Cyclic stratigraphy, sequence stratigraphy, and stratigraphic modeling from 1964 to 1989: Twenty-five years of progress?

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Abstract The evolution of concept development in stratigraphy between 1964 and 1989 is reviewed by comparing and contrasting the contents of the golden book volume on cyclic stratigraphy (Merriam, 1964) with the present volume. Although separated by more than 25 years, both volumes treat strikingly similar subject material with an emphasis on cyclic stratigraphy, time stratigraphy, and the genetics of basin fill. The collection of papers found in the earlier volume reflects the culmination of work from the most prominent stratigraphers of the 1940's through the early 1960's, a period strongly affected by the principles of sequence stratigraphy. Workers from this generation established many of the fundamental stratigraphic concepts that we view as modern. During the mid-1960's and 1970's emphasis shifted to research on facies models, and with few exceptions stratigraphic cyclicity, sequence stratigraphy, and the genetics of basin fill processes were scarcely considered. With the advent of seismic stratigraphy, in the late 1970's, sequence stratigraphy was reborn, and with it a new generation of researchers focusing on the genetics of basin fill. The earlier book and the present volume reflect two distinct episodes of stratigraphic concept development related to two separate episodes in the history of sequence stratigraphy. In contrast to the authors of the golden book, genetic stratigraphers in the present volume have the advantage of computer-based stratigraphic modeling tools. Armed with these tools and the body of knowledge about facies models accumulated in the past 25 years, the geologic community is poised to make great strides in the development of powerful predictive models for sedimentary basin evolution.

In 1964 a symposium on cyclic sedimentation was sponsored by the Kansas Geological Survey to commemorate the 100th anniversary of the survey's establishment. The result of that symposium was the golden book volume on cyclic sedimentation (Merriam, 1964), a historically significant collection of papers by the leading stratigraphers of the day. Twenty-five years later the Kansas Geological Survey sponsored a second symposium on a similar topic, entitled "Sedimentary Modeling: Computer Simulation of Depositional Sequences" (Franseen and Watney, 1989). The result of that symposium is the present volume. Although separated by 25 years, the two volumes treat strikingly similar subject matter.

To provide a historical perspective on the subject of stratigraphy, I compare and contrast the content of these two volumes, tracking the evolution in stratigraphic thinking that has occurred over the past 25 years. Both volumes deal with stratigraphic cyclicity, demonstrate a sophisticated understanding of the time-stratigraphic relationships in the rocks studied, and attempt to understand the controls on basin fill evolution. Differences lie mainly in the kinds of tools available (namely, computers) and the degree of systematics applied to stratigraphic analyses. Interestingly, the parallels between the volumes speak to two separate episodes in the history of sequence stratigraphy.

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Modern stratigraphy

The present volume represents the state of the art in stratigraphic thinking as reflected in stratigraphic modeling studies. The conceptual framework for these modeling studies has been strongly influenced by sequence stratigraphy, which (1) subdivides stratigraphy into unconformity bounded units (Sloss et al., 1949), (2) emphasizes the characterization of sediment packages within a strict time-stratigraphic framework, and (3) attempts to define a *genetic* relationship among basin fill geometry, unconformity development, and relative sea-level changes [for a review of evolving definitions of sequence stratigraphy, see Van Wagoner et al. (1987, 1990)].

Genetic models of basin fill development describe a predictable relationship between relative sea-level dynamics and depositional cycle subcomponents called systems tracts (Brown and Fisher, 1977; Posamentier et al., 1988). Computer simulations [e.g., Lawrence et al. (1987), Helland–Hansen et al. (1988), Jervey (1988), Lawrence et al. (1990), and Ross (1990)] have allowed workers to model the relative contribution of various processes (eustasy, subsidence, and sediment supply) that control basin fill evolution; and the modeling studies presented in this volume further expand the quantitative expression of the new, genetically oriented sequence stratigraphy.

How different are the concepts of the new sequence stratigraphy, manifested in quantitative stratigraphic models, from the conceptual framework developed and utilized by some of the most prominent stratigraphers of the 1950's and early 1960's? Surprisingly, little has changed in the past 25 years.

Golden book stratigraphy

If we compare modern stratigraphic concepts to the content of the 1964 volume on cyclic sedimentation, the similarities are striking. In fact, many of the fundamental tenets of sequence stratigraphy were laid down by the authors of the golden book (e.g., M. K. Elias, W. C. Krumbein, R. C. Moore, L. L. Sloss, H. R. Wanless, J. M. Weller, and H. E. Wheeler). During the 1940's and 1950's a significant body of work had been assembled to document the existence of regional depositional cycles, so that by the early 1960's the focus of stratigraphic studies shifted from documentation to genetic interpretation. The recognition of repetitive episodes of deposition, often separated by regional unconformity surfaces, was heralded as a significant advance in the subdivision, correlation, and analysis of basin fill sequences [e.g., Wheeler (1958, 1959, 1963) and Sloss (1963, 1964)].

Much of the conceptual framework and terminology that we think of as modern (e.g., sequence stratigraphy, systems tracts, and accommodation space models) had their origins in the studies on midcontinent cyclothems [e.g., Wanless and Weller (1932) and Moore (1936)] and North American Phanerozoic sequences (Sloss et al., 1949; Krumbein and Sloss, 1951; Wheeler, 1963; Sloss, 1963). The abundant evidence arguing for an allogenic base-level control on the late Paleozoic midcontinent sequences was so compelling that the sequences were immediately interpreted as genetic stratigraphic units and termed cyclothems. In the 1930's Moore (1936, p. 29) attempted to define the ideal cyclothem as a model to which other sequences could be compared. Moore proposed a sequence with nine units. Although no complete idealized cyclothem was ever located, the concept was used to determine missing events and to interpret geologic history. Moore's (1964) association of water depth to cyclothem units suggested an orderly relationship between sea level and the development of sedimentary sequences (fig. 1).

Further refinements of the cyclothem model were made by Wheeler and Murray (1957), who related components of the cyclothem to phases of glacial eustasy in a regional cross-sectional context (see their fig. 2), and by Van Siclen (1958, 1964), who described predictable arrangements of facies associations controlled by relative highstands and lowstands of sea level from the Permian basin in West Texas (Van Siclen, 1958) (fig. 2). These two works are an early effort to define a predictable arrangement of the subcomponents of complete sedimentary cycles controlled by base-level oscillations, and as such they are analogous to the systems tracts concept described within the context of the new sequence stratigraphy (Van Wagoner, 1985; Posamentier et al., 1988).

Early workers saw order in cyclically bedded rocks and were fascinated by it. This fascination led many to speculate on the possible causes of cyclicity and unconformity development using arguments and tools similar to those used today. For example, the Fischer plots utilized by Read et al. (this volume) and Goldhammer et al. (this volume) have their origins in a classic paper by Fischer in the 1964 volume. Accommodation space plots, which sum the effects of eustasy and subsidence to produce relative sea-level or base-level curves (Jervey, 1988; Posamentier et al., 1988; Ross, 1990), were clearly evident in the work of Moore (1964, fig. 44). Although hindered by the lack of high-speed computational tools, these early workers clearly contended with the same kinds of questions that are quantitatively addressed by modern workers in this volume.

Sequence stratigraphy reborn

It is apparent that sequence stratigraphy, which emphasizes genesis within a time-stratigraphic framework, was in place by the early 1960's and very much in evidence in the papers of the 1964 volume. Yet with few exceptions [e.g., unconformity recognition (Harms, 1966; McCubbin, 1969; MacKenzie, 1971; Chang, 1975) and time-stratigraphic correlation (Weimer, 1960; Asquith, 1970)], only a limited number of geologists exploited the benefits of this new conceptual framework over the next 15–20 years. Why didn't sequence stratigraphy catch on the first time around, and why did it reemerge in the 1970's with an extraordinary following? The reason for the two-stage development of sequence stratigraphy may be that only a few geologists approached stratigraphy from a broad, regional perspective.

Geologists such as Moore, Sloss, Wanless, and Wheeler and their students discerned time lines using biostratigraphic data collected over large areas. Most other geologists during the 1960's and 1970's worked on geographically restricted problems and, because of new developments in sedimentology [see Reading (1986) for a review], focused on depositional facies models. Consequently, the majority of the geologic community was unable to appreciate the significance of sequence stratigraphy in its application to everyday problems. With few exceptions (Vail and Wilbur, 1966; Vail and Sangree, 1971), stratigraphic cyclicity and the genetics of basin fill processes were scarcely considered.

Sequence stratigraphy was revived in the late 1970's and 1980's with the advent of high-resolution multichannel seismic data, which were utilized predominantly by workers in the petroleum exploration industry [e.g., Vail, Mitchum et al. (1977), Mitchum et al. (1977), Abbott (1987), Bally (1987–1989), and Cross and Lessenger (1988)]. When geologists looked at seismic data, they could see time-stratigraphic relationships, basin fill geometries, and unconformities

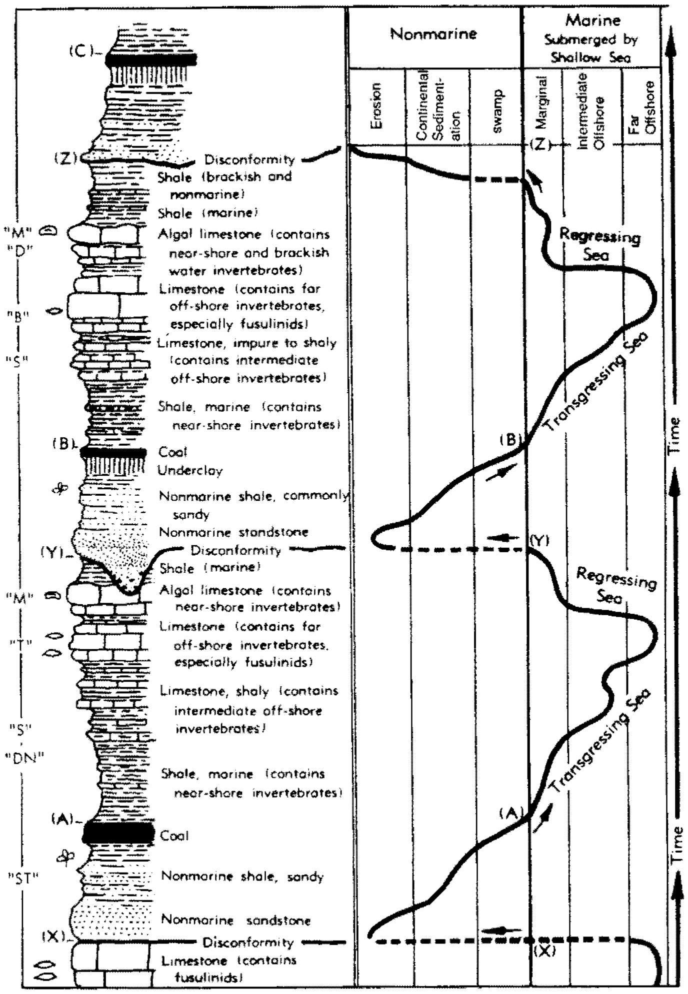

Figure 1. Diagrammatic section of successive cyclothems showing typical lithostratigraphic and biostratigraphic features, accompanied by interpretation of changes in environment with lapse of time [from Moore (1964)].

unobscured by time-transgressive lithostratigraphic information (Vail, Todd, and Sangree, 1977). On a single seismic display time-stratigraphic relationships could be viewed over several tens of miles. The same time-stratigraphic perspective would take a field geologist months or years of regional fieldwork to establish. Suddenly, basin fill architecture on a regional scale was readily apparent. Topset, foreset, and bottomset geometries could be observed to aggrade, prograde, and become incised. Rising base levels were apparent as coastal plain strata onlapping paleotopographic highs. Falling base levels were inferred as coastal plain strata that shifted basinward and onlapped highstand slope surfaces. As a consequence of these observations, the relationships between relative sea level, basin fill geometry, and unconformity development were once again proposed as a unifying concept for stratigraphy, and global eustatic sea-level changes were offered as a means of explaining interregional correlation of stratigraphic cyclicity (Vail, Mitchum, and Thompson, 1977).

Quantification of genetic models

The qualitative observations made possible using seismic data seemed to suggest that basin fill processes could be quantitatively represented and simulated by varying a relatively small set of first-order parameters, namely, eustatic sea level, subsidence, and sediment supply. In contrast, observations made at the outcrop scale are dominated by the effects of second-, third-, and fourth-order processes, such as climate, storms, and tides. The computer simulations created by oil industry workers [e.g., Lawrence et al. (1987, 1990), Jervey (1988), Helland–Hansen et al. (1988), and Ross (1990)] emphasized the rise and fall of relative base-level surfaces to create and destroy (accommodation) space for sediment deposition. The conceptual framework of these computer simulations is nearly identical with the ideas presented by Sloss (1962)—again a suggestion that the sequence stratigraphic approach, which came out of the 1940's and 1950's,

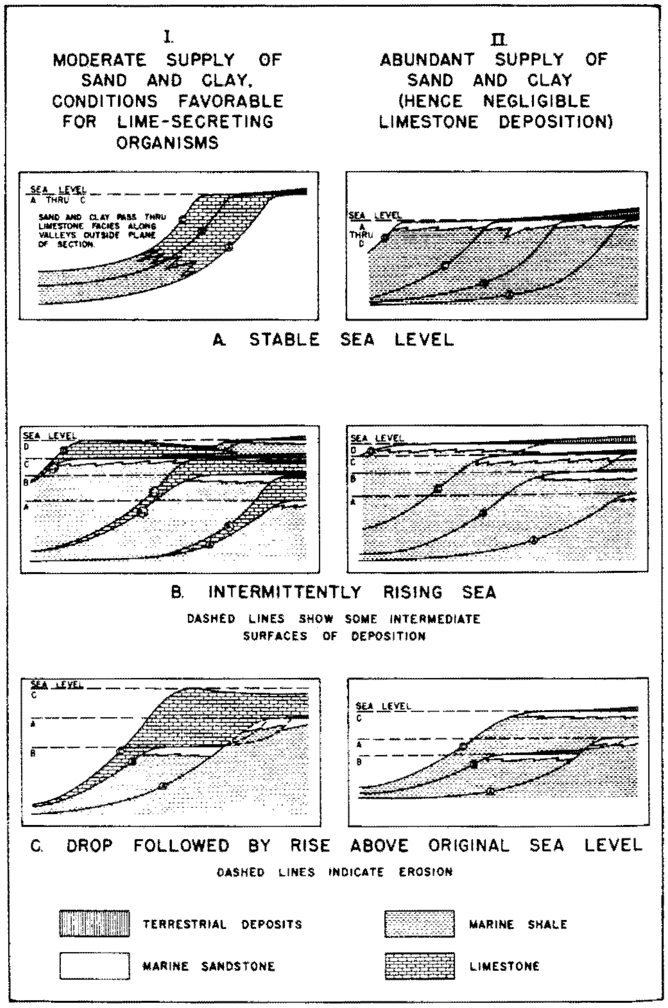

Figure 2. Diagrammatic section showing possible relations of more marine parts of successive cyclic sedimentary bodies [from Van Siclen (1957, fig. 9)]. The bottom diagram (C) demonstrates an acute awareness of distinct facies associations developed during periods of lowered sea level (i.e., a lowstand systems tract).

lends itself to the development of (first-order) genetic models.

Several of the studies that appear in the present volume utilize modeling tools to address general questions about the relative contribution of various input parameters to the development of basin fill geometries and facies belt migrations (e.g., Harris, Matthews and Frohlich, and Kendall et al.). More focused questions about the likely controls on stratigraphic cyclicity, from eustasy, autocyclicity, or sediment supply, are addressed by comparing model output to known sedimentary sections (Kendall et al., Read et al., Demicco et al., Watney et al., Goldhammer et al.) or by quantitatively analyzing sedimentary sections (e.g., Kominz et al., Bond and Kominz, and Bond et al.). Thus the ability of the model output to match the geometry and facies distribution of known geologic sections suggests that the combination of input parameters used is plausible and consistent with physical laws of nature that are built into the modeling software (e.g., conservation laws).

Geologists working with basin simulation programs ultimately gain insights into the interaction of natural processes that were not possible before these programs existed. New insights lead to new hypotheses that can be tested by gathering newly focused observations from the geologic record. The present volume emphasizes the use of stratigraphic data sets to constrain and test quantitative stratigraphic models. The computer has become a sophisticated new tool for geologists to test new ideas in stratigraphy. As a consequence of these modeling studies, geologists will revisit and reexamine old field areas. Their objective will be the collection of new observations to test predictions made by computer simulations. Armed with these tools and the body of knowledge about facies models accumulated in the past 25 years, the geologic community is poised to make great strides in the development of powerful, predictive models for sedimentary basin evolution.

Summary

During the last half-century the literature has not reflected a steady, progressive evolution of ideas in the area of stratigraphy. Instead, we see two separate explosive episodes of concept evolution based on sequence-stratigraphic thinking. The first episode was brought about by the work of a small select group of regional stratigraphers who integrated time-stratigraphic observations over continentwide areas. The second episode occurred through the development of seismic stratigraphy, a tool that would revitalize the discipline of sequence stratigraphy. Genetic basin fill models were born out of each episode, but the latest one had the benefits of sophisticated computer tools. Computer-based basin simulation programs have provided and will continue to provide geologists with new insights into stratigraphy, and their output will provide predictions for geologists to check for generations to come.

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