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INSIDE

STRATA:
Freeware for analyzing classic stratigraphic problems

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ABSTRACT

We use STRATA, a stratigraphic modeling package we have developed, to describe and illustrate several classic problems in both siliciclastic and carbonate stratigraphy that are still debated. Two simulations of clastic deposition show that, given constant subsidence rate, stratigraphic sequences can be generated by either eustatic sea-level change or variations in sediment supply, and that the resulting stratigraphic architectures are extremely similar. Two examples of carbonate deposition illuminate the development of meter-scale shallowing cycles, and a mechanism for generating "cycle bundling" that results from the interaction of sea-level change and the intrinsic dynamics of the carbonate system. Ultimately, stratigraphic models are most useful as a way of testing hypotheses of stratigraphic accumulation. We have found STRATA useful in research as well as geological education (it forms an integral component of stratigraphy classes at Penn State and MIT). We are releasing it as freeware over the Internet (http://hydro.geosc.psu.edu).

INTRODUCTION

Over the past two decades there has been a tremendous improvement in our ability to observe, describe, and interpret the stratigraphic record, made possible in large part by the advent of high-resolution seismic stratigraphic methods (e.g., Vail et al., 1977; Haq et al., 1987; Posamentier and Vail, 1988; Van Wagoner et al., 1990; Van Wagoner, 1995b; Christie-Blick, 1991; Christie-Blick and Driscoll, 1995). Forward modeling, which links sediment transport with basin subsidence, has played an important role in interpreting how complex depositional processes interact through time to produce the architectures observed in stratified sedimentary rocks (Read et al., 1986; Jervey, 1988; Jordan and Flemings, 1991; Lawrence et al., 1990). Developments in these fields have been extremely rapid. As a result, the literature is voluminous, and, particularly for those not intimately familiar with seismic and sequence stratigraphy, the terminology can be formidable (Van Wagoner, 1995a).

With the caveat that forward models are no better than their assumptions, either explicit or implied, stratigraphic modeling provides an objective basis for researchers to independently test hypotheses conceived in the field, or for teachers to illustrate complex sequence stratigraphic concepts with a minimum exposure to terminology. From a pedagogical perspective, an important advantage of forward models is that they can illustrate stratigraphic development through time, whereas the rock record provides only the final result, from which previous stages of evolution must be inferred.

It is now generally accepted that the three most important variables controlling stratigraphic geometry and the distribution

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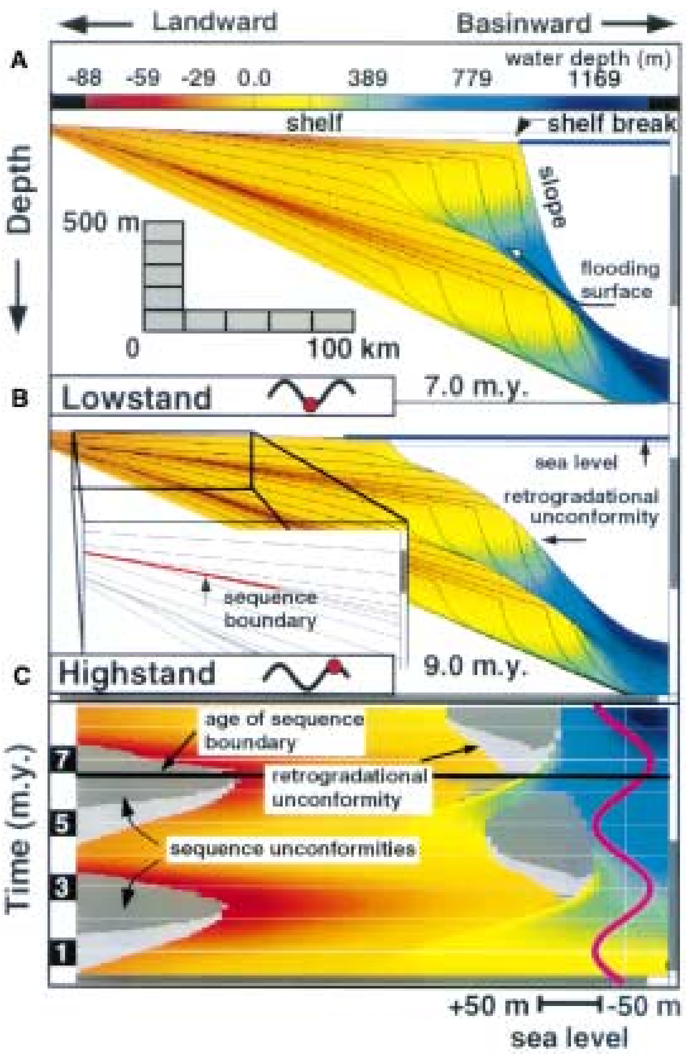

Figure 1. Generation of depositional sequences by eustatic sea-level change. A and B: Depth cross sections of evolving sedimentary basin at two time-steps (7 and 9 m.y.). Inset in B expands the sequence-boundary unconformity formed during falling sea level. Colors record water depth at which stratum accumulated (scale at top). Horizontal dashed line is a fixed reference datum (0 m absolute sea level); dark blue horizontal line marks sea-level position at the time of the display. Strata between successive black "time lines" were all deposited over the same 0.5 m.y. interval. C: Wheeler or chronostratigraphic diagram (vertical axis is time instead of depth). Gray areas represent lacunae, locations and times for which no deposition is recorded. Light gray records degradational vacuity (e.g., times and locations for which deposition occurred, but later the strata were eroded). Dark gray records hiatuses (e.g., times and locations for which there was no deposition). Eustatic sea-level history is shown on right-hand side. Parameters are listed in Table 1.

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of unconformities are tectonic subsidence, eustasy, and sediment flux (Christie-Blick and Driscoll, 1995). Simple as it seems, separation of these variables on the basis of field data alone, or using sophisticated inversion techniques (Kominz and Bond, 1990), can be troublesome (Kendall and Lerche, 1988). In contrast, forward numerical modeling provides the user with clear information about what the role and relative importance of the different variables can be. Despite their simplicity, forward models produce remarkably realistic results and generate many of the characteristics commonly observed in the stratigraphic record.

In this paper, we use STRATA to describe and illustrate several classic problems in both siliciclastic and carbonate stratigraphy that are still debated. We hope that these simple examples will serve as a foundation for other workers to use this stratigraphic model in their own efforts to understand the stratigraphic record.

SILICICLASTIC STRATIGRAPHY

Modeling Siliciclastic Deposition

STRATA assumes that sediment transport, or flux, is proportional to slope. When combined with the assumption of conservation of mass, the result is the diffusion equation

$$\frac{\partial h}{\partial t} = K\frac{\partial^2 h}{\partial x^2}, \tag{1}$$

where h is elevation, t is time, K is the diffusivity constant, and x is horizontal position. Equation 1 states that deposition or erosion is proportional to the change in local topographic slope. Diffusive processes are those in which the time-rate of change of some property is proportional to spatial gradients in that property (e.g., heat conduction, Darcy flow, or chemical dispersion of solutes). The advantage of this approach is that a single equation can produce a broad range of stratal geometries that result from variations in initial and boundary conditions. The disadvantage of the diffusion-based approach is that it is a gross approximation of sediment transport behavior.

This approach has been applied in a wide variety of depositional settings. Begin et al. (1981) and Kenyon and Turcotte (1985) proposed that sediment transport could be described as a diffusive process in fluvial and deltaic environments, respectively. Jordan and Flemings (1991) linked these approaches to simulate stratigraphy in an evolving basin. Kaufman et al. (1991) proposed that the diffusion constant (K) declined as a function of water depth in marine settings. Paola et al. (1992) derived equation 1 for braided and meandering fluvial settings, and Rivaneaes (1992) used a multicomponent diffusion equation to describe the transport of individual grain sizes.

Siliciclastic Depositional Sequences

Shallowing-upward, siliciclastic depositional sequences, overlain by relatively deep water facies, are one of the most commonly observed signatures in the stratigraphic record. Over the past century, stratigraphers have come to understand that this basic attribute can be mapped in three dimensions and through time. For example, the depositional sequence often is interpreted to record progradation (basinward shift of facies) followed by retrogradation (landward shift of facies) driven by relative changes in sea level (Vail et al., 1977; Christie-Blick and Driscoll, 1995).

Two simulations of passive margin depositional sequences are illustrated. The first is caused by absolute (eustatic) sea-level change (Fig. 1). The second is driven by changes in sediment supply (Fig. 2). We assume for both simulations that the subsidence rate is zero at the left (landward) margin and increases linearly to the right (basinward). For the first example (Fig. 1),

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sediment is supplied at a constant rate along the left-hand margin, no outflux is allowed to occur along the right margin, and sea level is varied sinusoidally with a 4 m.y. period and an amplitude of 50 m.

The model results are shown in the form of a lithostratigraphic cross section at two different times during the evolution of this basin (Fig. 1, A and B). At each point in the simulation, the depositional surface has a flat "shelf" on the landward (left) side which merges with a steeper "slope" on the basinward (right) side (Fig. 1A). This geometry is simulated by varying the diffusion constant (*K*) so that it decreases as a function of water depth; this approximates the more efficient sediment transport found in the fluvial and shallow-marine environment relative to that in the deeper marine environment. Shelf sediments are deposited at shallow depths (shaded yellow to red in Fig. 1). In contrast, slope sediments are deposited in deeper water (shaded in blue). The boundary between the shelf and slope is referred to as the shelf break (Fig. 1A).

Lowering and subsequently raising absolute sea level (Fig. 1, A and B) produces progradation (migration of the shelf break basinward [right]) (Fig. 1A) followed by retrogradation (migration of the shelf break landward [left]) (Fig. 1B). Maximum progradation is coincident with the eustatic sea-level lowstand (dark blue line in Fig. 1A is 50 m below dashed line, which is a fixed datum). Maximum retrogradation occurs slightly before the highstand in sea level (Fig. 1B).

The model generates two unconformities. The first unconformity is the sequence boundary and is formed during sea-level fall; this unconformity develops on the landward side of the basin (left). As the shelf break migrates basinward during progradation, the unconformity also propagates basinward. This unconformity exposes older strata to erosion and is marked by the intersection and truncation of the timelines at the topographic surface (Fig. 1A). This unconformity is then onlapped during the ensuing retrogradation (Fig. 1B, inset). The second unconformity is a marine unconformity formed during retrogradation. During sea-level rise, the relict shelf break is eroded (Fig. 1B) before it is ultimately overlain by downlapping strata during the ensuing progradational cycle. A chronostratigraphic plot known as a Wheeler diagram (Fig. 1C; Wheeler, 1964) is particularly useful for visualizing how unconformities develop in time. Both the progradational

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TABLE 1. PARAMETERS FOR FIGURES 1, 2, 4, AND 5

Fig.	Width (km)	Subsidence rate (mm/yr)	Nonmarine diffusion constant (m^2/yr)	Marine diffusion constant (m^2/yr)	Sea-level 1st order amplitude (m)	Sea-level 1st order period (m.y.)	Sea-level 2nd order amplitude (m)	Sea-level 2nd order period (m.y.)	Sediment flux (m^2/yr)	Max. carbonate sed. rate (mm/yr)
1	300	0.200	50,000	200	50.00	4.00	0.000	-	20	-
2	300	0.200	50,000	200	0.00	-	-	-	Variable 0–40	-
4	150	0.027	10	10	2.00	0.724	1.750	0.120	0.00	0.30
5	600	0.029	1	1	1.00	0.100	-	-	0.00	0.50

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(sequence boundary) and the retrogradational unconformities are clearly illustrated.

The simulated stratigraphy (Fig. 1) captures much of what we observe in depositional sequences and provides insight as to how these stratigraphic architectures might evolve. Sequence boundaries are formed during sea-level fall as the landward unconformity steps basinward (Fig. 1, A and C). When the rate of sea-level fall decreases, the unconformity is covered by sedimentation (onlapped) progressively from right to left (Fig. 1, B and C). During this time, subsidence continues in the basinward zone (right), and the old shelf break is drowned and eroded. This retrogradational unconformity is analogous to a transgressive ravinement surface (e.g., Nummedal and Swift, 1987). Above this unconformity, a marine flooding surface is formed (marked by blue over orange in Fig. 1B). Between any two progradational unconformities (which form sequence boundaries) lies one depositional sequence. Figure 1C suggests that sequence boundary unconformities shrink basinward and ultimately converge with the overlying flooding surfaces as actually observed in outcrop (e.g., Van Wagoner, 1995b).

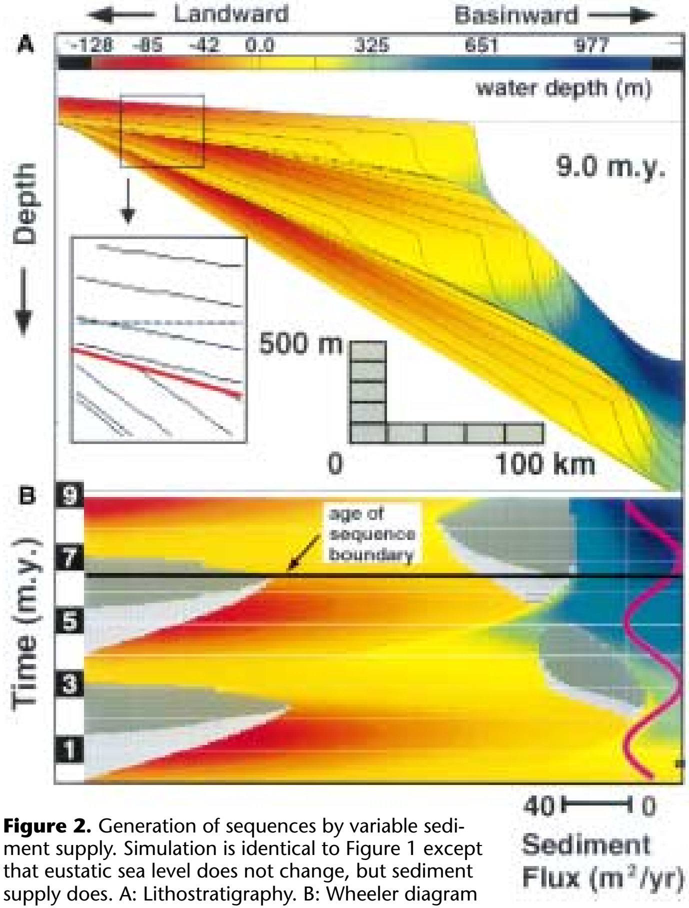

Figure 2. Generation of sequences by variable sediment supply. Simulation is identical to Figure 1 except that eustatic sea level does not change, but sediment supply does. A: Lithostratigraphy. B: Wheeler diagram illustrates that unconformities are formed during times of decreasing sediment supply. Note similarity of Figure 2 to Figure 1, even though the driving mechanism is different. Parameters are listed in Table 1.

Figure 3. The Milroy Member of the Middle Ordovician Loysburg Formation (person at lower right is about 2 m tall). Four of the six measured carbonate cycles are visible; the dashed lines delineate their tops. Darker rock is the subtidal facies; lighter rock is the intertidal facies. Cycle thicknesses are greater at the base and thinner in the middle. Located at intersection of Rt. 322 and Rt. 26, State College, Pennsylvania.

The temporal evolution of the sequence boundary unconformity portrayed here (Fig. 1C) has important implications for the interpretation of the timing of eustatic sea-level change. The approach espoused by Vail (1977) is to assume that onlap of the sequence boundary occurs slowly through time and that offlap, or formation of the sequence boundary, is instantaneous. In contrast, the results presented here suggest that erosion starts at the landward (left) side much earlier than at the basinward (right) side, as was originally predicted by Wheeler (1964). In accordance with the original prediction of Pitman (1978) and with the current Exxon approach to interpreting the timing of sea-level fall (Posamentier and Vail, 1988), the maximum rate of sea-level fall (the time of minimum creation of accommodation space) is roughly coincident with the onset of onlap of the sequence boundary (Fig. 1C) (see Christie-Blick and Driscoll [1995] for further discussion).

Flux-Driven Depositional Sequences

We contrast the eustatically driven depositional sequence (Fig. 1) with one driven by sediment supply (Fig. 2). Sediment supply is input from the left margin and changes sinusoidally with an amplitude of 20 m^2/yr and a period of 4 m.y. (Fig. 2B). Progradations and retrogradations correlate to increases and decreases in the rate of sediment supply. The progradational unconformity, or sequence boundary, is formed during times of decreasing sediment supply, while the retrogradational unconformity is formed during times of increasing sediment supply (Fig. 2B). In this case, the age of the sequence boundary (determined by the age of the first strata to onlap the unconformity) slightly postdates the maximum rate of decrease in sediment supply (Fig. 2B). This occurs in much the same manner as in the case of a sea-level–driven sequence (Fig. 1), for which the age of the unconformity immediately postdates the maximum rate of fall in sea level. The sediment-flux–driven simulation (Fig. 2) is extremely similar to the sea-level–driven example (Fig. 1).

This illustrates the complexity of the base-level concept. Variable sediment supply, coupled with constant subsidence, naturally results in stacked depositional sequences. Galloway (1989) emphasized that certain depositional sequences are driven by delta-lobe switching, rather than eustasy. STRATA (Fig. 2) clearly supports the plausibility of this alternative mechanism. Furthermore, unlike the prediction of Christie-Blick (1991), it appears to generate depositional sequences that are essentially indistinguishable from those generated by sea-level change. Jordan and Flemings (1991) showed that variable subsidence also can generate stratigraphic sequences, but we do not explore this here.

CARBONATE STRATIGRAPHY

Carbonate sedimentation differs fundamentally from clastic sedimentation, because most carbonate sediments are produced within, rather than external to, the sedimentary basin. Therefore, carbonate sediment generally does not undergo the extreme lateral sediment transport typical of siliciclastic sediment (Wilson, 1975). Studies of modern carbonate depositional environments show that carbonate production rates are extremely high in shal-

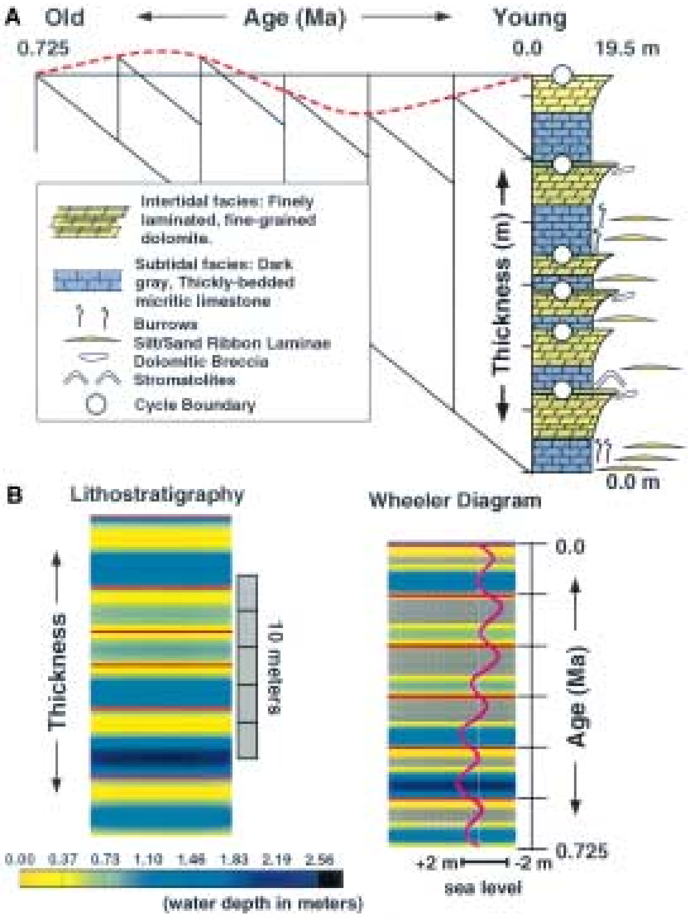

Figure 4. A: Fischer plot (left) and measured section of Milroy Member (right). B: Lithostratigraphy and Wheeler diagram simulated by STRATA. Red horizontal lines mark 0.12 m.y. intervals, which correspond to the cycle durations. Gray zones are disconformities. Parameters are illustrated in Table 1. The 0.725 m.y. duration of this section was calculated by dividing the thickness of these rocks (19.5 m) by the mean accumulation rate (during the Middle Ordovician) of these strata (0.027 mm/yr). Similarly, the 0.12 m.y. cycle duration is interpreted by dividing the total duration (0.725 m.y.) by the number of cycles (six).

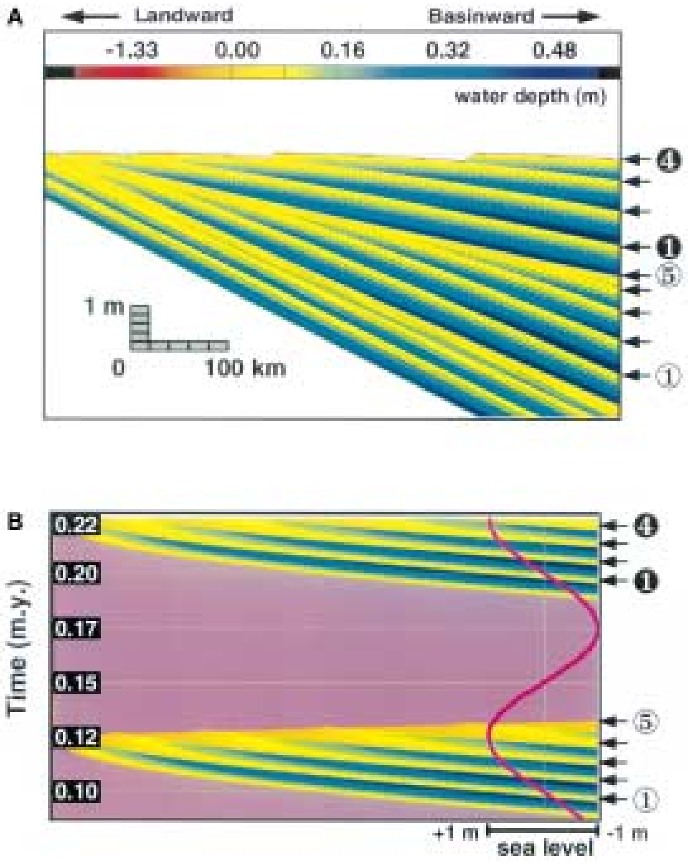

Figure 5. A: Cycle bundling as a result of "autocyclic" sedimentation dynamics. A 0.1 m.y. sea-level oscillation with a 1 m amplitude is imposed on a subsiding basin. Five cycles (circled numbers) are formed during the rising limb of the 0.1 m.y. sea-level change (fifth cycle has not yet formed for last 0.1 m.y. cycle). Deposition results in aggradation to sea level when it then stops for the 7000 yr lag time before it begins again; fortuitously, 5:1 cycle bundling is produced. B: In this Wheeler diagram, major unconformities tie to falling sea level. High-frequency cycles are diachronous, intersecting progressively younger time lines from right to left. Cycles are thickest at the base, during the maximum rate of rise of long-term sea level. Parameters used are illustrated in Table 1.

low water (1–1000 mm/yr) but decline rapidly within a few tens of meters of water depth (Schlager, 1981). STRATA approximates this behavior by assuming that carbonate production is an exponentially declining function of water depth.

Meter-Scale Shallowing-Upward Cycles

Meter-scale shallowing-upward cycles have been an essential component of carbonate platforms for at least the past 2 b.y. of Earth history. Their origin has been hotly debated (e.g., do these cycles record orbital forcing of global climate?); compare Goodwin and Anderson (1985), Algeo and Wilkinson (1988), and Koerschner and Read (1989). Modeling studies, beginning with those of Read et al. (1986), have helped quantify processes that occur on time scales shorter than the constraints offered by biostratigraphy and longer than human observation or radiocarbon dating can calibrate.

A simple example of how STRATA can be used to provide insight into understanding the origin of these shallowing-upward cycles is based on observations of the Middle Ordovician Milroy Member of the Loysburg Formation of central Pennsylvania (Figs. 3, 4A). Six successive shallowing-upward cycles progressively thicken and thin. Figure 4A illustrates a plot of differential cycle thickness through time (Fischer diagram) in which, through the assumption that cycle duration is constant, the progressive deviations in cycle thickness can be used to infer changes in accommodation space through time (Fischer, 1964; Read and Goldhammer, 1988; Sadler et al., 1993). One interpretation of Figure 4A is that sea level rose and then fell in a sinusoidal fashion over the 0.725 m.y. duration of these rocks. However, we note that the total number of cycles used in this analysis is well below the minimum required for the result to be rigorously valid (Sadler et al., 1993).

In a forward model of this outcrop (Fig. 4B), we impose a long-term eustatic sea-level change with an amplitude of 2.0 m and a period of 0.725 m.y. (see red curve on Wheeler diagram, Fig. 4B). On top of this we impose a high-frequency oscillation of 1.75 m and a period of 0.12 m.y. To simulate the biologic inertia associated with recolonization of the sea floor and "jump starting" the carbonate factory, we impose a lag-time of 5000 yr in carbonate production following complete shallowing to sea level (lag depth rather than lag time, or a combination of both, is possible with STRATA).

In an illustration of six modeled shallowing-upward cycles (Fig. 4B), the modeled and observed cycle thicknesses are similar; furthermore, both the observed and modeled cycles show that thicker cycles have a greater component of deeper water facies

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(dark blue) than thinner cycles. All of the modeled cycles shallow asymmetrically upward, as is observed in the outcrop. The Wheeler diagram (Fig. 4B) shows that the unconformities at the top of each shallowing-upward cycle are associated with the falling limb of the high-frequency sea-level change. In contrast, the base of each cycle is associated with the rising limb of each high-frequency sea-level change. During the times of long-term rise in sea level, which correspond to the thick cycles at the bottom and top of the section, the lacunae (disconformities) present between successive cycles are of a much smaller duration than those present during the falling limb of the sea-level cycle. During the long-term fall in sea level (the middle three cycles), the majority of time is recorded by a hiatus, because sea level is falling faster than subsidence and the shelf is exposed. Significantly, the Wheeler diagram shows that over half of the geologic time represented by the section is not recorded by rocks, similar to results previously obtained by Read et al. (1986), Grotzinger (1986), and Wilkinson and Drummond (1993) for other cyclic strata deposited under conditions of minimal long-term accommodation increase. STRATA suggests that these hiatuses may be preferentially partitioned within the rock record as a function of sea-level change (however, see below and Fig. 5 for an alternative explanation of hiatal origins). Finally, we note that even with the relatively slow sedimentation rate used, it is impossible to generate deepening-upward cycles without a lag time or a lag depth, because sea level is varying by only 1 m and sedimentation can always keep up with sea level.

Cycle Bundling

As a last example (Fig. 5), it is interesting to couple the long-term evolution of a carbonate shelf with high-frequency sea-level change. In this case, subsidence increases linearly from left to right. Two orders of high-frequency, shallowing-upward cycles are present, consisting of thicker cycles driven by sea-level change (0.1 m.y. period, 1.0 m amplitude) and thinner cycles that arise solely from the interaction between differential subsidence and sediment production. The latter mechanism for cycle generation is often referred to as "autocyclicity" (Ginsburg, 1971; Bosellini and Hardie, 1973; Wilkinson, 1982). The thicker cycles are defined by a systematic, upward decrease in the thickness of the thinner cycles that is related to the decreasing accommodation associated with the 0.1 m.y. sea-level oscillation. Cycle asymmetry in both sets results from the intrinsic lag time in carbonate production following complete shallowing to sea level. However, the "cycle bundling" does not result from nested sea-level oscillations, but rather reflects the lag in sedimentation, following shallowing to sea level. The shelf aggrades to sea level during the 0.1 m.y. cycle, but carbonate production shuts off, and the shelf subsides for 7000 yr every time it reaches sea level. This may occur numerous times as long as accommodation space is available. Here, through a fortuitous (but not unreasonable) combination of subsidence, lag time, and eustatic periods, this results in approximately 5:1 "bundling." This is interesting given that the observation of similar bundling in the rock record has been interpreted and modeled assuming multiple sea-level oscillations with frequencies (~0.1 and 0.02 m.y.) corresponding to the Milankovitch periods (Goldhammer et al., 1987; Goodwin and Anderson, 1985). Drummond and Wilkinson (1993) also investigated this behavior with a one-dimensional model.

In Figure 5A, the upward-shallowing cycles can be seen prograding in the direction of decreasing subsidence, away from the shelf margin and toward the inner part of the shelf (right to left). This pattern results not from any dependency on slope (there is no diffusive component) or other directional sediment transport terms, but because of the influence of lag time (lag depth produces similar geometry) operating in concert with differential subsidence. As the shelf is continuously flooded following the lowstand in the 0.1 m.y. sea-level period, the lag time progressively turns on and then off, allowing sedimentation and aggradation to occur. Accordingly, the time at which the sedimentation lag turns off is diachronous and so is the time at which shallowing to sea level takes place at any given point on the shelf. Both decrease in age up dip (to the left). The final result is that sedimentation at any point is aggradational, but the geometry of the cycle is progradational and the cyclic facies are markedly diachronous. A Wheeler diagram illustrates that the prominent unconformities correspond to the times of sea-level fall associated with the 0.1 m.y. oscillation (Fig. 5B). In contrast, the high-frequency cycles are unrelated to eustatic sea level and are diachronous, crossing time lines from right to left (Fig. 5B).

DISCUSSION

Examples from clastic and carbonate sedimentation illustrate how simple forward models can be used in conjunction with observation to provide insight into our interpretation of the stratigraphic record. The examples presented are not original, but have been chosen to illustrate STRATA's capabilities (and limitations) in addressing some of the classic (as well as more modern) problems in stratigraphy. The main goal of this paper is to demonstrate that simple physical descriptions of depositional processes, when integrated through time, can predict realistic stratigraphy. The modeling predicts the development of specific stratigraphic geometries and therefore provides independent tests of how rocks and unconformities are distributed in the stratigraphic record.

We emphasize that any model is only as good as its assumptions. This is particularly shown by the two clastic and carbonate examples. Depositional sequences in clastic rocks can be generated by variations in sediment supply, sea level, or subsidence. Cyclic carbonates can result from either extrinsic or intrinsic processes. Ultimately, perhaps, stratigraphic modeling is most useful in establishing the limits of our ability to reasonably distinguish driving variables based on existing data sets. Thus, modeling becomes a very useful tool in suggesting approaches to a new generation of field experiments required to test competing hypotheses.

Finally, we have found modeling to be a great asset to all students of stratigraphy. Although we have provided only a few simple examples, there are an infinite variety of questions a stratigrapher may ask. We hope that by releasing this software, we will allow students to pursue those questions independently. STRATA may be downloaded at http://hydro.geosc.psu.edu. Several additional stratigraphic examples are also presented therein.

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