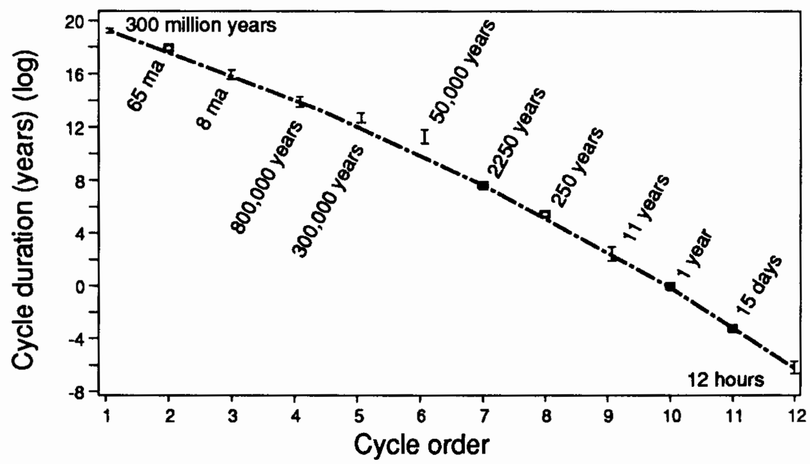

FIGURE 1—Spectrum of geological cycles; durations of higher-order cycles (1st through 6th) derived from various sequence-stratigraphic sources. Intermediate order cycles (2,250 and 250 yrs) are inferred; 11-yr cycle is average sunspot cycle, and lowest order cycles are related to tidal deposition.

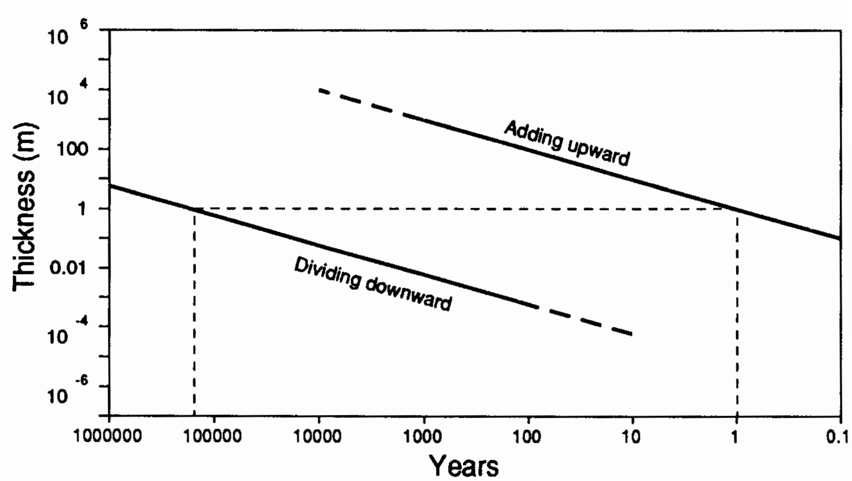

FIGURE 2—Differences in estimating lengths of time for deposition of the Mansfield Formation (Pennsylvanian) of southwestern Indiana. Line labeled "adding upward" based upon rates of sedimentation derived from analyses of daily, biweekly, and yearly tidal cycles. Conversely, line labeled "dividing downward" is based upon average long-term rates derived by dividing total formational thickness by total formational time. For 1 m (3.3 ft) of sediment, the two techniques yield rates that differ by over five orders of magnitude.

Depositional-sequence analysis of Lower Permian progradational systems, Midland basin, Texas

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Late Pennsylvanian and Permian strata in the Midland basin of west Texas comprise thick, dominantly progradational wedges that infilled the basin by Guadalupian time. The lower Permian section (Wolfcampian and lower Leonardian) on the north platform of the Midland basin (fig. 1A) is a complex mosaic of carbonate and siliciclastic depositional systems (fig. 1B) whose development was influenced by the interplay among recurrent sea-level fluctuations, periodic subaerial exposure, and variable subsidence rates through time (Mazzullo and Reid, 1989). The resultant sedimentary architecture of platform and basinal facies consists of three separate progradational sequences represented by the Wolfcamp and lower Leonardian Wichita and Lower Clear Fork formations (fig. 1B). Parasequences (definition following Van Wagoner et al., 1988) of variable time duration compose these sequences and record disparate constructional and destructional phases of platform development (fig. 1C). Such complexity, which is not entirely evident seismically (fig. 1D), is resolvable only by detailed regional subsurface lithologic and biostratigraphic studies.

The cumulative thickness of the Wolfcamp, Wichita, and Lower Clear Fork formations in the study area is 915–1,220 m (3,020–4,026 ft), representing a duration of approximately 22 m.y. (16.5 m.y. assigned to the Wolfcamp, 5.5 m.y. to the Wichita and Lower Clear Fork; fig. 1C). Calculated sedimentation rates are 42–55 m (139–182 ft)/ m.y. The Wolfcamp sequence is divided into seven units (e.g., "early early," "middle early," etc.; fig. 1B, C) on the basis of fusulinid biostratigraphy (Mazzullo and Reid, 1989); the late middle Wolfcamp is absent in the study area. The seven units correspond to parasequence sets that can be identified seismically throughout the Midland basin (fig. 1D). The estimated duration of each of these sets is 2.36 m.y. Individual parasequences (e.g., "A," "B," etc.; fig. 1B) within parasequence sets variously record periods of platform erosion, progradation, or backstepping (figs. 1B, C); the thinnest of these parasequences are beyond seismic resolution. The estimated duration of each of these parasequences is 0.8–1.2 m.y. Biostratigraphic subdivision of the Wichita and Lower Clear Fork is not possible because of the rarity of fusulinids. Instead, the formations were each subdivided into various parasequences ("A–D") on the basis of lithologic and mechanical log correlations; the Tubb Sandstone Member is the fifth, uppermost parasequence in the Lower Clear Fork (fig. 1B). The estimated duration of these parasequences is 0.7 m.y. in the Wichita and 0.55 m.y. in the Lower Clear Fork. Except for the Tubb Sandstone Member, these parasequences generally are beyond seismic-resolution limits (fig. 1D). Parasequences in the Wichita are progradational in lower beds of the formation and aggradational in the upper part (fig. 1B). Parasequences in the Lower Clear Fork are mostly aggradational, and those in the Tubb are aggradational to, locally, progradational (fig. 1B).

Shallow platform and coeval deep-basinal facies are recognized within the parasequences in the Wolfcamp and lower Leonardian section (fig. 1B). Platform lithologies in Wolfcampian and lower Leonardian rocks include pervasively dolomitized lagoonal fossiliferous wackestones to packstones and local patch-reefs and platform margin reefs composed mainly of phylloid algae, *Tubiphytes*, sponges, and encrusting foraminifera. Varicolored shales and siliceous carbonates, interpreted as colluvium, are present throughout the section (fig. 1B). Peritidal dolomites and evaporites, platform-margin ooid shoals, and sandstones also occur in lower Leonardian rocks in the study area (fig. 1B). Basinal lithologies include dark shales, resedimented platform-carbonate debris, and in lower Leonardian strata, interbedded sandstones (fig. 1B).

Component parasequences of the Lower Permian platform sections (duration 0.55–1.2 m.y.) variously are composed of colluvial beds associated with either thin (2.5–7.0-m [8–23-ft]), stacked, shoaling-upward cycles of shallow subtidal and peritidal dolomites (and locally evaporites) or deepening-upward cycles (fig. 1B). The four sandstone beds in the Tubb parasequence are each interpreted as sea-level low-stand deposits separated by shoaling-upward carbonate cycles. Such cyclicity within component parasequences throughout the Lower Permian section reflects a basic control on facies development of short-term, relative eustatic changes through time (Mazzullo and Reid, 1989). This short-term cyclicity likely represents third and fourth-order variations within second-order cycles (the latter represented by individual parasequences in the Lower Leonardian and parasequence sets in the Wolfcampian) of 0.55–2.36 m.y. duration (figs. 1B, C). The estimated duration of these third-order cycles is 100 k.y.; these, and fourth-order cycles, likely represent Milankovitch cycles. The second-order cycles are, in turn, components of first-order cycles that are directly coincident with long-term variations in basin-subsidence rates through time (fig. 1C).

Maximum basinward progradation of carbonate platforms occurred in early and late Wolfcampian and, to a lesser extent, in earliest Leonardian (early Wichita) times. Approximately 22 km (13 mi) of progradation, during Wolfcampian time, was facilitated by the deposition of thick sections of basinal shales that served as foundations over which carbonate platforms built (Mazzullo and Reid, 1989). This progradation was coincident with a first-order high stand punctuated by relatively few second- through fourth-order low stands of long duration (figs. 1B, C). In contrast, upper Wichita and Lower Clear Fork platforms essentially accreted vertically in a regime of high basin-subsidence rates but were affected by relatively more numerous second- through fourth-order low-stand cycles of relatively shorter and magnitude than those inferred for underlying rocks (fig. 1C; Mazzullo and Reid, 1989).

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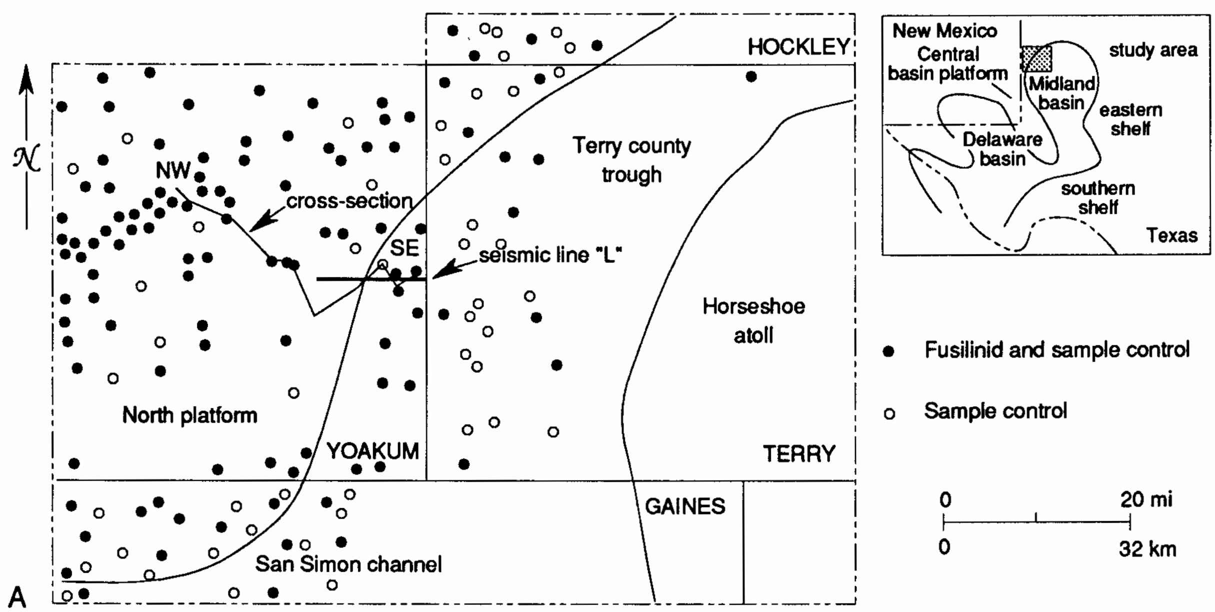
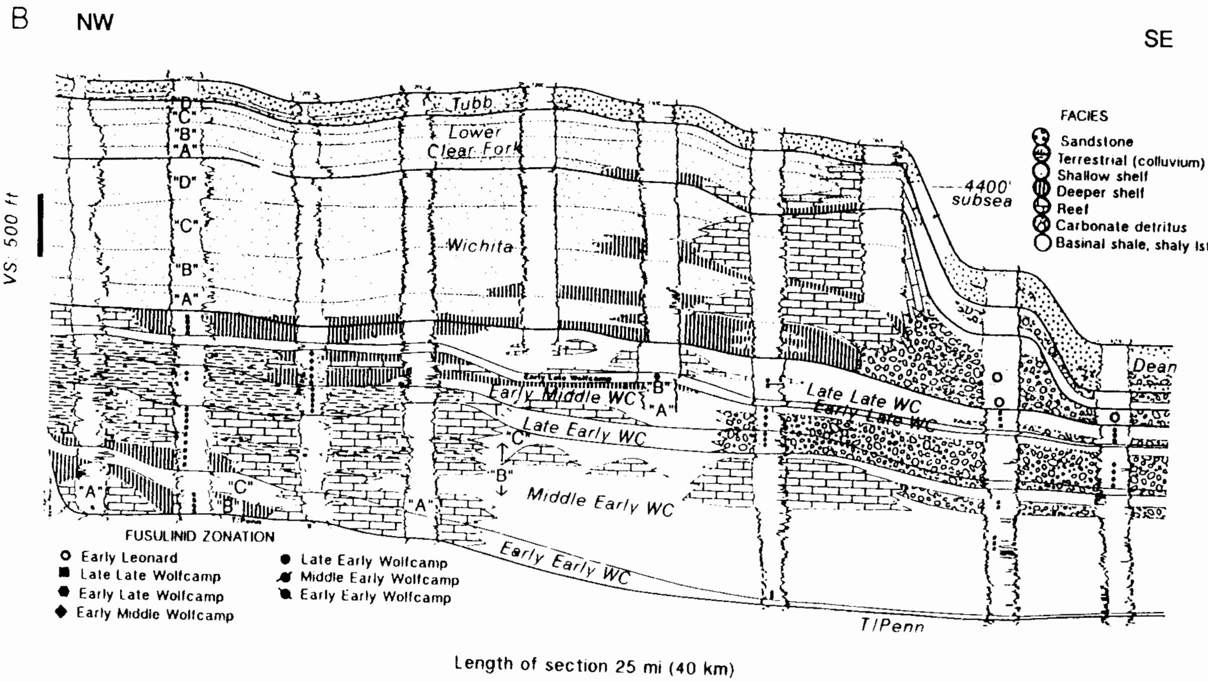
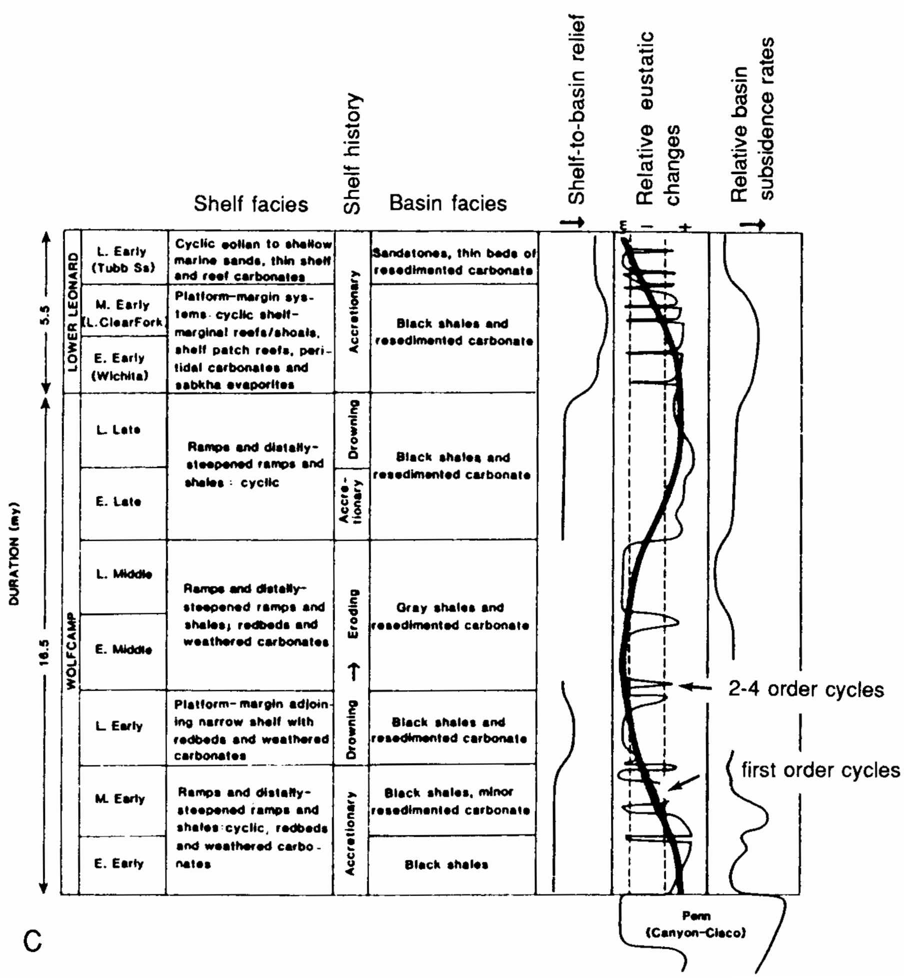
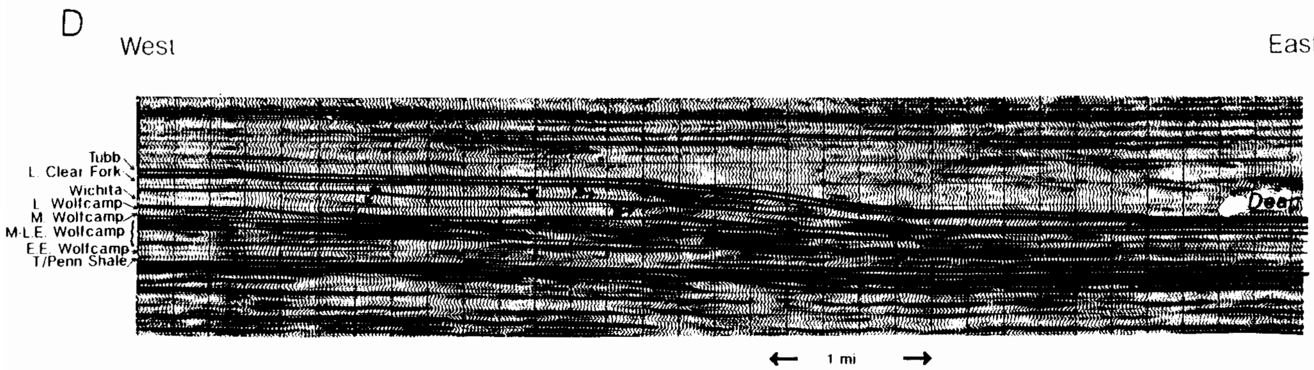


FIGURE 1—A) North platform Midland basin study area, west Texas, and location of NW–SE cross section in Yoakum County; B) Platform-to-basin section (subsea datum) in Lower Permian strata, illustrating subdivisions of Wolfcamp, Wichita, and Lower Clear Fork into parasequence sets composed of parasequences "A–D" (and Tubb Sand in Lower Clear Fork); C) Relationships among relative sea-level and subsidence-rate changes and platform development; and D) Platform-to-basin seismic line"L" parallel to cross section (see 1A for location). Arrows in Wichita and Lower Clear Fork point to low-stand surfaces. All illustrations modified from Mazzullo and Reid (1989).


B
NW
SE
VS: 500 ft
Tubb
Lower Clear Fork
Wichita
"D"
"C"
"B"
"A"
4400' subsea
FACIES
Sandstone
Terrestrial (colluvium)
Shallow shelf
Deeper shelf
Reef
Carbonate detritus
Basinal shale, shaly lsl
Dean
Late Late WC
Early Late WC
Early Middle WC
Late Early WC
Middle Early WC
Early Early WC
T/Penn
FUSULINID ZONATION
Early Leonard
Late Late Wolfcamp
Early Late Wolfcamp
Early Middle Wolfcamp
Late Early Wolfcamp
Middle Early Wolfcamp
Early Early Wolfcamp
Length of section 25 mi (40 km)


Shelf facies
Shelf history
Basin facies
Shelf-to-basin relief
Relative eustatic changes
Relative basin subsidence rates
DURATION (my)
5.5
16.5
LOWER LEONARD
WOLFCAMP
L. Early (Tubb Ss)
M. Early (L.ClearFork)
E. Early (Wichita)
Cyclic eolian to shallow marine sands, thin shelf and reef carbonates
Platform-margin systems: cyclic shelf-marginal reefs/shoals, shelf patch reefs, peritidal carbonates and sabkha evaporites
Accretionary
Sandstones, thin beds of resedimented carbonate
Black shales and resedimented carbonate
L. Late
E. Late
Ramps and distally-steepened ramps and shales: cyclic
Drowning
Accretionary
Black shales and resedimented carbonate
L. Middle
E. Middle
Ramps and distally-steepened ramps and shales; redbeds and weathered carbonates
Eroding
Gray shales and resedimented carbonate
L. Early
Platform-margin adjoining narrow shelf with redbeds and weathered carbonates
Drowning
Black shales and resedimented carbonate
M. Early
E. Early
Ramps and distally-steepened ramps and shales: cyclic, redbeds and weathered carbonates
Accretionary
Black shales, minor resedimented carbonate
Black shales
2-4 order cycles
first order cycles
Penn (Canyon-Cisco)
C


D
West
East
Tubb
L. Clear Fork
Wichita
L. Wolfcamp
M. Wolfcamp
M-L.E. Wolfcamp
E.E. Wolfcamp
T/Penn Shale
Dean
1 mi

Revelation of small features in Kansas cyclothems using high-resolution reflection seismology

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Resolution is directly related to the bandwidth of a signal, and detection of thin beds is directly related to the wavelength of the signal. High-frequency data generally are also broader band and are also shorter wavelength. In other words, improving the high-frequency content of a signal improves the resolution and thin-bed-detection capabilities of a seismic signal dramatically. Typical bed thicknesses of cyclothems in Kansas are generally less than 10 m (33 ft) and often about 2 m (7 ft). Given an average velocity of about 3,200 m (10,560 ft)/sec, this suggests that frequencies of at least 400 Hz are needed to resolve the beds as thin as 2 m (7 ft). This is based on the resolution of thin beds being one-quarter wavelength. This generalization is related to the rock type of the bed; low-velocity shales (~2,000 m [6,600 ft]/s) require only about 250 Hz and high-velocity limestones (~4,000 m [13,200 ft]/s) require about 500 Hz for the same resolution. Furthermore, tuning will occur in a thin bed such that the instantaneous frequency of a reflection response will depend on the thickness and interval velocity of the bed.

With standard exploration reflection seismology, the frequency band is generally less than 100 Hz. As a consequence, the seismic response is greatly generalized. For instance, the Kansas City–Lansing groups are commonly seen as a strong ringy (tuned to 50–60 Hz) reflection. The low-frequency content of the signal is not only unable to resolve the individual beds of the groups, it is only able to return the reflection response of the two groups combined.

It is found that when the reflection signal content includes frequencies as high as 500 Hz or greater that the reflection response will include all but the thinnest of the individual beds. Instantaneous frequency response will depend on the bed thickness and the velocity of the bed, and the amplitude of the reflection will depend on the frequency (high frequencies having lower amplitudes), the bed thickness, cyclic repetition (constructive interference), and the strength of the reflector. In other words, a limestone of 2-m (7-ft) thickness will respond with a small amplitude reflection of about 500-Hz signal. A series of alternating shales and limestones will respond with a relatively large amplitude reflection and a frequency appropriate for the tuning character of the cycles.

The reflection character of the eastern Kansas cyclothems for signals as high as 500 Hz is generally that of thin beds because bed thicknesses are usually less than 10 m (33 ft). For thick-bed response there is an isolated reflector for both the top and the bottom of the bed. For thin-bed response the top and the bottom reflectors interfere, resulting in a single response for the bed as a whole. Consequently, individual reflectors in the eastern Kansas cyclothems generally represent beds rather than interfaces. With the simple application of a phase-shift filter, it is possible to process the data such that positive reflectors (peaks) represent thin-bed limestones and negative reflectors (troughs) represent thin-bed shales and sandstones. This simplification may make classical interpreters shudder because it is one of the first generalizations that they are taught to avoid; however, in the case of cyclothems it is valid for much of the section.

When high-resolution, high-detail data are obtained, Kansas cyclothems are revealed to not be the typical layer-cake that most geophysicists and even many geologists think. The section (see fig. 1) is of sufficient detail that inspection of it is reminiscent of looking at an outcrop from the distance of a few tens of meters. It is found that lateral sampling (trace interval of the section) of less than 1 m (3.3 ft) is necessary to see the lateral changes that are taking place in the section. Beds are found to change character in the distance of only a few meters. Most of the lateral changes are occurring in sandstones and shales, but even limestones can change character within a few tens of meters. These changes include presence of sand channels and sandstone-bedding structure, small faults, thickness variation, and facies changes.

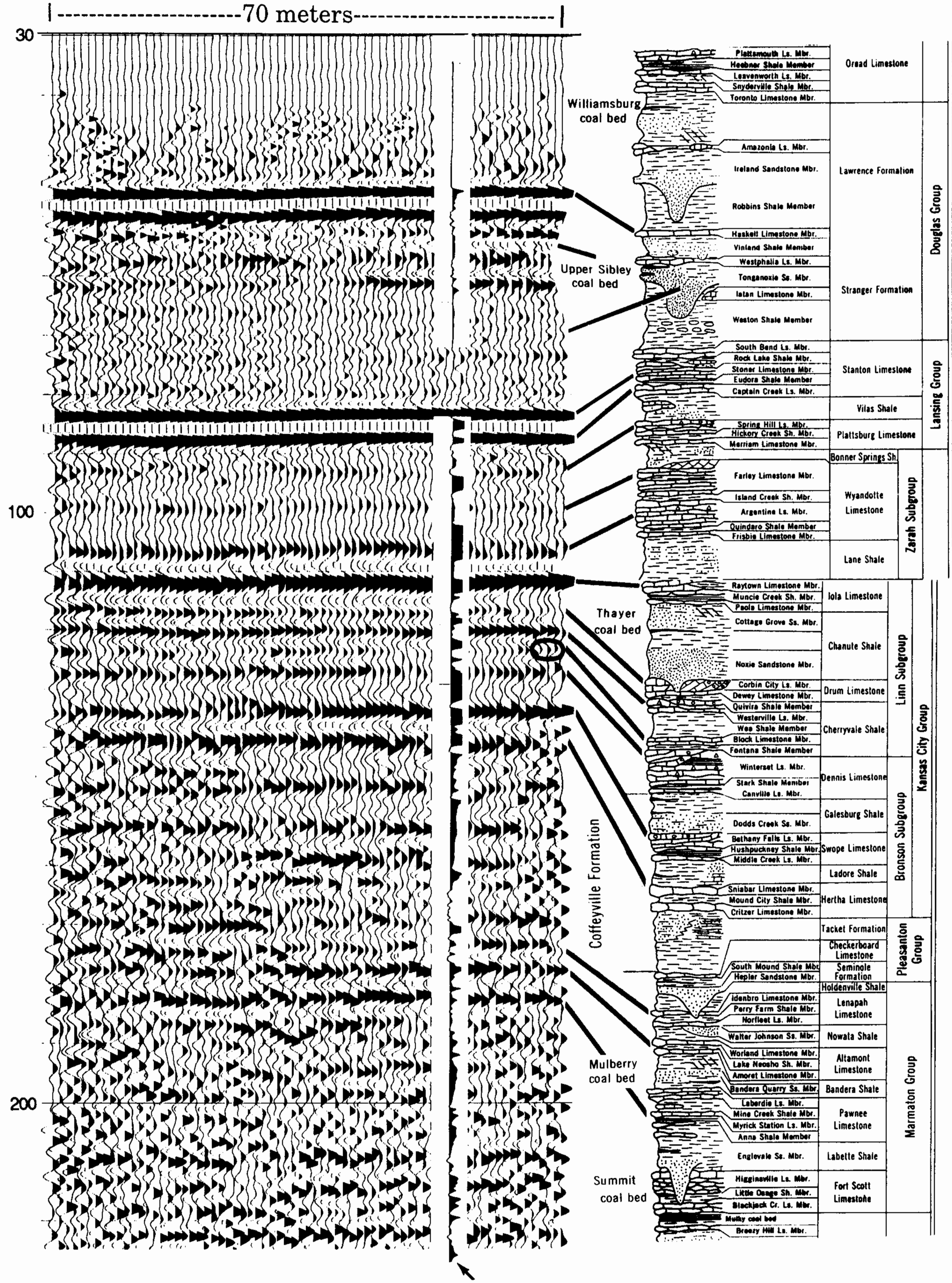

FIGURE 1—SEISMIC SECTION OF THE PENNSYLVANIAN BENEATH LAWRENCE, KANSAS, with a velocity log (arrow) and formation identification, 1-m (3.3-ft) trace interval.

Paleotectonic control of reservoir facies

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It has been well established that the basement structural fabric of the Paradox basin (Utah and Colorado) affected sedimentary facies throughout Phanerozoic time. Continental-scale conjugate basement wrench-fault zones, originally activated during 1.7 to 1.6 Ga, were rejuvenated repeatedly throughout the Paleozoic. The Paradox pull-apart basin was formed along the northwest-southeast-trending Olympic–Wichita lineament in Middle Pennsylvanian time, facilitated by basement faults of the northeast-southwest-trending Colorado lineament. These continental-scale basement lineaments conform to a global regmatic structural fabric that has been well documented in Precambrian and younger rocks. Structurally controlled shoaling conditions, formed by reactivation of basement faults, fostered marine-sandstone reservoirs in Late Devonian time, crinoidal Waulsortian buildups in the Early Mississippian, and phylloid-algal mounds in Middle Pennsylvanian time.

Apparently similar basement wrench-fault zones, dating at about 1.1 Ga, are present in Kansas. The midcontinent rift system is a north-northeast/south-southwest-trending fault zone that was reactivated several times during the Paleozoic. Northwest-southeast-trending faults along the Central Kansas–Bourbon arch complex seem to have offset structures of the midcontinent rift. Both trends are interpreted to be continental-scale conjugate wrench-fault zones, with sinistral displacement along the midcontinent rift and dextral displacement along the Central Kansas–Bourbon arch complex. Stratigraphic relationships suggest a long history of reactivation prior to Middle Pennsylvanian uplift and erosion of the major structural features.

In both regions, major structural lineaments are associated with smaller scale rhomboidal fracture patterns, drag-related en echelon folds, and complex, mutually offsetting fault patterns, especially in areas of intersecting basement structures. Reactivation of these structural features through time created unconformity-bounded trapping conditions at several stratigraphic intervals, and structurally controlled water-depth variations localized algal accumulations in Pennyslvanian carbonates.

Evidence is accumulating in Kansas that tectonically controlled paleotopography and paleobathymetry are major predictable factors in reservoir localization. Recognition of reactivated regmatic basement structural fabrics is important to facies and reservoir analysis and can provide significant constraints on reservoir characterization and modeling.

Lithofacies and geochemical-facies profiles from modern wireline logs—new subsurface templates for sedimentary modeling

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The use of wireline logs in subsurface studies is all too often restricted to the correlation of selected stratigraphic horizons. The value of such correlations to sedimentary modeling lies in their definition of three-dimensional surfaces which express the large-scale geometry of sedimentation units. However, the set of correlation surfaces is purely a *topological* skeletal framework, as it is based entirely on depths and geographic coordinates. Explicit *geological* information linked with the magnitudes of the log measurements can be used to infill the body of the framework. The traces of older logs reflect primarily shale content and pore volume and provide crude but effective indicators of gross geological variation. The demands of modern reservoir engineering have stimulated the development of new wireline tools whose measurements are sensitive to mineral and elemental compositions in clastics, carbonates, and shales. These tools are now run commonly and their logs can be transformed to continuous and quantitative profiles of interpreted composition and geochemistry.

The lithodensity-neutron tool combination simultaneously records apparent bulk density, photoelectric absorption, and neutron porosity, together with a conventional gamma-ray measurement. The contrast between the neutron and density curves has been used successfully for a number of years in the distinction of quartz, calcite, and dolomite, as well as the recognition of some evaporite minerals. The more recent determination of photoelectric absorption provides a measure of aggregate atomic number. This is a valuable additional variable in the resolution of complex mineral mixtures. It also appears to be useful in the distinction of clay-mineral facies within shale sequences, although the controlling parameter is probably clay-mineral iron content. The spectral gamma-ray tool partitions the total natural gamma ray flux of the subsurface formation between contributions attributed to isotopes of potassium-40 and the uranium and thorium series. The logs are scaled in units of parts-per-million (uranium and thorium) and percent (potassium). The computation of a thorium-potassium ratio has proved useful in the qualitative distinction between potassium-rich illite/mica/feldspar and potassium-poor kaolinite/smectite/chlorite. A log of thorium/uranium ratio accentuates zones of relative uranium enrichment or impoverishment. This ratio can often be interpreted in terms of redox potential, either due to depositional processes or diagenetic modification.

Graphic profiles of lithofacies and KUT (potassium-uranium-thorium) geochemical facies were generated by computer processing of lithodensity-neutron and spectral gamma-ray logs from two Kansas subsurface sections. The two logged sections were chosen as case-study demonstrations of the great potential of modern wireline logs to be used in conjunction with sedimentary modeling. The first section is from a hydrologic observation well in central Kansas which was drilled through the Cretaceous into the Permian Cedar Hills Formation (fig. 1). A drastic shift on the thorium-potassium ratio log highlights the basal Cretaceous unconformity, caused by the higher feldspar content of the Permian sandstones. Fluctuations of the ratio within the deltaic sandstones and shales of the overlying Dakota Formation appear to be broad reflections of contrasts between illite-rich marine regimes and more kaolinitic freshwater environments. The photoelectric absorption factor is an additional aid in the subdivision of shale facies, probably linked with iron content of different clay minerals. Relatively high uranium zones indicate fixation under reducing conditions which are often marine, as attested by glauconite and other marine indicators seen in the drill-cuttings. Mobilization of uranium under oxidizing conditions in nonmarine and subaerial environments would account for the repetitions of thin uranium-poor zones which characterize much of the Dakota Formation. The repetitive character probably reflects high lateral variability in deltaic facies and interplay between mostly brackish and freshwater regimes. By contrast, the uranium enrichment of the overlying limestones and shales shows a long-term (115-m [380-ft] wavelength) cyclic pattern which is interpreted to be the product of regional transgression/regression alternations on an open-marine shelf.

The second case study is taken from a gas well in southwestern Kansas which penetrated the Permian Chase Group. The section consists of an alternating sequence of carbonates and shales. The carbonates are variable, consisting of dolomites with some anhydrite, ranging to limestones, which can have a high chert content. Processing of the lithodensity-neutron log combination generated continuous composition profiles of dolomite, chert, calcite, anhydrite, and shale. The thorium-potassium ratio log indicates that the shales are primarily illitic in character. Core studies classified subdivisions in terms of the depositional environments, ranging from shallow marine to supratidal, and these are ordered in distinctive transgressive/regressive sequences. The thorium-uranium ratio curve shows good concordance with the classification cyclic pattern, oscillating between the extremes of relatively enhanced uranium marine limestones and uranium-poor supratidal shales. However, realistic geochemical interpretations must incorporate considerations of the role of diagenesis, especially linked with dolomitization.

The two case studies provide useful demonstrations of the kind of geological information that is now available from computer processing of modern wireline logs. The data can be incorporated in either forward- or reverse-modeling modes in the simulation and analysis of sedimentary sequences. In addition to their geologic-information content, they have the useful property of being quantitative, and so they can be used easily as input for numerical-modeling programs. In addition, the logs provide lengthy and continuous records of sections of interest. This contrasts with many traditional sources of geological observations which are often short, prosaic, and discontinuous.

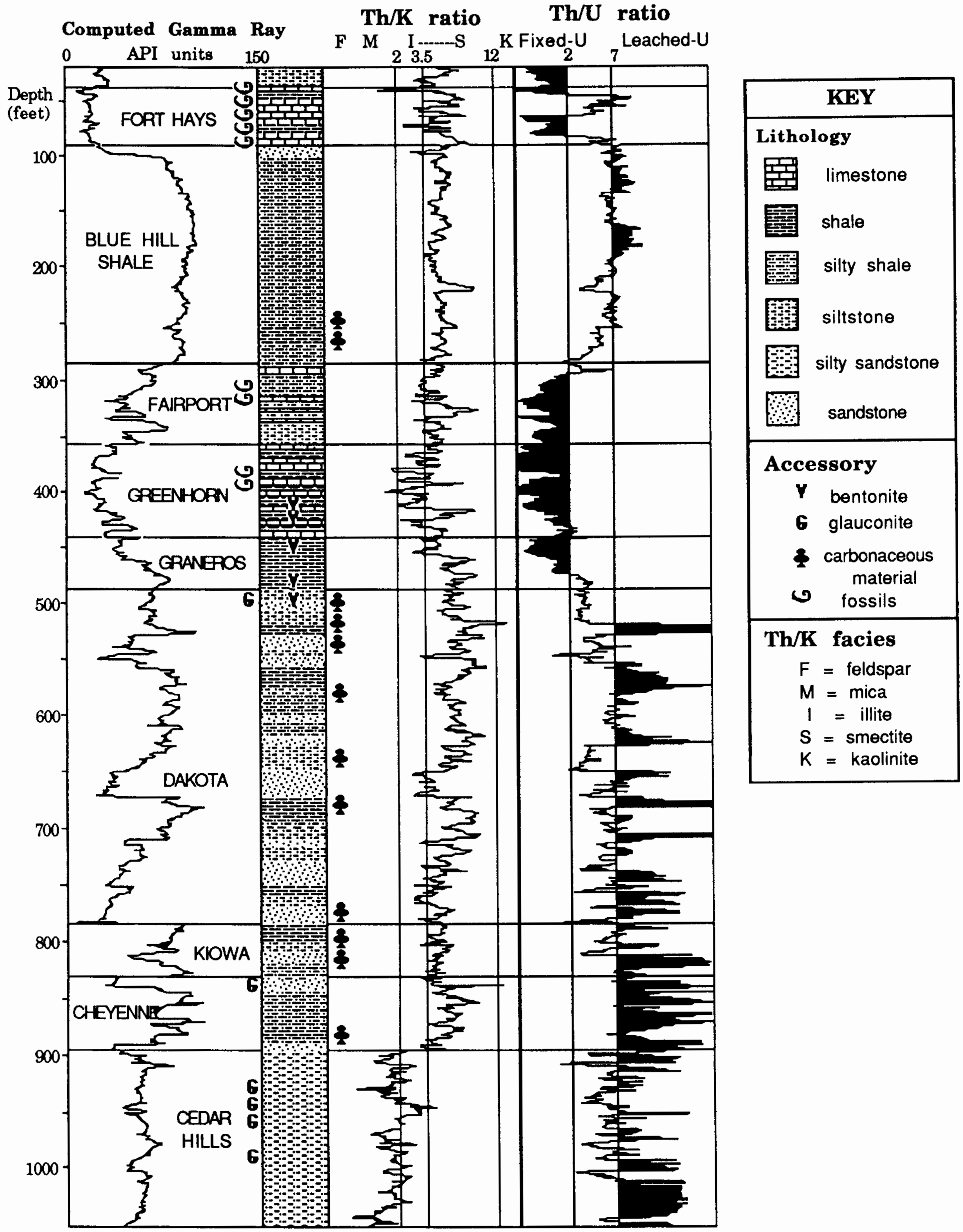

FIGURE 1—Gamma-ray, lithology, and thorium-potassium-uranium ratio logs of a Permian to Cretaceous section in Ellis County, Kansas.

Modeling diagenetic styles—an integral part of basin analysis

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Basin analysis has its roots in the first half of the twentieth century when tectonic settings were shown to control the compositions of rock associations. The importance of diagenesis became apparent as petroleum-exploration efforts expanded into deep basins and into relatively unstable potential reservoir-rock facies. Research dealing with the role of diagenesis in basin analysis is proceeding along several lines, including: 1) determination of the effects of provenance on sandstone mineralogy and on diagenetic style, 2) delineation of the relationships between depositional settings and sandstone-reservoir characteristics, and 3) construction of integrated diagenetic models that can be used to predict rock properties.

Diagenetic styles are controlled by eight interactive variables: 1) sediment compositions, 2) temperature histories, 3) rates of subsidence (pressure histories), 4) age (time that sediments have been exposed to other variables), 5) sediment textures, 6) sediment-body structures (internal architectures), 7) sediment-body external geometries, and 8) fluid-chemistry histories. Each of these variables is affected by variations in the other variables, and each is an integral part of any basin analysis. Thus, diagenesis studies are intimately intertwined with basin analysis.

Tectonic and paleogeographic settings determine the primary compositions of both chemical and siliciclastic sediments. Siliciclastic provenances are reflected by the mineralogy of sandstones. The source or sources of sediment in sandstone units within genetic sequences and the contribution of each source need to be evaluated in terms of quantitative effects on the various diagenetic styles observed. Diagenetic studies are currently underway in the Pennsylvanian of the midcontinent and the Cretaceous of the Western Interior. Composition and reservoir properties of sandstone units in these two realms were controlled by provenance, sedimentary processes, and diagenetic alterations. These interrelated parameters were affected by sea-level fluctuations in both realms.

Pennsylvanian sandstones are being studied by using a combination of petrographic and geochemical techniques. These include light microscopic examination, cathodoluminescence (CL), SEM, TEM, and x-ray microanalysis techniques. CL analysis is used to help segregate mineral grains into different compositional classes. Microanalytic techniques are used to identify and quantify elemental differences. These analyses have indicated that some quartz arenites are diagenetic in origin, having been deposited as subarkoses that subsequently underwent feldspar dissolution. Core samples from Iowa are being used to study the origins of mineral grains, such as feldspars and micas, by subjecting them to rubidium/strontium (Rb/Sr) isotopic analysis in order to match isotopic ratios with potential siliciclastic sources. Matches made in this manner are used with sedimentologic data to reconstruct sediment-transport pathways between sources and basin-facies tracts, and to relate mineral grains in sandstones to potential siliciclastic sources.

Similar analyses of Cretaceous sandstones, such as the Parkman and Shannon formations of Wyoming, have shown that reservoir properties can be predicted by relating diagenetic styles to tectonic and sedimentary settings. For example, marine sandstones of the Parkman deltaic-shelf system, which interfinger with marine shales, have early diagenetic chlorite coatings on quartz grains that retarded later mineral precipitation resulting in the preservation of reservoir properties. Sandstones in more proximal positions that are not in contact with the shales lack these coatings and were later pervasively cemented with silica. Nonmarine sandstones in this system that were exposed to acidic waters in an organic-rich fluvial setting have kaolinite pore fillings probably derived from dissolution of feldspars and micas.

Once paleoenvironmental interpretations are made and cyclic sedimentary sequences are delineated, diagenetic styles can be interpreted with respect to cyclic changes in sea level. Early diagenetic processes are evaluated in terms of chemical reactions that would take place between original sediment pore waters inferred to be present in each environment and both inorganic (mineralogical) and organic componenets of sands and surrounding muds. Distributions and concentrations of ionic components in sediment pore fluids are critical variables that must be considered in any diagenetic model. For example, some Pennsylvanian fluvial sandstones in the midcontinent show evidence of early feldspar dissolution. These phenomena resulted from the circulation of low pH, organic-rich waters through a moderately open hydrologic system. As burial conditions vary and reactions take place, dissolution, precipitation, and mineral alterations proceed at rates determined by temperatures, resident times, and ionic concentrations.

Petrographic characteristics are correlated statistically with paleodepositional settings determined from the mapping and cross sectioning of outcrop, well-core, and geophysical well-log data. Paleoenvironmental interpretations are made by integrating all stratigraphic, sedimentologic, and paleontologic data available for the basin being studied. Genesis and delineation of cyclic sedimentary sequences allow diagenetic styles to be interpreted with respect to cyclic changes in sea level. Early diagenetic processes are evaluated in terms of chemical reactions that would take place between original sediment pore waters inferred to be present in each environment and both inorganic (mineralogical) and organic components of sands and surrounding muds. Distributions and concentrations of ionic components in sediment pore fluids are critical variables that must be considered in any diagenetic model. As burial conditions vary and reactions take place, dissolution, precipitation, and mineral alterations proceed at rates determined by these conditions and ionic concentrations.

With the use of modern settings as partial analogs, sedimentologic and petrographic data can be used to reconstruct sandstone architectures and original fluid chemistries. Subsidence histories and sea-level fluctuations are then used to reconstruct geochemical histories of each sandstone body within a time-temperature basin-setting framework. These geochemical and hydrogeological reconstructions are required to establish geochemical schemes for each paleodepositional setting. As more insight is gained into the relationships between tectonic settings, depositional settings, and diagenetic styles, geohistory analysis and backstripping methods will play increasingly important roles in basin analysis. The volumes of data and complexities of relationships between data sets will require computer-based data-handling systems.

Diagenetic modeling is an integrative process because each of the variables interacts with the other variables in a complex manner so that no single aspect can be accurately isolated. Artificial intelligence in the form of expert systems is ideally suited for this type of modeling because of its abilities to integrate large amounts of data from many sources and to iteratively calculate the simultaneous influences of multiple processes upon a sedimentary system during successive time intervals. Once models are generated for sandstones from various paleodepositional settings and cyclic positions, they can be used to predict reservoir qualities, such as porosity and permeability. A complete basin analysis designed to produce models for predictive purposes must include diagenesis because alteration of rock properties can vary from nil to complete recrystallization, removal, or replacement during the history of a basin.

Diagenetic responses to sea-level change—integration of field, stable-isotope, paleosol, and cement-stratigraphy research to determine history and magnitude of sea-level fluctuation

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Developing realistic models of sedimentary systems depends on constraining the controlling variables. One important variable is the history and magnitude of relative sea-level change. During a low stand in sea level, shallow-water carbonate sediments commonly are exposed subaerially and subjected to diagenesis by meteoric fluids. Identification of surfaces on which subaerial exposure has occurred and the paleotopography along these surfaces helps to reveal the history and magnitude of sea-level change. Paleosols, stable-isotopic shifts, and cement-stratigraphic discontinuities are useful indicators for identifying ancient surfaces of subaerial exposure.

A good example of the utility of paleosols is the Pennsylvanian Holder Formation of southern New Mexico, which consists of about 20 carbonate-siliciclastic cycles deposited on the edge of the Pedernal uplift. The limestone units in the cycles show evidence of shallowing upward, but for the most part, appear to have been deposited entirely in the subtidal realm. For many cycles, paleosols cap the carbonate units. Rhizoliths, tangential needle fibers of calcite, alveolar texture, ribbon spar, irregular coatings on grains, micritized grains, glaebules, desiccation cracks, and laminated crusts provide good evidence of paleosols and thus indicate repeated subaerial exposure during deposition of the Holder. As most of the paleosols are developed on subtidal carbonate rocks, simple aggradation into the subaerial realm must have caused subaerial exposure; a relative fall in sea level is required. Some paleosols are laterally continuous and can be traced from the shelf to more basinal positions. Onlapping relationships of overlying beds and original topography in bioherms reflect 30–50 m (99–165 ft) of paleotopography on marine rocks capped by a single paleosol, indicating a relative fall in sea level of at least 30–50 m (99–165 ft; Goldstein, 1988a).

Subaerial exposure, however, is not always recorded unambiguously in the stratigraphic record. Paleosols may be eroded during exposure or subsequent transgression. Meteoric diagenesis associated with subaerial exposure may occur well below the actual exposure surface. Features resembling paleosols may occur at the water table and paleokarst may occur far below the subaerial surface.

Stable isotopic analysis of whole-rock samples commonly is used to identify ancient surfaces of exposure. The method, developed by Allan and Matthews (1982), predicts that stabilization of marine-carbonate sediment in the subaerial realm could yield a light-carbon signature from soil-gas CO_2, a heavy-oxygen signature from evaporation, and an overall shift in oxygen isotopic composition because of different diagenetic histories across the surface. Whole-rock samples across paleosol-capped cycles of the Holder Formation provide data by which this method can be evaluated. The light carbon shift is not consistently present, the heavy oxygen signal is missing, and overall oxygen shifts across the surfaces of subaerial exposure are absent (fig.1). The light-carbon and heavy-oxygen signatures are present, however, in soil-precipitated microcomponents. These data suggest that the whole-rock isotopic method for subaerial surface identification should be supplemented with petrographic observations and isotopic data on soil-precipitated microcomponents.

When cyclically deposited stratigraphic units are consecutively subjected to subaerial exposure, infiltration of meteoric water may result in low-Mg calcite cementation. Low-Mg calcite cement can provide a record of the history of subaerial exposure, which in turn, allows interpretation of the history of sea-level change. Obvious indicators of subaerial exposure are calcite cements with gravity-asymmetric or meniscus fabrics. Cement stratigraphy of cathodoluminescent zonation in calcite may provide a more subtle record of subaerial exposure. Cross-cutting relationships are essential to show that cement zones are related to events of subaerial exposure. Merely tracing of cathodoluminescent zones relative to stratigraphic surfaces may be misleading because of the complexities of paleoaquifer chemistry.

In calcite cements of the Holder Formation limestones, cross-cutting relationships with paleosol features, early fractures, and clast boundaries in intraformational conglomerate relate zones of calcite cement to events of subaerial exposure. Vertical tracing of different sequences of cement zones indicates at least 15 events of subaerial exposure of limestones. The cements are best developed in a shelf-crest setting and tend to die out in a basinal direction (Goldstein, 1988b). Sandstones directly underlying limestones capped by surfaces of subaerial exposure may contain early meteoric calcite cement that correlates with the cements in limestones. In contrast, subaerial exposure in the clastic phase of a cycle does not result in calcite cementation of underlying limestones. Subaerial exposure of limestone appears to be required for development of calcite cement in underlying strata (Bowman, 1987).

The Pennsylvanian Lansing–Kansas City groups of northwestern Kansas consist of carbonate-siliciclastic cyclic strata that show evidence of repetitive subaerial exposure (Watney, 1980). Most of the cathodoluminescent cement zones cannot be related to events of subaerial exposure and much cement post-dates compaction. Fluid-inclusion data indicate calcite cementation from brines rather than freshwater (Anderson, 1989). Deposition was in a local paleotopographic low area which was not conducive to development of abundant meteoric calcite cement. Thus, cement stratigraphy in this setting is not closely related to sea-level history.

In contrast, carbonate sediments deposited and exposed on paleotopographic high areas show preferred development of meteoric calcite cements. An example is the Lisburne Group in the Sadlerochit Mountains of northeastern Alaska. During the Pennsylvanian, as many as 40 shallowing-upward carbonate sequences developed in this shelf-crest setting (Carlson, 1987). Major and minor events of subaerial exposure within the Lisburne may have provided meteoric waters that precipitated nonferroan calcite cement with complex cathodoluminescent zonation. The upper limit of early cement zones commonly coincides with the tops of shallowing-upward sequences. Upward pinchouts of zoned calcite cement also occur at major lithologic discontinuities in which rocks containing *Microcodium* (indicate subaerial exposure) bound different types of shallowing-upward sequences. These early cements commonly occlude as much as 50% of the original porosity and are associated with uncompacted textures. Some cement zones can be traced for less than 10 m (33 ft), whereas others range over stratigraphic intervals of up to 70 m (231 ft). Further research will seek cross-cutting relationships to better relate cementation to events of subaerial exposure. Discontinuities in cement zonation can be used as a guide for locating potential ancient surfaces of subaerial exposure and interpreting history of sea-level change.

Cement stratigraphy, stable-isotope trends, and paleosols provide useful diagenetic evidence of subaerial exposure that, when applied properly, may help constrain history and magnitude of sea-level change.

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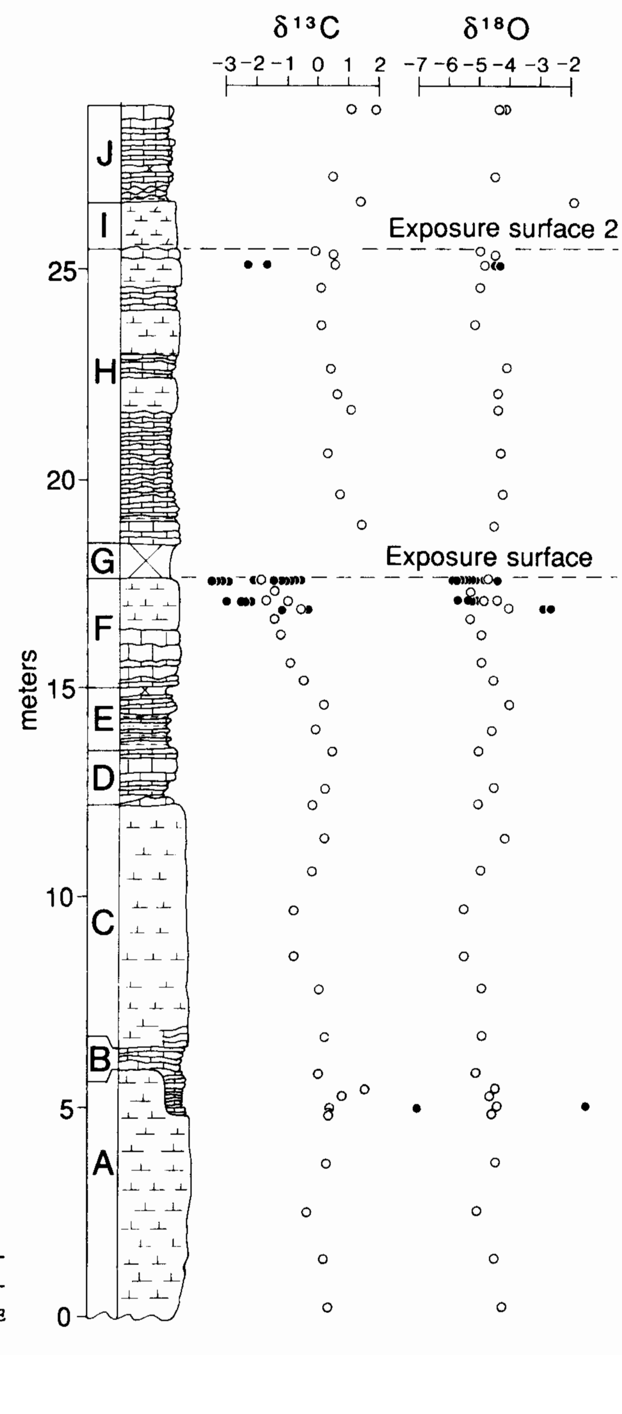

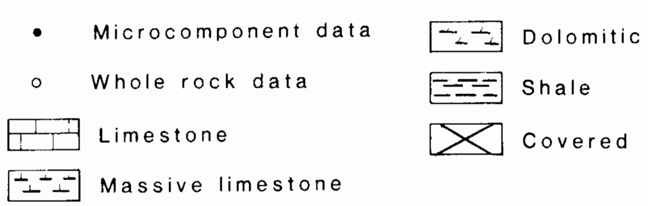

FIGURE 1—STABLE-ISOTOPIC COMPOSITION OF SOIL-FORMED MICROCOMPONENT AND WHOLE-ROCK SAMPLES RELATIVE TO STRATIGRAPHIC POSITION OF TWO SURFACES OF SUBAERIAL EXPOSURE IN THE HOLDER FORMATION.

Paleontological communities in sedimentary modeling

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Since the mid-1960's, when high-speed, digital computers enabled sedimentary geologists to begin thinking about modeling, a concurrent but more or less unrelated revitalization of paleontology has produced significant advances in our understanding of fossils and the ancient communities of which they were a part. Among other effects of the revitalization has been an increased interest in *paleobiology*, the biology of ancient organisms. Now fewer paleontologists than in the past study biostratigraphy, and paleontologists new to the profession are likely to concern themselves with paleoecology, taphonomy, evolution, or extinction.

Paleontology has advanced on a broad front in the past two and a half decades. Such topics as taphonomy, time averaging, temporal resolution, species richness and diversity, constructional morphology, punctuated equilibrium, community evolution, competition theory, and extinction, now a part of every paleontologist's tool kit, had scarcely been thought of when the era of modeling began (fig. 1A). Because of this emphasis on paleobiology, however, advances in paleontology that are directly applicable to sedimentary modeling are sometimes not readily available to sedimentologists, especially those interested primarily in modeling physical processes. My goal, emphasizing ancient communities, is to summarize some of the aspects of paleontology that can be incorporated into sedimentary models. I set this goal in the belief that sedimentary models and discussions of sedimentology or stratigraphy are incomplete unless they incorporate information from paleontology.

From the plethora of definitions of *biological community* (fig. 1B) one can distill the essence: communities comprise groups of organisms that live together and interact in various ways and to varying degrees (Kauffman and Scott, 1976; Strong et al., 1984). The interaction may include, but is not limited to, transfer of energy among trophic groups. Until recently, many ecologists judged that communities were structured by competition between species (McIntosh, 1987), and clear-cut instances of such competition have been observed (Smythe, 1986). It is now evident, however, that most of the competition in communities is between conspecific organisms. Moreover, other kinds of interactions are at least as important as competition (Price, 1984), and in many communities one searches in vain for conclusive evidence of the impact of interspecific competition (e.g., Price et al., 1984).

Changes that have taken place in *paleocommunities*, biological communities from the geological past (Scott and West, 1976), may be considered at various time scales (fig. 1C). Short-term changes took place over a few days or weeks, perhaps in response to short-term sedimentological events. Long-term changes may have taken as long as a geological period (see, e. g., Fagerstrom, 1987). Neglecting information about the relevant paleocommunities at any time scale will have a cost to a sedimentary model that is expressed in precision, realism, or generality (Levins, 1966; Schopf, 1972).

Understanding both qualitative and quantitative changes that have taken place in paleocommunities is complicated by three factors: taphonomy, time averaging, and temporal resolution in the stratigraphic record (fig. 1D). *Taphonomy*, while it tells us a lot about sedimentary processes, results in loss of paleobiological information because many organisms are selectively removed from the subfossil or fossil record by taphonomic processes (Lawrence, 1968, 1971; Kidwell and Behrensmeyer, 1988). *Time averaging*, caused by bioturbation, slow rates of sedimentation, and coarse sampling, obscures our understanding of communities by mixing organisms that did not live together (Walker and Bambach, 1971; Fursich, 1978). Finally, lack of *temporal resolution*, often a product of time averaging, means that whole classes of interesting and important, short-term, biological properties of ancient communities cannot be resolved in much of the sedimentary record (Schindel, 1980; Sadler, 1981).

Short-term changes in species richness and diversity and the whole process of succession (Connell and Slatyer, 1977) are typically impossible to resolve in much of the fossil record (Walker and Bambach, 1971). The causative environmental changes, however, are sometimes readily apparent from the sedimentological record. Pitfalls include expecting all important environmental changes that were important to organisms to have been recorded in the sedimentary rock and, conversely, expecting all sedimentological changes to have been important to organisms.

Long-term changes in species richness and diversity, if they were not taphonomically induced, are likely to have resulted from community evolution and environmental tracking by organisms or communities of organisms (Brondos and Kaesler, 1976). In principle, *community evolution*, the long-term, irreversible, temporal changes in the structure and composition of a community, can be tracked through thick sections of sedimentary rock such as occur in the late Paleozoic rocks of the midcontinent (Moore, 1964). The replacement of one species by another that results in community evolution (fig. 1E) does not imply that the two species are necessarily closely related nor that niches cannot be split and recombined. Either the precursor, its replacement, or both species may be missing from the fossil record.

Perhaps the most important changes in ancient communities have been mass extinctions (Jablonski, 1986). In recent years the search for the cause of mass extinctions has been intensive. Evidence now suggests that at least some mass extinctions in the geological past have resulted from bolides (McLaren, 1983), but other causes have been suggested as well. Understanding mass extinctions and incorporating them into sedimentary models depend on isolating their causes, and although the periodicity of mass extinctions (Sepkoski and Raup, 1986) may allow them to be fit into sedimentary models, we are a long way from understanding their effects. What kinds of organisms were most likely to have been affected by mass extinctions? What were the concomitant effects on paleocommunities? Has extinction been of such overriding importance that natural selection has been relegated to the role of mere fine tuning? Seeking answers to these questions will occupy paleontologists for the rest of this century (fig. 1F) Their results will impact strongly the work of sedimentary modelers.

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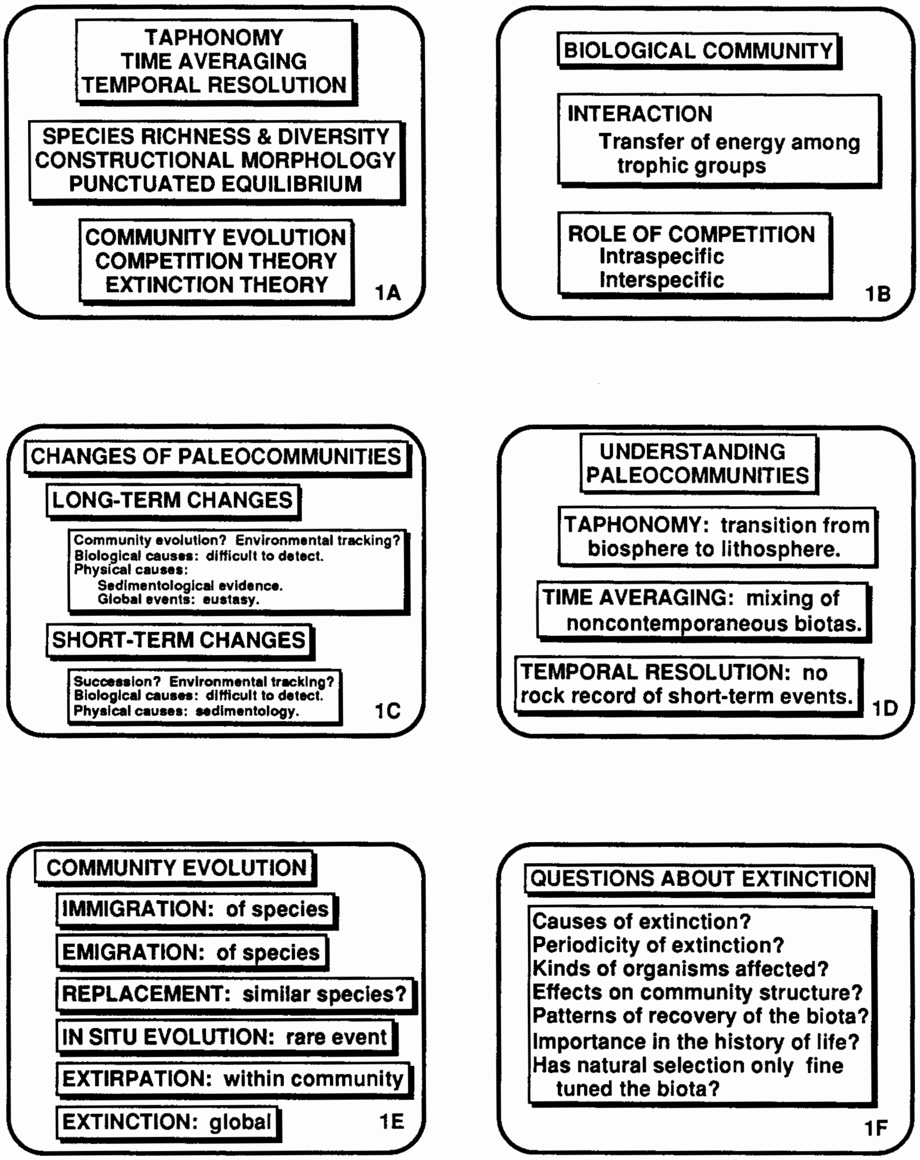

FIGURE 1—A) Paleontological subjects that impinge on modeling of sedimentology and stratigraphy; B) competition and other interaction in biological communities; C) short-term and long-term changes in paleocommunities; D) factors that complicate our understanding of changes in paleocommunities—taphonomy, time averaging, and temporal resolution; E) aspects of community evolution; and F) questions about extinction.

Evidence for glacial-eustatic control over Pennsylvanian cyclothems in midcontinent North America and resulting stratigraphic patterns from shelf to basin—some examples of "ground truth" for computer modeling

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At least 20 Middle/Upper Pennsylvanian major marine cyclothems, each consisting of a thin transgressive limestone, thin offshore dark phosphatic shale, and thick regressive limestone member, extend along outcrop for 600 km (360 mi) from the northern shelf region of Iowa, Nebraska, Missouri, and Kansas, to the basinal region of central Oklahoma. Each is correlated lithostratigraphically throughout a gridwork of long cores in the northern region beneath Pleistocene cover, and in good exposures southward. This correlation is confirmed along the entire outcrop belt biostratigraphically, using a combination of conodonts (fig. 1, tailed diamond symbol), fusulinids (fig. 1, letters T, E), and ammonoids.

Most of the cyclothems are separated by thin terrestrial deposits with paleosols, but only rare deltaic deposits, for about the northern half of the outcrop distance (fig. 1), which rules out shifting of delta lobes as a general control for the vertical alternation of terrestrial and marine deposits across the broad shelf. On the northern shelf, all major cyclothems are traced across the cratonic Forest City basin and over the adjacent Nemaha uplift (core NAC on fig. 1) with little change, which rules out local differential tectonics as a general cause. Presence of Gondwanan glacial deposits at this time, in conjunction with the estimated frequencies of all the Pennsylvanian cycles (major to minor) within the Milankovitch band (20 ka to 400 ka) of earth's orbital parameters (Heckel, 1986), indicate that glacial eustasy is a probable cause. No known tectonic mechanism can raise sea level fast enough (>3 mm/yr; Heckel, 1984) and high enough (>150 m [495 ft]; Heckel, 1977) to outstrip carbonate production and form thin transgressive limestones overlain by subthermocline black shales over such an immense area, then lower sea level a similar amount, and do this repeatedly at a 200–400 ka period. This leaves glacial eustasy as the only reasonable possibility so far known for the main control over the cyclothems.

The major cyclothems are well developed and easily recognized on the northern part of the midcontinent shelf where the marine limestone-shale units are separated from one another by the terrestrial deposits and paleosols (shown by hachures on top of the named limestone-dominated units on fig. 1), indicating complete withdrawal of the sea southward between times of marine inundation. The stratigraphy of all the cyclothems becomes more complex southward, where most intervening terrestrial deposits thicken greatly into deltaic to prodeltaic shales that then thin abruptly basinward. The overlying limestones drape over the thick shales, sometimes thickening basinward as phylloid algal mound complexes. Farther southward, they converge with the top of the underlying limestones over the distal end of the prodeltaic shales (fig. 2A), which has led to major miscorrelations at certain horizons. Correction of the miscorrelations by means of conodont faunas shows that much of the Missourian sequence in east-central to southeastern Kansas displays a southward-dipping slope that prograded basinward in an en echelon fashion of the thickest units, as Van Siclen (1958) described in coeval deposits along the east side of the Midland basin in Texas.

The exact position of the thickening of the various units depended on the relationship of the extent of marine withdrawal to the underlying depositional topography. Prodeltaic shales are thickest just basinward of the maximum extent of withdrawal, particularly over topographic lows that were seaward of an underlying slope. Deltaic to alluvial shales became thickest over topographic lows at times when the sea withdrew further toward the basin center. Regressive limestones became thickest where algal sediment built basinward in the optimal part of the photic zone as sea level dropped. Prodeltaic shale slopes were preserved when sea level rose and stymied delta formation by marine transgression (fig. 2A). Phylloid algal limestone slopes were preserved when sea-level rise elevated the optimal photic zone above the sediment surface (fig. 2B–2b), or when sea-level drop exceeded the rate of outbuilding and subaerially exposed the carbonate slope (fig. 2B–2c), or when an encroaching prodelta overwhelmed carbonate production (fig. 2B–2a). Whether or not prodeltas overwhelmed the algal limestone depended both on an available detrital source nearby, and on enough time during falling or stable sea level for this sediment to prograde into the area in question.

Although computer modeling should test all possible reasonable combinations of potentially controlling parameters, the actual outcrop and subsurface patterns, and the most probable causes inferred therefrom, provide important constraints as to which of the modeling parameters were most likely to have been significant in developing the stratigraphic sequence.

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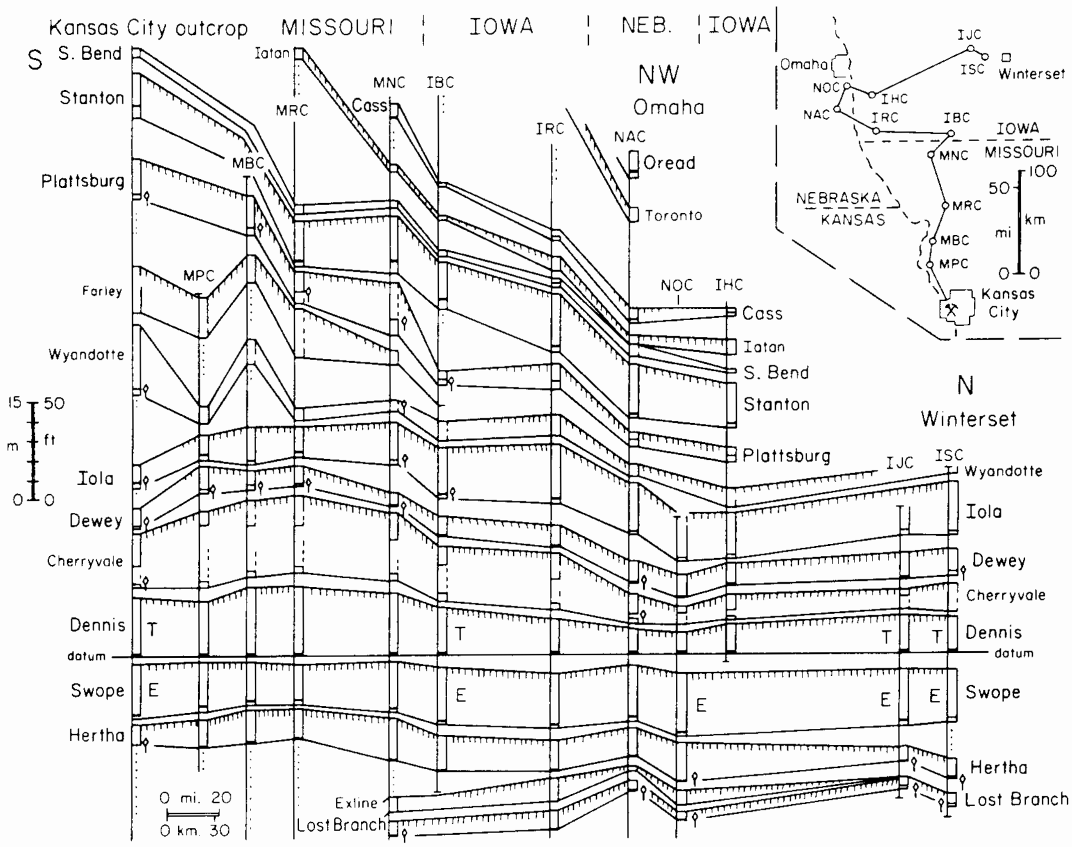

FIGURE 1—NORTHERN SHELFWARD CORRELATION OF CYCLOTHEMS IN LONG CORES.

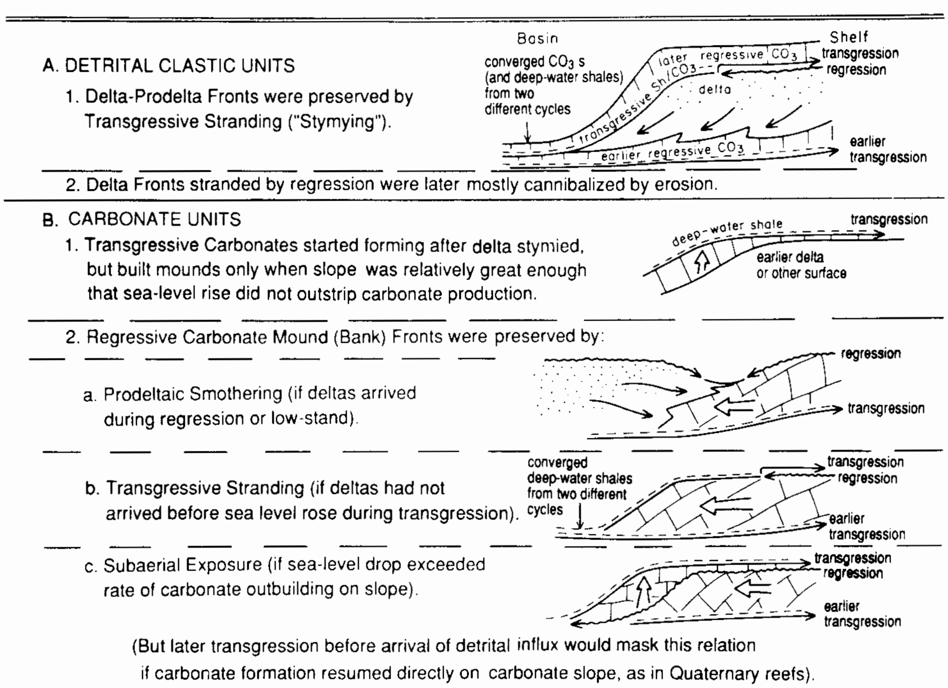

FIGURE 2—MODELS FOR BASINWARD STRATIGRAPHIC RELATIONS OF EUSTATIC CYCLOTHEM UNITS TO STRANDLINE POSITION AT MAXIMUM REGRESSION AND PRESENCE OF DETRITAL INFLUX.

Depositional-sequence analysis and computer simulation of Upper Pennsylvanian (Missourian) strata in the midcontinent United States

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Upper Pennsylvanian (Missourian) mixed carbonate-siliciclastic depositional sequences in the upper midcontinent United States accumulated on ramp and platform settings along margins of the episodically subsiding Arkoma and Anadarko basins. These distinctive, often cyclical deposits are similar to those that accumulated in many parts of the world during the late Paleozoic (Ross and Ross, 1988). Varied allogenic and autogenic causal mechanisms have been proposed to explain these successions; these include glacial eustasy (Heckel, 1986) and tectonic subsidence (Klein and Willard, 1989). Regional subsurface studies in Kansas indicate that changing shelf configuration (differential relief and tectonic subsidence) and eustasy were both important in generation of the Missourian sequences (Watney, 1985; Watney et al., 1988). Computer modeling coupled with sequence-stratigraphic analysis will more rigorously address the relative importance of the causal mechanisms.

The Missourian depositional sequences include several genetic units: a basal flooding unit, a condensed section, a shallowing-upward unit, and, on the middle and upper shelf, regionally significant subaerial exposure surfaces (Watney et al., 1988). The components of these Missourian depositional sequences on the upper carbonate platform closely parallel the lithofacies of the transgressive-regressive "Kansas cyclothem" defined by Heckel (1986), and fifth-order transgressive-regressive cycles of Busch and Rollins (1984). The genetic units within a depositional sequence can vary considerably between siliciclastic-dominated and carbonate-dominated depositional systems in shelf and basin settings. Genetic units can be extended to the concept of systems tracts (Vail, 1987) as information is obtained on stratal geometries and facies through subsurface and surface investigations.

The computer model is a forward (process-response) stratigraphic simulation with input parameters that include sea-level elevation, tectonic subsidence, sedimentation rate, and elevation of the depositional surface. The modular Turbo Pascal program contains special algorithms that modify rate of sedimentation as a function of rate of change of sea level or water depth.

A glacial-eustatic sea-level curve has been approximated for the Missourian using a modified version of the del-O^{18} curve of the Late Pleistocene. The average period of major cycles used is 400 ka, the longest period suggested by Heckel (1986). A maximum amplitude of 110 m (363 ft) is used, which is similar to that of the Pleistocene. Sediment-surface elevations used in modeling range over 50 m (165 ft), as estimated from regional subsurface studies of the northern midcontinent depositional sequences in western Kansas (Watney, 1985).

Output consists of a plot of time versus depth showing the elevations of sea level and the sediment surface, and the subsidence path (fig. 1A). Water depth, sediment thickness, and distinctive genetic units (including flooding units, condensed sections, shallowing-upward units, and subaerial-exposure horizons) can be examined and compared with observed strata. The output also portrays sequence development versus time which is useful in restoring the sequences at various time steps (fig. 1B) or in construction of Wheeler diagrams. Model results are sought which closely reflect empirical, and at this stage of our understanding, conceptual models of shelf sequences (fig. 1C).

Features of the simulated carbonate-dominated depositional sequences that resemble the rock record include 1) thicker sequences toward the basin margins that are characterized by increasingly higher preservation due to lower elevation and longer periods of sediment accumulation, which results in increased resolution of the sedimentary record; 2) low average sediment accumulation rates of the sequences compared to modern sedimentation rates, largely because sediment accumulation is interrupted by significant hiatuses associated with condensed sections and subaerial-exposure surfaces; compaction and dissolution no doubt play a role as well; 3) complex successions of units occur within a depositional sequence due to rapid temporal changes in sediment accommodation, resulting, for example, in repeated genetic units within one depositional sequence; and 4) progressive loss in elevation of the shelf through high subsidence rates coupled with rapid fluctuating sea level results in sustained sediment starvation for parts of the section.

Inverse modeling (transformation of stratigraphic column to processes versus rate profiles) will be required to interpret and model specific sequences observed in the rock record. Coherent signals in estimated rates and magnitude of sedimentary parameters versus time obtained from inverse modeling can be potentially extracted through mathematical and statistical analysis.

Preliminary comparison of two study areas, one in western Kansas and the other in eastern Kansas, reveals contrasting styles of sedimentation and challenges to sequence analysis and modeling. Western Kansas was the site of a broad, carbonate-dominated ramp adjacent to the Anadarko basin, then an active foreland basin. A succession of thick (up to 25 m [83 ft]) oolitic grainstones accumulated on a ramp created by long-term, but episodic, differential tectonic subsidence during the early Missourian (Watney, 1985). The ramp setting reverted occasionally to a platform due to episodic waning subsidence. Progradation of the shoal-water carbonate facies over the ramp formed stacked sedimentary wedges that are exemplified by the Dennis and Swope sequences in the lower Kansas City Group, with each extending over 150 km (90 mi) across the shelf. Estimated relief across this shelfward portion of the ramp amounted to at least 15 m (50 ft; 0.1 m/km [0.3 ft/mi]). A minimum progradation rate of 0.38 m (1.25 ft)/ka is suggested for a 400,000-year sequence period.

A considerable portion of the relief on the ramp was apparently filled in by the wedges of shoal-water carbonates. However, subaerial exposure and an ensuing depositional hiatus that terminated the sequence apparently led to reestablishment of ramp conditions due to increased subsidence toward the Anadarko basin in southwestern Kansas. Estimated average subsidence rates during the Missourian range from less than 0.05 m (0.17 ft)/ka in southern Nebraska to greater than 0.20 to 0.30 m (0.7–1 ft)/ka along the margin of the Anadarko basin in southern Kansas (Kluth, 1986). Computer simulations support the feasibility of these subsidence rates.

The geometries of depositional sequences in the lower Kansas City Group in eastern Kansas appear to be strongly influenced by preexisting depositional topography along margins of broad platform and localized delta lobes (Heckel et al., 1985; Heckel, 1988; French, 1988). Relief and gradient of slopes associated with this topography range from 25 to 30 m (83–99 ft) over a distance of 10–30 km (6–18 mi; 2.5 to 3 m/km [8.3–10 ft/mi] or 25 to 30 times the slope of the western Kansas shelf). While oolitic grainstones are the dominant facies in the progradational wedge in western Kansas, phylloid algal carbonate buildups dominate the narrower progradational or aggradational wedges in many of the cycles in eastern Kansas. In southern Kansas, along the margin of the Arkoma basin, alternating siliciclastic and carbonate aggradation/progradation episodically extended the shelf margin southward beyond an original shelf margin position that occurred along a relatively steep (as compared to western Kansas), basinward-directed slope on the edge of a delta platform in the Pleasanton Group. Subsidence during the early Kansas City interval was minimal during development of the Sniabar and Swope depositional sequences. Increased subsidence during the succeeding Dennis Sequence led to backstepping of the shelf margin over underlying shelf deposits, facilitating accumulation and preservation of apparent parasequences. Computer simulations recreate basinal and lower shelf conditions that correspond to these scenarios by utilizing the best available estimates of sedimentary parameters.

Problems that remain to be resolved in Missourian sequences include establishing the details of internal stratigraphy and obtaining better estimates of accumulation rates, durations, and water depths of sediment accumulation.

Refined computer simulation, coupled with sequence-stratigraphic analysis, will become a tool that can substantially improve our understanding of the controlling parameters on deposition and stratal geometries. Modeling will be useful in constraining and testing these parameters and in increasing the accuracy and precision of geologic interpretations. Once more precise modeling parameters are known, simulations will become useful in the prediction of sequence characteristics related to mineral-resource appraisal.

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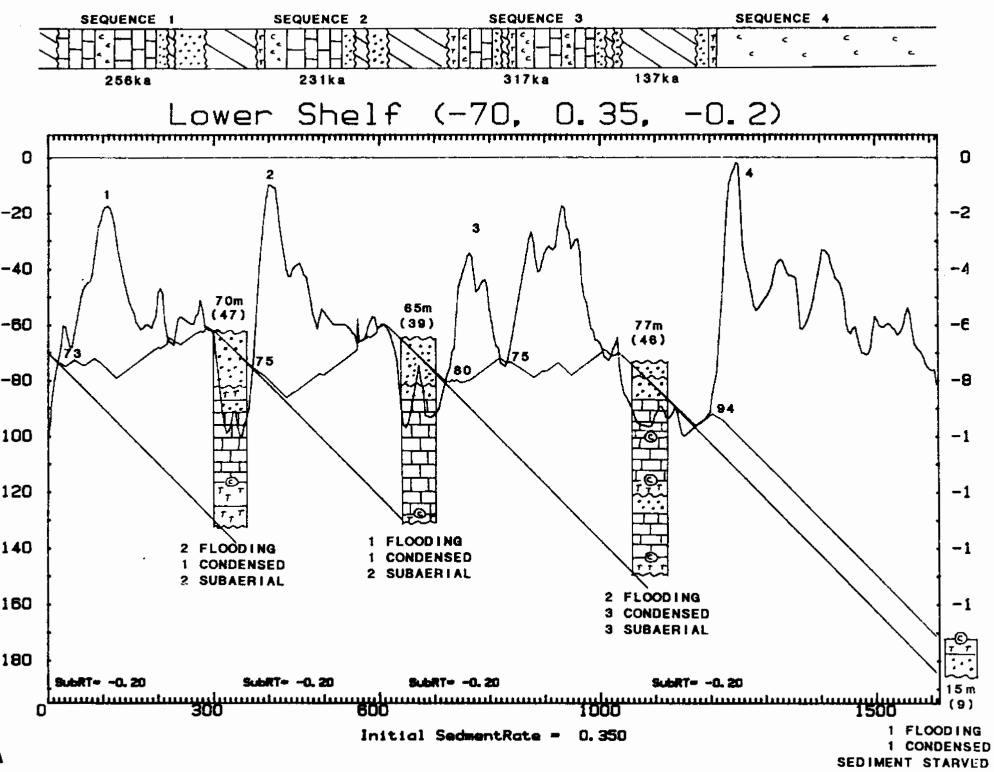
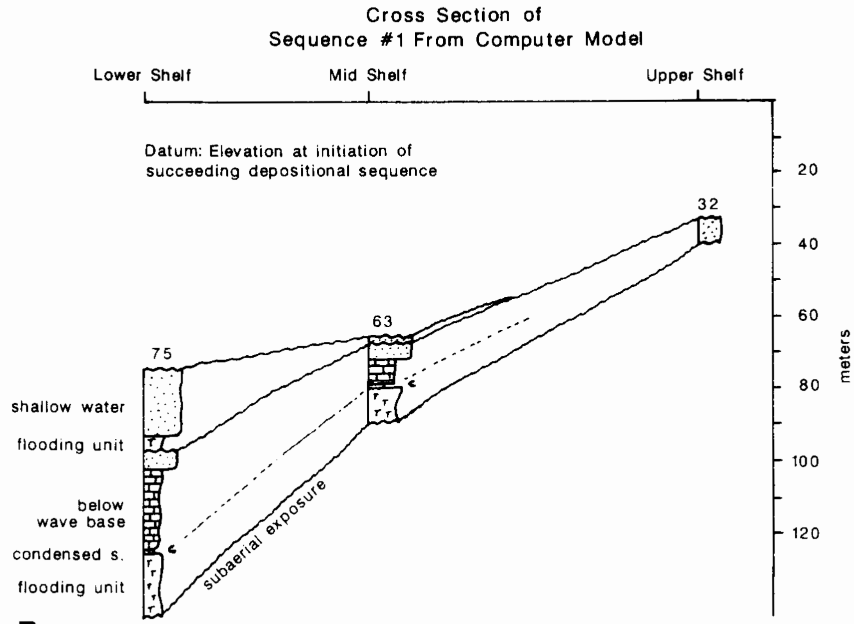
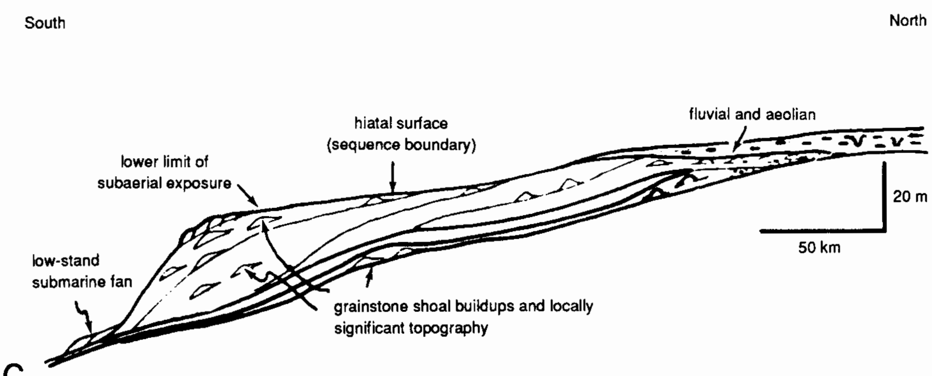


A

FIGURE 1—A) Example of a forward computer model of mid-shelf Pennsylvanian carbonate-dominated depositional sequences deposited in a lower shelf setting. Simulated stratigraphic sequences consist of water deposits, <3 m (10 ft; dot pattern), below wavebase (brick), flooding units (T's), and condensed section (C). Sea-level curve is derived from expansion of Pleistocene del-O^{18} cycles to 400,000 years. Presentation is both in depth (reference elevations in meters) along the vertical axis, and time in thousands of yeras along the horizontal axis; B) Depth cross section defined by elevations derived for simulated sequence #1 including information from model shown in (A). Section shows top lap between upper and lower shelf position and more "high fidelity" record in lower shelf vertical sequence; C) Conceptual model for Dennis sequence for western Kansas showing extent of sequence from landward limit to sediment-starved basinward limit in western Anadarko basin.


Cross Section of
Sequence #1 From Computer Model
Lower Shelf
Mid Shelf
Upper Shelf
Datum: Elevation at initiation of
succeeding depositional sequence
32
63
75
shallow water
flooding unit
below
wave base
condensed s.
flooding unit
subaerial exposure
20
40
60
80
100
120
meters

B


South
North
hiatal surface
(sequence boundary)
fluvial and aeolian
lower limit of
subaerial exposure
20 m
50 km
low-stand
submarine fan
grainstone shoal buildups and locally
significant topography

C

Correlative genetic units (chaetetid intervals) within Marmaton limestones

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The Marmaton Group (Desmoinesian) in Kansas is composed of four limestone formations: the Fort Scott, Pawnee, Altamont, and Lenapah, and four mudstone formations: the Labette, Bandera, Nowata, and Holdenville (fig. 1). The Fort Scott, Altamont, and Lenapah are each composed of three members: a lower limestone, a middle mudrock/shale, and an upper limestone. The Pawnee is more complex (fig. 1). Traditionally, three members have been interpreted as a cyclothem with the lower limestone interpreted as a transgressive phase, the middle unit as a deeper water phase, and the upper limestone as a regressive phase. Knight (1985) recognized two lithostratigraphic packages (cyclothems), rather than one in the Fort Scott. Within all these cyclothems studied to date, it is possible to recognize within these cyclothems correlative genetic sequences which provide a better understanding of the geologic history (Suchy, 1987).

Such genetic sequences are the chaetetid intervals in the Houx–Higginsville Limestone Member of the Fort Scott Limestone and in the Amoret Limestone Member of the Altamont Limestone. Other such genetic sequences may be the chaetetid intervals in the Blackjack Creek Limestone of the Fort Scott Limestone, Myrick Station and Laberdie Limestone Members of the Pawnee Limestone, and Worland Limestone Member of the Altamont Limestone. Chaetetids are unknown from the Lenapah Limestone, although they are known from younger rocks (Missourian) in Texas. Chaetetid-bearing limestones are sought for use in road construction and produce hydrocarbons in Kansas, Oklahoma, and Texas.

Genetic surfaces, and thus genetic sequences, may be recognized by subtle changes in lithologic and biologic characteristics. Taphonomic aspects and features associated with subaerial exposure are particularly useful. Whereas autocyclic surfaces and events may be local, any surfaces and events for which the controlling mechanism is extrabasinal are allocyclic.

Our studies of the Fort Scott and Altamont formations indicate that allocyclic genetic sequences, at a scale smaller than the lithostratigraphic cyclothem, are recognizable and greatly enhance understanding of these intervals. The lithostratigraphic cyclothem itself represents a shorter interval of time (on the order of 300 to 500 ka) than can be recognized biostratigraphically (Rollins et al., in press). We are now able to accurately differentiate genetic sequences within a given cyclothem and with this finer temporal framework and enhanced stratigraphic resolution are better able to reconstruct ancient paleogeography and palaeoceanography. Using these, and similar data, it should also be possible to model more realistic situations for less well studied intervals.

Five transgressive surfaces occur within the "Upper Fort Scott cyclothem" as recognized by Knight (1985). These surfaces delineate four complete and two partial other sixth-order (time frame for each sixth-order unit is approximated at from 50 to 130 ka, Rollins et al., in press) transgressive-regressive units as defined by Busch and Rollins (1984). Chaetetid masses occur in only one of these sixth-order transgressive-regressive units. In the Amoret Limestone Member of the Altamont Limestone, two genetic events (an oncolite bed and an apparent exposure surface) suggest that seafloor topography localized the occurrence of chaetetid "patch reefs" (Voegeli, 1989). Thus, clearly the chaetetids are not randomly distributed in the limestones of the Marmaton Group. Rather, they occur in predictable stratigraphic and paleoecologic sequences that are discernible and predictable using detailed genetic stratigraphy.

Modeling of genetic sequences will benefit greatly from studies such as those reviewed here. As stratigraphic and environmental models are developed, data from such studies must be available for testing and refining the models. Finally, the fullest possible integration of the often subtle changes in lithologic and biologic characteristics are essential for the interpretation and modeling of sedimentary sequences.

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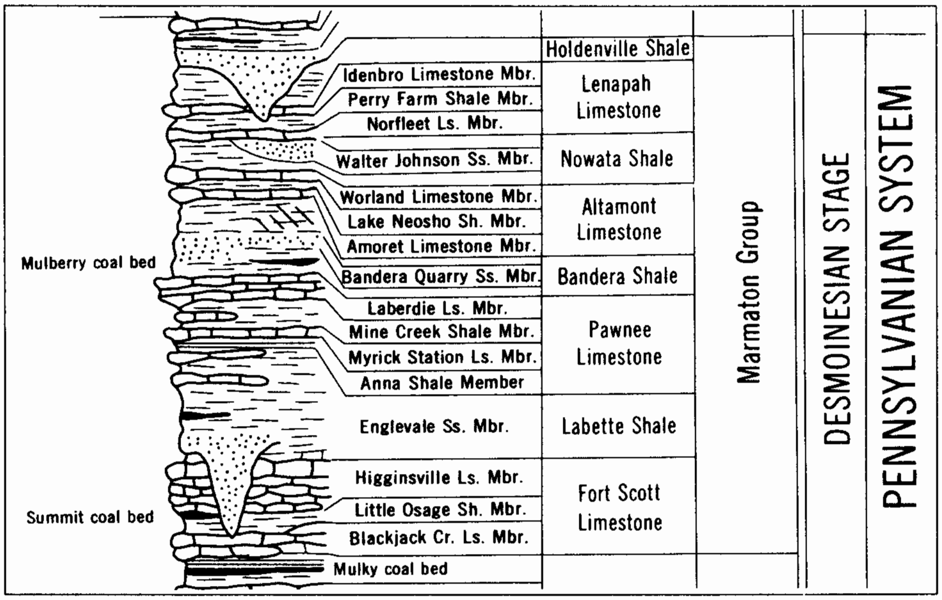

FIGURE 1—Stratigraphic column of the Marmaton Group (modified from Zeller, 1968).

Rates and durations for accumulation of Pennsylvanian black shales in the midwestern United States

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One of the most popular models for deriving metals for enriched black shales is accumulation from contemporary sea water during slow sedimentation in deep anoxic basins. The mechanism is simple, plausible, and actualistic in that it can be demonstrated for modern sediments (Holland, 1979). Ancient anoxic seas may have been similar to the present day Baltic Sea and the Black Sea where the most enriched metal values typically occur in offshore basins (Pilipchuk and Volkov, 1974). Although there are problems with exact analogies, the anoxic-basin model generally works so well that stratigraphic intervals of black shale are often equated with deposition in deep-water, sediment-starved conditions and the shales are referred to as condensed (thin, long duration) sections in sequence stratigraphic literature. However, tremendous amounts of metals (table 1) occur in prominent Pennsylvanian black shales that accumulated rapidly (e.g., the Mecca Shale Member) near a shoreline of siliciclastic deltas and peat swamps that were undergoing marine inundation. Hence metal-rich black shales do not always represent slow rates of sedimentation nor long-term sediment-starved conditions, thus they are not always condensed sections.

Thin, black Pennsylvanian marine shales are almost invariably enriched in organic matter and heavy metals, such as zinc and uranium. Based on three factors (depositional environment, organic matter type, and inorganic geochemistry), Pennsylvanian marine black shales form two distinct, but intergradational varieties (fig. 1): 1) Mecca-type (molybdenum-rich) shales that formed near the ancient (deltaic) shoreline and are enriched in terrestrial organic matter, very enriched in Mo, V, U and Se, but only slightly phosphatic and 2) Heebner-type (molybdenum-poor) shales that formed offshore and contain lesser amounts of terrestrial organic matter, lesser amounts of Mo, V, U and Se, but abundant phosphate. Mecca-type shales yield sulfur-isotope values that are more variable but distinctly richer in ^{34}S than Heebner-type shales and shales from euxinic environments (table 1). Some "transitional" Middle Pennsylvanian shales from the western midcontinent craton have characteristics intermediate between those of Mecca-type and Heebner-type shales.

Heavy-metal concentration and organic-matter accumulation in black shales have been attributed to bottom stagnation due to upwelling onto platforms along continental shelves (Brongersma–Saunders, 1969) and to salinity stratification from freshwater runoff (Demaison and Moore, 1980). In both models the bottom stagnation provides a trap for organic matter under long-term, high-stand, sea-level conditions. Studies of Quaternary sapropels of similar composition are beginning to reveal significant information about types, rates, and duration of processes leading to formation of black shales deposited during glacioeustasy. For example, the most Mo-rich Black Sea sediments formed over a very limited time between 6,000 and 1,600 yrs B.P. (Calvert et al., 1987) near the centers of topographic basins (Pilipchuk and Volkov, 1974). Even allowing for errors in radiometric dates, the formation of Old Black Sea sapropel (~30 cm [12 inches] thick) containing up to 245 ppm Mo and averaging 115 ppm Mo (Pilipchuk and Volkov, 1974) took no more than 4,400 years.

Calculations for the Mecca Shale imply that Mo enrichments would have taken at least 150,000 years of sedimentation (Coveney and Glascock, 1989) *if* they derived Mo solely from Pennsylvanian oceans containing as much Mo as today's sea water. However it is possible, as Zangerl and Richardson (1963) suggested, that the shales and metals were deposited several orders of magnitude more quickly and derived their metals from submarine hydrothermal venting as suggested by Coveney and Glascock (1989).

Significantly, organic matter in metal-rich sediments from the Black Sea is fully marine but accumulated under ephemeral conditions of increased productivity during the relatively rapid transition from Pleistocene lacustrine conditions to the more fully marine conditions of today. Calvert et al. (1987) infer that the most fully developed sapropel (and most metal-rich) sediments were deposited during marine flooding (due to glacial melting) rather than under static euxinic conditions. Calvert et al. (1987) note that increased marine production rates caused by influx of water from the Mediterranean Sea may have been more important than the presence of anoxic waters in the development of Old Black Sea sapropel. Inflowing ocean waters may have added significant amounts of Mo during dynamic flux conditions to the "stagnant" Black Sea basin (Pilipchuk and Volkov, 1974). Other sites of significant sapropel accumulation during Quaternary flooding episodes have been identified on several continental shelves preceding sea-level high stand. These include the eastern Mediterranean and fringes of the shelves near the Amazon and Mississippi River deltas. While water was relatively deep (>100 m [330 ft]), causal mechanisms appear to include enhanced organic productivity and bottom stratification due to increased freshwater runoff or presence of basinal brines. In general, flooding at the high rates and magnitude caused by Quaternary glacioeustasy, coupled with climate perturbations, led to sapropel development.

Evidence for nearshore and exaerobic conditions in midcontinent Pennsylvanian shales come from independent analyses. Molybdenum and some other metals are most abundant near the ancient shoreline in beds containing abundant terrestrial-type organic matter as inferred by pyrolysis gas-chromatography and Rock-Eval analyses (Coveney et al., 1987). Quinby–Hunt et al. (1988) note that dark shales with similar appearances can form under oxic as well as under anoxic conditions and that metal ratios (V:Fe:Mn) reflect depositional environments as defined by oxidation potential and organic productivity. For example, occasionally high Mn concentrations in Pennsylvanian shales imply periodic oxic conditions. From projected rates of burial of fish fossils, Zangerl and Richardson (1963) inferred that the extensive Middle Pennsylvanian Mecca and Logan quarry shales of Indiana were deposited relatively quickly in shallow water as epeiric seas transgressed rapidly across the midwestern United States accumulating debris from coastal peat swamps. Mecca-type shales contain abundant terrestrial-type organic matter (Coveney et al., 1987), erratic sulfur-isotope values (Coveney and Shaffer, 1988) and thin intercalated oxic zones (Maples, 1986), all of which fit rapid deposition near the ancient shoreline and fluctuating water conditions (fig. 1). Heebner-type shales of the Middle and Upper Pennsylvanian (fig. 1) may have accumulated more slowly offshore in deeper waters, but in some cases these beds are associated with local facies transitions suggestive of shallow water or vertically limited anoxic bottom water or slower rates of transgression (e.g., the Eudora shale, Heckel, 1975). In addition, some offshore beds contain significant amounts of terrestrial-type organic matter concentrated at basal positions in the black shale suggesting flooding conditions with a significant component of freshwater runoff (Wenger and Baker, 1986) preserved by rapid burial.

Any model of origin for metal-rich Pennsylvanian shales or their host cyclothems must take into account the differences between Mecca-type and Heebner-type shales. The presence of enriched metal values in near-shore shales, such as the Mecca, invalidates the common assumption that metal-rich shales necessarily reflect slow deposition of a compressed section in a starved basin filled with anoxic waters. The presence of Mecca-type shales in addition to Heebner-type shales in Pennsylvanian cyclothems poses complications in modeling of sedimentation of the late Paleozoic of the Midwest. Data that can provide information on timing and environmental conditions of sapropel formation in glacioeustatic-derived Quaternary depositional sequences need to be examined more systematically worldwide to further quantify parameters in their formation. Moreover, interdisciplinary studies based on regional microstratigraphic sampling of individual black-shale events are needed through varied settings of Pennsylvanian depositional sequences.

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TABLE 1—VALUES FOR SELECTED HEAVY ELEMENTS AND SULFUR-ISOTOPES IN MECCA-TYPE, HEEBNER-TYPE, AND TRANSITIONAL SHALES. Middle Pennsylvanian Mecca-type shales were deposited near an ancient shoreline characterized by abundant peat swamps and deltaic siliciclastic sediments. They contain large amounts of molybdenum (Mo). Upper Pennsylvanian Heebner-type shales, which contain less Mo, formed offshore, probably in relatively deep waters. Values for Mo in transitional Middle Pennsylvanian shales are intermediate.

Sulfur-isotope values (means and standard deviations for hand-picked grains of pyrite and sphalerite) are listed as per mil deviations relative to the Ca˜on Diablo meteorite troilite (CDT) standard (from Coveney and Shaffer, 1988). Values for Mecca-type shale and transitional shale are respectively for the Mecca Shale Member of the Illinois basin and the unnamed shale in the Verdigris Formation of Missouri, Kansas, and Oklahoma. Note that sulfides in the offshore (transitional) shales of the Verdigris are more depleted in ^{34}S than the nearshore Mecca. Typically euxinic shales are very depleted in ^{34}S typically yielding ^{34}S values near -20 to -40 per mil (Ohmoto and Rye, 1979). Hence Mecca-type shales differ isotopically from euxinic beds which are more closely approximated by Heebner-type and transitional beds.

	ppm (g/T)							wt. %			^{34}S (per mil)		
	Mo	V	Mn	Cd	U	Se	Zn	Fe	P_2O_5	C_{org}	Mean		N
Mecca-type	1141	1830	283	69	133	162	1530	4.2	0.3	24.9	-10.2	8.7	15
Transi-tional	287	1127	302	48	54	107	1210	~2	2.6	8.3	-14.5	5.3	10
Heebner-type	90	1050	150	55	55	95	1400	2.6	1.8	14.8	-27.2	3.1	7

Note: Values for Mecca-type shales from Coveney and Glascock (1989) [40 samples of M. Penn. shales from Indiana, Kentucky, and Illinois]; P_2O_5 and Corg from Coveney et al. (1987). Values for transitional shales from Coveney and Glascock (1989) [16 offshore M. Penn. samples from Iowa, Missouri, Kansas, and Oklahoma]; P_2O_5 and Corg from Coveney et al. (1987). Values for Heebner-type shales from Coveney and Glascock (1989), (six U. Penn. black shales from Kansas and Missouri; Corg estimated from loss on ignition at 600°C [1112°F]). Isotope values for black (euxinic) shale from Ohmoto and Rye (1979).

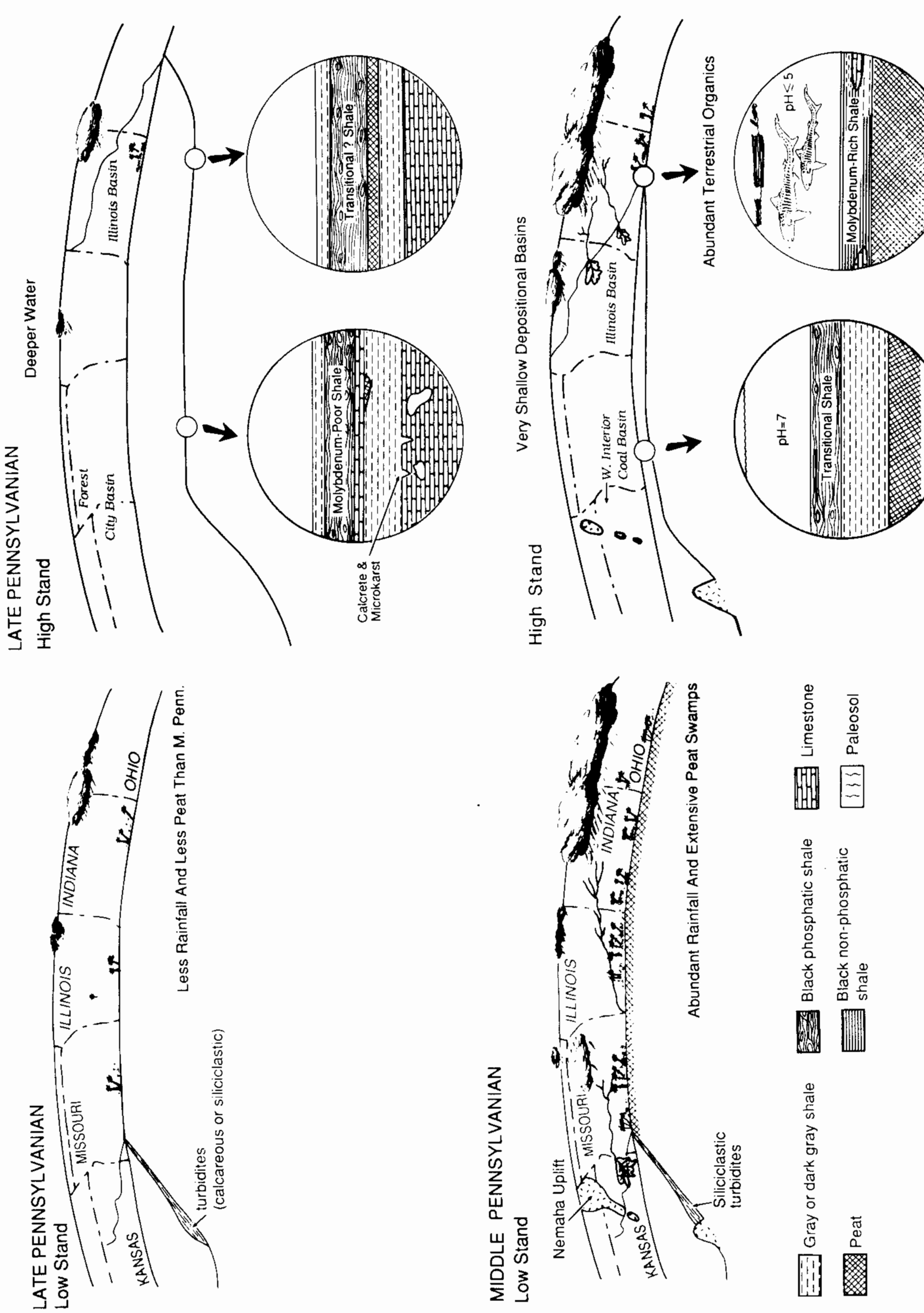

FIGURE 1—Paleogeographic settings of high- and low-stand conditions and resulting stratal succession in Middle and Late Pennsylvanian.

Controls on carbonate deposition on a Pennsylvanian sloping shelf with mixed carbonate-siliciclastic sedimentation

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In Pennsylvanian strata of the midcontinent, cyclic strata consist of mixed carbonate-siliciclastic sediments that were deposited in a single depositional system, which is the basis for a complex and integrated mixed carbonate-siliciclastic depositional model. Pennsylvanian cyclic sediments were deposited primarily on sloping shelf surfaces (carbonate modelers refer to these as distally steepened ramps), on which carbonate sedimentation occurred preferentially on mid- to inner-shelf positions, in moderate to shallow water depths. Carbonate deposition was roughly depth-controlled. Shoreward and outward of the carbonate zone, siliciclastic sediments accumulated, characteristically as clay muds on the outer side and as quartzose sands and clay muds on the shoreward side. Siliciclastic sediment was deposited over the entire shelf, but within the carbonate zone enough carbonate sediment was produced to dilute (but not exclude) siliciclastics and generate carbonate deposits within the otherwise pervasive blanket of siliciclastics. Migration of these bands during changing sea levels over wide continental shelves (up to 100 km [60 mi]) produced the characteristic alternating siliciclastic and carbonate layers of cyclothem sequences.

The depositional relationships of carbonate and siliciclastic sediments on Pennsylvanian shelves is determinable from characteristic lithologic succession in cyclothem deposits. Cyclothems were deposited during times of regularly fluctuating sea levels, and the deepest water deposits occur in the middle of the cyclothem. This deep-water layer is siliciclastic. Both transgressive and regressive hemicycles typically contain a lithologic layer between the deep-water siliciclastics and the shorezone siliciclastics (Heckel, 1984). Consequently, carbonate deposition is more related to water depths on the shelf than to distance from the shoreline, a contradiction of ideas that the outer shelf is the primary area of carbonate deposition. Carbonate layers result from migration of carbonate-generating windows across the shelf.

In the Kansas–Oklahoma and north Texas areas, the depositional surface is known to be a shelf with highland or exposed areas on one side, and shelf-slope break to a basin on the other (Bennison, 1984; Brown et al., 1973). A sloping character for this surface can be inferred from considerations of the best geoetry for cyclothem accumulation, and from comparisons with modern continental shelves. Nearly all modern continental shelves slope basinward, on shelves with mixed carbonate-siliciclastic sedimentation as well as sisliciclastic sedimentation (Ginsburg and James, 1974). Higher rates of sediment accumulation nearshore result in a gradient on the shelf. Shelf gradients can be sustained during times of fluctuating sea levels (such as the Quaternary and Carboniferous), because migrating shorelines move zones of higher and lower sedimentation back and forth across the shelf. On the eastern shelf of Texas, similar inclination of depositional surfaces occurs at many levels despite the sporadic development of local carbonate buildups (Brown et al., 1973). Wide modern shelves along the Gulf of Mexico have gradients ranging from 0.4 to 0.7 m/km (1.3–2.3 ft/mi) over widths of 100–200 km (60–120 mi; for siliciclastic western Gulf and carbonate eastern Gulf), which is a reasonable figure for Pennsylvanian shelves. Such a shelf is fundamentally a ramp surface and may be called a distally steepened ramp. Confusion on terms arises from the practice of carbonate modelers to use shelf to mean a platform surface and ramp to include all graded surfaces, while noncarbonate surfaces with the same graded condition as a ramp (including the shelves that are present on modern continental margins) continue to be called shelves.

Siliciclastic-mud accumulation in deeper waters and depth control on carbonate deposition indicate that large amounts of clay mud moved across the shelf, since the central shale is commonly 5–10 m (17–33 ft) thick in Texas cyclothems. This siliciclastic mud could have bypassed the carbonate zone by transport along specific routes such as areas of deltaic deposition, or by widespread suspension transport over the carbonate sediments during storm episodes. The latter mechanism is more compatible with development of the cyclothem sequence and is a means of continually passing clay and silt across the entire carbonate belt. Many fine- and coarse-grained limestones in cyclothems contain a 20–40% noncarbonate component, and they commonly contain thin shale-parting layers, which represent short-term suppression of carbonate-sediment production. They probably record events when large amounts of siliciclastic sediment moved onto and across the carbonate zone. Boundaries between carbonates and siliciclastics should be gradational, and this is commonly seen, especially in the thicker regressive sequences of cyclothems. Gradations may be confined to 20–30-cm (8–12-inch) intervals (in vertical section) but show the expected lithologic gradient in which the margins are more argillaceous and shell-rich than the platy algal-rich beds within the central parts of the carbonate interval. Within a carbonate-deposition area, siliciclastic input is diluted but not excluded. Coated-grain and ooid-bearing deposits that occur at the tops of regressive carbonate sequences indicate conditions of very low clay-mud input into the ocean, conditions which developed only during times of ocean withdrawal from the shelf surface.

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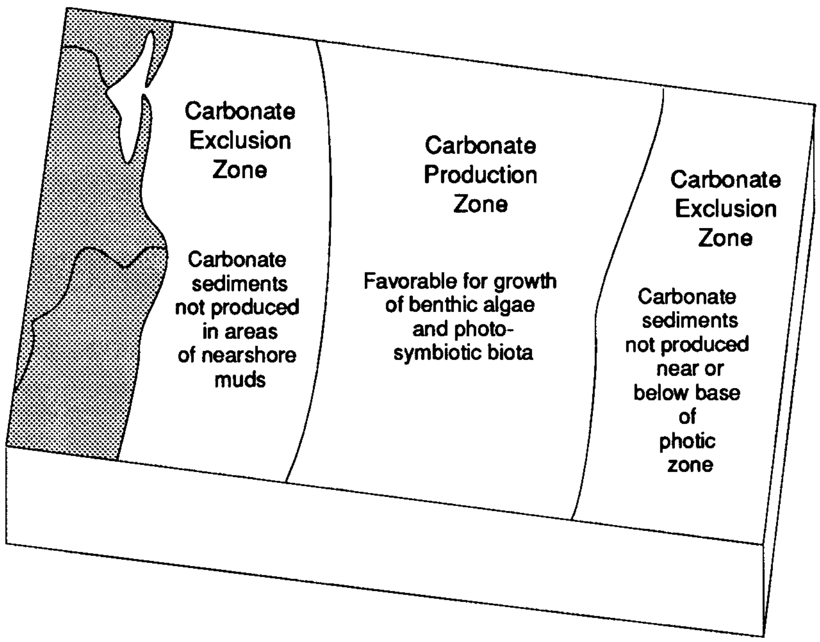

FIGURE 1—Controls on carbonate-sediment productionon an inclined shelf.

Glacial-eustatic control of faunal distribution in Late Pennsylvanian strata of the midcontinent—implications for biostratigraphy and chronostratigraphy

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The glacial-eustatic control mechanism for Late Pennsylvanian cyclothems in the North American midcontinent has been postulated for some time beginning with Wanless and Shepard (1936), and more recently further developed by Shenck (1967), Evans (1967), Heckel (1977, 1980, 1989), Boardman et al. (1984), Boardman and Heckel (1989), and Boardman and Malinky (1985). However, the effects of the glacial-eustatic sea-level fluctuations on the distributions of invertebrate faunas have yet to be adequately investigated.

Preliminary analysis of ammonoids, conodonts, and fusulinids from Late Pennsylvanian strata in both the northern and southern midcontinent (north-central Texas) show profound patterns of faunal distribution that can be best attributed to the repetitive changes in sea-level. Five faunal intervals have been identified from latest Desmoinesian to early Virgilian strata (fig. 1). These faunal intervals are bounded either by major unconformities (Type 1), or major transgressions.

The Desmoinesian–Missourian boundary, corresponding to the boundary between the Latest Desmoinesian and the Early Missourian Faunal Interval, is characterized by several major extinction events including the conodonts *Neognathodus, Idiognathodus delicatus, I. concinnus,* and *I. antiquus*, the ammonoid *Gonioglyphioceras*, the fusulinid *Beedeina*, and the chonetid brachiopod *Mesolobus*. This extinction event separating these two faunal intervals corresponds to a major lowering of sea level (Type 1 unconformity) that also marks the Middle-Upper Pennsylvanian (Oklanian–Kawvian) Series boundary. The initial Missourian transgression (KAV–1) is of an intermediate magnitude and is characterized by relatively few new occurrences. However, among the first occurrences at this boundary include the appearances of the nodose *Idiognathodus* species group including *I. lobatus, I. eccentricus, I. clavulatus, I. sagittalis.* Additionally, strata deposited during this transgression is marked by the appearances of the ammonoid *Pennoceras*, and the gastropod *Plocezyga* (*Plocezyga*) *costata*. Within the Early Missourian Faunal Interval, the largest transgression KAV–3 is marked by the appearances of the conodonts *Gondolella sublanceolata, G. denuda*, and the first species of *Streptognathodus sensu stricto* (*S. cancellosus*). Additionally, the appearance of the fusulinid *Eowaeringella* and the ammonoid *Schistoceras* is noted.

The Early Missourian–Middle Missourian Faunal Interval boundary is marked by a Type 1 unconformity characterized by the extinctions of the fusulinid *Eowaeringella*, the conodonts *I. eccentricus, I. clavulatus, I. sagittalis, Streptognathodus cancellosus* along with the ammonoids *Pennoceras, Eoschistoceras, Bisatoceras*, and *Maximites*. The base of the Middle Missourian Faunal Interval corresponding to the KAV–4 transgression is characterized by the appearance of the fusulinid *Triticites*, conodonts *Streptognathodus confragus, Idiognathodus magnificus*, and *I. toretzianus* as well as the ammonoid *Somoholites kansasensis*. Additionally, this transgression marks a major ecologic shift in the *Idiognathodus–Streptognathodus* plexus. After the KAV–4 transgression, *Streptognathodus* occupies the more nearshore carbonate and terrigenous clastic facies while *Idiognathodus* is more common in the more offshore facies previously characterized by *Neognathodus*. Ammonoid assemblages after the KAV–4 transgression also demonstrate a changeover in generic composition. For the first time, *Schistoceras, Gonioloboceras, Subkargalites*, and *Prouddenites* are dominant components of the faunal association. Within the Middle Missourian Faunal Interval, several faunal changes of lesser magnitude are also noted. Strata deposited during the second major transgression (KAV–5) are characterized by the appearance of the *Streptognathodus elegantulus–S. gracilis–S. excelsus* species group of conodonts, and the first occurrences of the ammonoids *Preshumardites, Paraschumardites*, and *Uddenoceras*. The third major transgression (KAV–6) produced a minor change in conodont and ammonoid faunas, characterized by the striking acme of large lobed *Idiognathodus magnificus*, the appearance of *Streptognathodus oppletus*, and the first occurrences of the ammonoids *Gleboceras* and *Aristoceras*.

The boundary separating the Middle–Upper Missourian Faunal Interval is not characterized by an identifiable Type 1 unconformity and accompanying major extinction horizon. However, this boundary corresponds to a major transgressive event (KAV–10) which produced a plethora of first occurrences including the conodonts *Idiognathodus simulator, Streptognathodus firmus*, and *S. alekseevi*, the first thickly fusiform fusulinid *Triticites primarius*, the ammonoids *Neoglaphyrites, Cardiella*, and ?*Aktubites* n.sp. The regression following the KAV–10 transgression, however, is responsible for the extinction of the *Streptognathodus elegantulus,–S. gracilis–S. excelsus* species group.

The Upper Missourian–Early Virgilian Faunal Interval is typified by a Type 1 unconformity. A major changeover in ammonoid faunas characterizes this boundary, including the appearances of ?*Aktubites stainbrooki, Vidrioceras, Marathonites, Neopronorites, Emilites incertus*, and

Uddenoceras harlani. Additionally, the appearance of the conodont *Streptognathodus zenthus*, and the gastropod *Plocezyga (Plocezyga) obscura* is prominent.

Late Pennsylvanian faunal intervals, as defined herein, are usually marked by Type 1 unconformities, which, although short-lived, are responsible for relatively major and perhaps periodic extinctions. When these extinction events were followed by major transgressions, the faunal-interval boundaries are also marked by extensive speciation events. When these faunal-interval boundaries were followed by minor transgressive intervals, the boundaries are primarily recognized by extinction events only. Faunal-interval boundaries marked by major transgressions without accompanying Type 1 unconformities are recognized primarily by speciation events without major extinctions. Previous interpretations showing Type 1 unconformities at all cyclothemic boundaries are not supported by extensive field evidence nor by faunal data. The use of faunal-extinction data to cross-check interpretations for magnitudes of sea-level drops is a potentially important tool for sequence stratigraphic modeling.

All of the above-described faunal intervals are present in both the northern as well as the southern midcontinent. Additionally, preliminary analysis suggests that they can be recognized in the Illinois basin, Appalachian basin, Marathon uplift, and the southern Urals, suggesting that these faunal intervals are indeed controlled by major glacial-eustatic fluctuations. The potential exists for developing a system of biostratigraphic zones using a combination of ammonoids, conodonts, and fusulinids within a cyclothemic framework that can be employed to effect correlations on a global scale.

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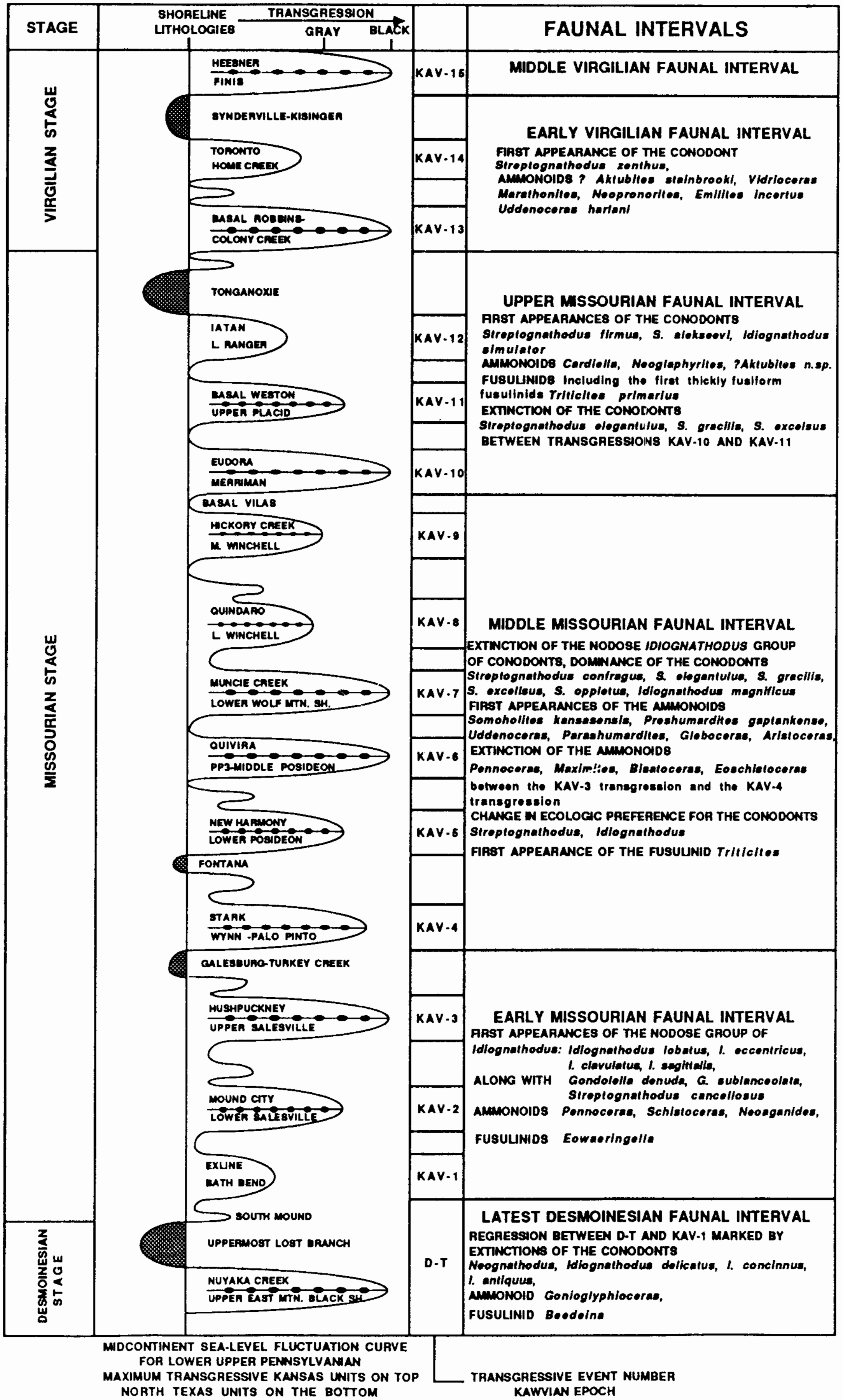
FIGURE 1—Midcontinent sea-level fluctuation curve for lower Upper Pennsylvanian showing maximum transgressive Kansas units on top and the north-central Texas units on the bottom; KAV–1 to KAV–15 represents Kawvian Epoch transgressive event numbers; faunal intervals with appropriate faunal characterization on the right.



STAGE
SHORELINE LITHOLOGIES
TRANSGRESSION
GRAY
BLACK
FAUNAL INTERVALS
VIRGILIAN STAGE
MISSOURIAN STAGE
DESMOINESIAN STAGE
HEEBNER
FINIS
SYNDERVILLE-KISINGER
TORONTO
HOME CREEK
BASAL ROBBINS-
COLONY CREEK
TONGANOXIE
IATAN
L. RANGER
BASAL WESTON
UPPER PLACID
EUDORA
MERRIMAN
BASAL VILAS
HICKORY CREEK
M. WINCHELL
QUINDARO
L. WINCHELL
MUNCIE CREEK
LOWER WOLF MTN. SH.
QUIVIRA
PP3-MIDDLE POSIDEON
NEW HARMONY
LOWER POSIDEON
FONTANA
STARK
WYNN -PALO PINTO
GALESBURG-TURKEY CREEK
HUSHPUCKNEY
UPPER SALESVILLE
MOUND CITY
LOWER SALESVILLE
EXLINE
BATH BEND
SOUTH MOUND
UPPERMOST LOST BRANCH
NUYAKA CREEK
UPPER EAST MTN. BLACK SH.
KAV-15
KAV-14
KAV-13
KAV-12
KAV-11
KAV-10
KAV-9
KAV-8
KAV-7
KAV-6
KAV-5
KAV-4
KAV-3
KAV-2
KAV-1
D-T
MIDDLE VIRGILIAN FAUNAL INTERVAL
EARLY VIRGILIAN FAUNAL INTERVAL
FIRST APPEARANCE OF THE CONODONT
Streptognathodus zenthus,
AMMONOIDS ? Aktubites steinbrooki, Vidrioceras
Marathonites, Neopronorites, Emilites incertus
Uddenoceras harlani
UPPER MISSOURIAN FAUNAL INTERVAL
FIRST APPEARANCES OF THE CONODONTS
Streptognathodus firmus, S. alekseevi, Idiognathodus
simulator
AMMONOIDS Cardiella, Neoglaphyrites, ?Aktubites n.sp.
FUSULINIDS including the first thickly fusiform
fusulinids Triticites primarius
EXTINCTION OF THE CONODONTS
Streptognathodus elegantulus, S. gracilis, S. excelsus
BETWEEN TRANSGRESSIONS KAV-10 AND KAV-11
MIDDLE MISSOURIAN FAUNAL INTERVAL
EXTINCTION OF THE NODOSE IDIOGNATHODUS GROUP
OF CONODONTS, DOMINANCE OF THE CONODONTS
Streptognathodus confragus, S. elegantulus, S. gracilis,
S. excelsus, S. oppletus, Idiognathodus magnificus
FIRST APPEARANCES OF THE AMMONOIDS
Somoholites kansasensis, Preshumardites gaptankense,
Uddenoceras, Parashumardites, Gleboceras, Aristoceras,
EXTINCTION OF THE AMMONOIDS
Pennoceras, Maximites, Bisatoceras, Eoschistoceras
between the KAV-3 transgression and the KAV-4
transgression
CHANGE IN ECOLOGIC PREFERENCE FOR THE CONODONTS
Streptognathodus, Idiognathodus
FIRST APPEARANCE OF THE FUSULINID Triticites
EARLY MISSOURIAN FAUNAL INTERVAL
FIRST APPEARANCES OF THE NODOSE GROUP OF
Idiognathodus: Idiognathodus lobatus, I. eccentricus,
I. clavulatus, I. sagittalis,
ALONG WITH Gondolella denuda, G. sublanceolata,
Streptognathodus cancellosus
AMMONOIDS Pennoceras, Schistoceras, Neoaganides,
FUSULINIDS Eowaeringella
LATEST DESMOINESIAN FAUNAL INTERVAL
REGRESSION BETWEEN D-T AND KAV-1 MARKED BY
EXTINCTIONS OF THE CONODONTS
Neognathodus, Idiognathodus delicatus, I. concinnus,
I. antiquus,
AMMONOID Gonioglyphioceras,
FUSULINID Beedeina
MIDCONTINENT SEA-LEVEL FLUCTUATION CURVE
FOR LOWER UPPER PENNSYLVANIAN
MAXIMUM TRANSGRESSIVE KANSAS UNITS ON TOP
NORTH TEXAS UNITS ON THE BOTTOM
TRANSGRESSIVE EVENT NUMBER
KAWVIAN EPOCH

Coral taxonomy and distribution-enhanced stratigraphic modeling of the Middle Pennsylvanian Sageeyah and Wimer School Limestone Banks, Oklahoma and Kansas

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Corals of the supposedly coeval Sageeyah and Wimer School limestones and accompanying stratigraphic modeling indicate that these strata accumulated at different times in geographically separated areas on the Chautauqua platform. Although both limestones are similar in being dominantly irregularly bedded, brown to gray, algal-lime mudstones to wackestones within the upper Labette Shale, their physical connection in surface outcrops is controversial.

The Sageeyah Limestone is about 20 m (66 ft) thick in the vicinity of its type locality in Rogers County, but northward in Nowata County it thins to less than 0.5 m (1.7 ft) of tidal to subtidal limestones where it is locally truncated by the Childers School Limestone (the basal transgressive member of the Pawnee Limestone), which locally overlies the Lexington coal bed and underclay. About 8–20 m (26–66 ft) stratigraphically below the Pawnee Limestone are outcrops of Wimer School Limestone as much as 2 m (7 ft) thick in Nowata County, but generally less than 1 m (3.3 ft) thick northward in Labette County. Southward, in northernmost Rogers County, stratigraphic modeling indicates that both the Wimer School and Sageeyah limestones are missing because of probable truncation over an east-west-trending pre-Pawnee anticlinal uplift that exceeds 20 m (66 ft) in amplitude and is about 22 km (13 mi) wide.

The Sageeyah Limestone is composed of fossilferous lime mudstones to wackestones, relatively barren siliceous mudstones, and crinoidal grainstones with local interbeds of shallow marine to onshore siliciclastics. Such variations indicate an unstable shelf environment of considerable bathymetric relief prior to the erosional event preceding Pawnee Limestone deposition. Such renewed marine transgressions served to introduce new coral populations on the Chautauqua shelf and proves their value as supplemental chronostratigraphic markers.

Unlike most Middle Pennsylvanian carbonate banks on the Chautauqua platform, the Sageeyah and Wimer School limestones lack anoxic core shales. Both the Wimer School and the Sageeyah limestones contain the shallow water *Lophamplexus–Amandophyllum* Coral Assemblage that, with abundant algae and other invertebrates, characterizes parts of the transgressive, regressive, and transgressive-regressive limestones of Missourian and Virgilian units. The assemblage is not clearly recognized in the Morrowan and Atokan.

The corals of the units studied differ considerably at the species level, supporting evidence that the Sageeyah Limestone is younger than the Wimer School Limestone which was deposited somewhat more distally on the Chautauqua platform. *Amandophyllum* has four species (three—Wimer School; one—Sageeyah). The genus is most common to the intermediate- to shallow-water regressive and transgressive-regressive limestones. A single species of *Sestrophyllum* occurs in each of the units studied. *Sestrophyllum* is most common in the deeper water regressive, transgressive, transgressive-regressive limestones but is the most common dissepimental genus in transgressive limestones. A species of *Orygmophyllum* occurs in Sageeyah. The genus typically occurs in the moderate- to shallow-water limestones in regressive and transgressive carbonates. The Sageeyah caninoid bothrophyllids are represented by two species, one of which is nonfossulate with a weak columella, the other species has the typical bothrophyllid characters of 1) long major septa, 2) a columella that is either a rhopoloid structure or a fusion of major septal ends, and 3) a persistent cardinal fossula. A single Wimer School species is generally similar but is clearly a different species. The Middle and Upper Pennsylvanian caniniids—including the bothrophyllids—occur in moderately deep- to shallow-water regressive and transgressive-regressive limestones.

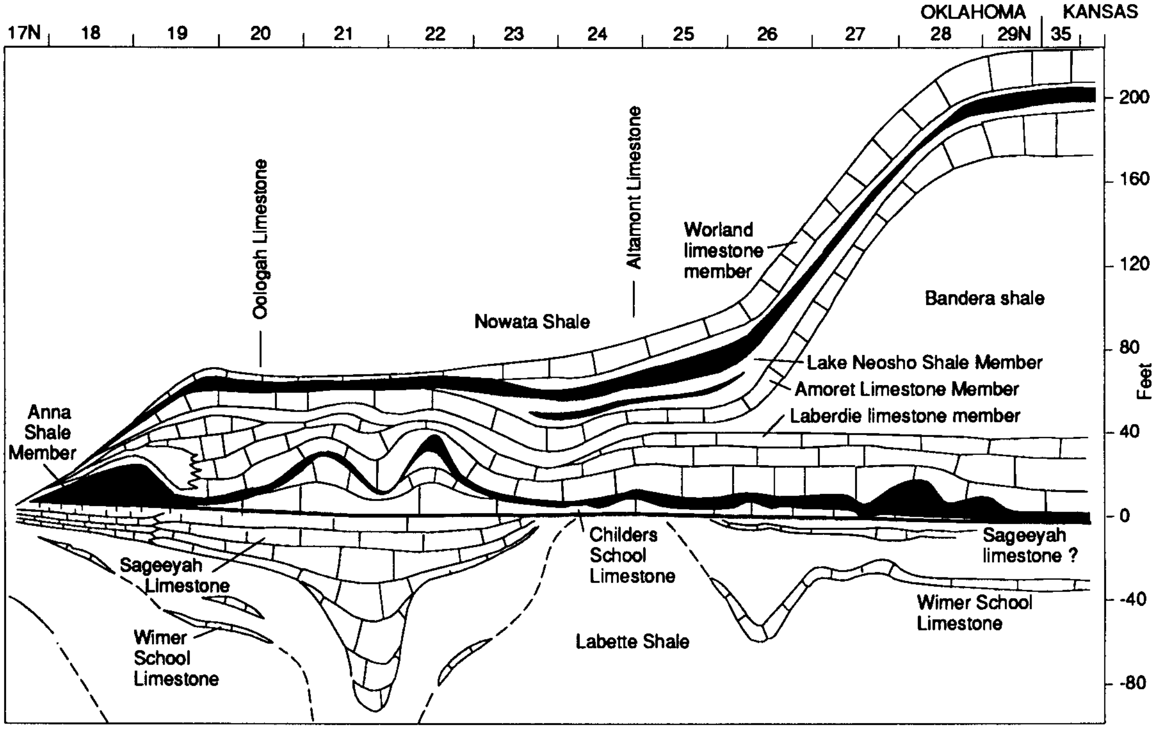

FIGURE 1—SCHEMATIC STRATIGRAPHIC SECTION OF THE WIMER SCHOOL TO ALTAMONT LIMESTONE BANKS AND ASSOCIATED STRATA IN NORTHEAST OKLAHOMA; datum is base of Pawnee Limestone (Childers School Limestone Member).

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