STRATA: Freeware for analyzing classic stratigraphic problems

by

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Abstract

We have developed a stratigraphic modeling package, "STRATA," which we are releasing as freeware over the internet (here for more information). In this article, we use STRATA 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 where it forms an integral component of stratigraphy classes at Penn State (here for PSU classes) and MIT.

Note: If you are already using STRATA you can download the simulations used in this paper. If you do not have the most recent version of STRATA, you can download it freely. Version 2.13 was released in January '97, after the publication of this paper; if it's been a while since then, there may have been further releases.

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, 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 of unconformities are tectonic subsidence, eustacy, and sediment flux (Christie-Blick and Driscoll, 1995). Simple as it seems, separation of these variables based on 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:

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

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 which 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 multi-component 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 last 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 (Figure 1). The second is driven by changes in sediment supply (Figure 2). We assume for both simulations that the subsidence rate is zero at the left (landward) margin and increases linearly to the right (basinwards). For the first example (Figure 1), 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 four million year period and an amplitude of 50 meters.

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Figure 1 Mpeg Movie
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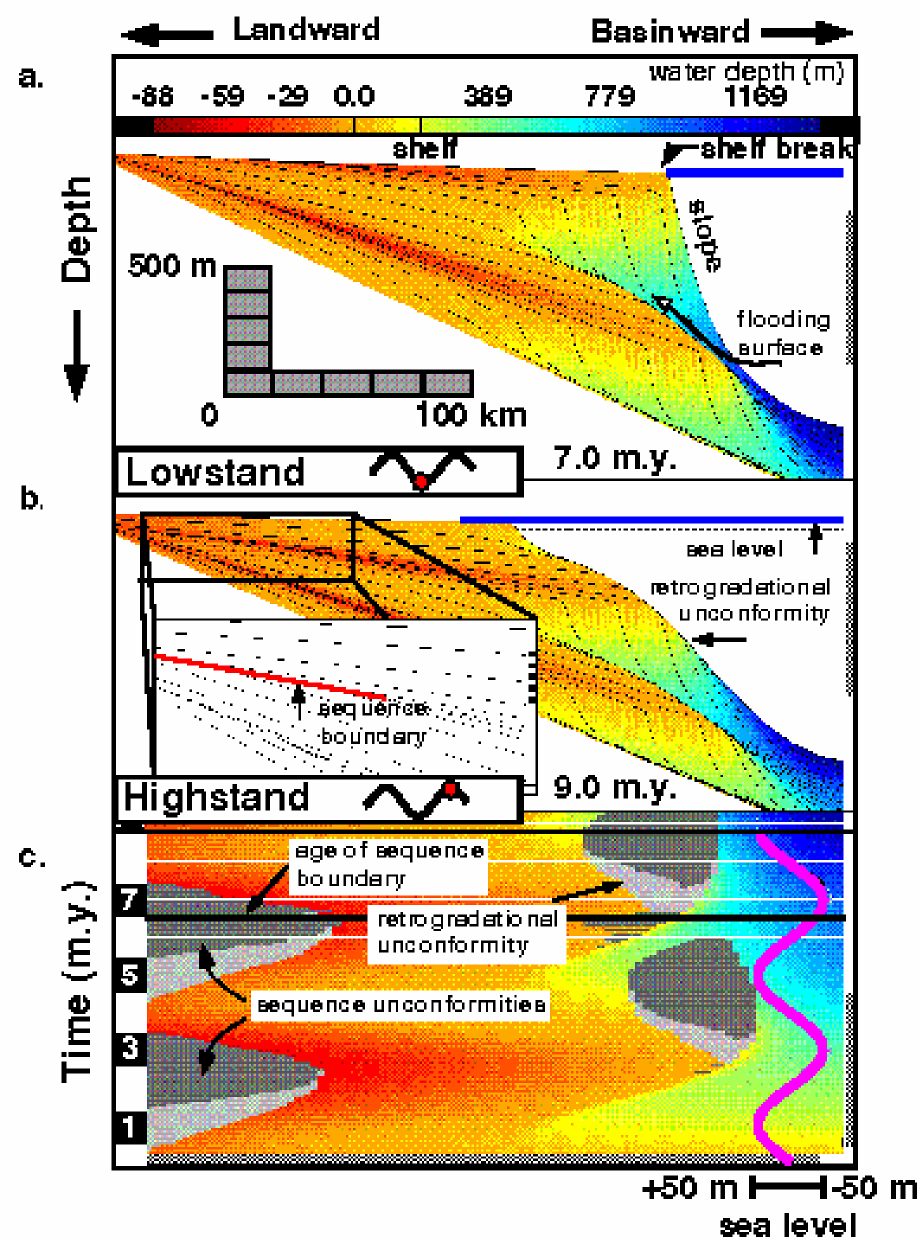

Figure 1: Generation of depositional sequences by eustatic sea-level change. A-B) Depth cross-sections (landward is to left, basinward to right and the vertical axis is depth) of evolving sedimentary basin at two time-steps (7 and 9 m.y.). Inset (B) expands the sequence-boundary unconformity formed during falling sea-level. Colors record water depth at which stratum accumulated (scale at top). Horizontal dashed line is a fixed reference datum (0 meters 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 million year interval. C) Wheeler or chronostratigraphic diagram (vertical axis is here time instead of depth). Areas in gray represent lacunae, which are locations and times for which no deposition are 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 shown on right-hand side. Parameters listed in Table 1.

The model results are shown in the form of a lithostratigraphic cross-section at two different times during the evolution of this basin (Figure 1a -1b). 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 (Figure 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 and are shaded yellow to red. In contrast, slope sediments are deposited in deeper water and are shaded in blue. The boundary between the shelf and slope is referred to as the shelf break (Figure 1a).

Lowering and subsequently raising absolute sea level (Figures 1a-1b) produces progradation (migration of the shelf break basinwards (right)) (Figure 1a) followed by retrogradation (migration of the shelf break landwards (left)) (Figure 1b). Maximum progradation is coincident with the eustatic sea level lowstand (dark blue line is 50 meters below the dashed line which is a fixed datum (Figure 1a)). Maximum retrogradation occurs slightly before the highstand in sea level (Figure 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 (Figure 1a). This unconformity is then onlapped during the ensuing retrogradation (Figure 1b, inset). The second unconformity is a marine unconformity formed during retrogradation. During sea-level rise, the relict shelf break is eroded (Figure 1b) before it is ultimately overlain by downlapping strata during the ensuing progradational cycle. Figure 1c shows a chronostratigraphic plot known as a Wheeler Diagram (Wheeler 1964). The Wheeler Diagram is particularly useful for visualizing how unconformities develop in time. Both the progradational (sequence boundary) and the retrogradational unconformities are clearly illustrated.

The simulated stratigraphy (Figure 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 (Figure 1a, 1c). When the rate of sea-level fall decreases, the unconformity is covered by sedimentation (onlapped) progressively from right to left (Figure 1b and 1c). 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 Figure 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 is actually observed in outcrop (e.g. Van Wagoner, 1995 b).

The temporal evolution of the sequence boundary unconformity portrayed here (Figure 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 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 (Figure 1c) (see Christie-Blick and Driscoll (1995) for further discussion).

Flux-Driven Depositional Sequences

We contrast the eustatically-driven depositional sequence (Figure 1) with one driven by sediment supply (Figure 2). Sediment supply is input from the left margin and changes sinusoidally with an amplitude of 20 m2/yr. and a period of 4 million years (Figure 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 (Figure 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 (Figure 2b). This occurs in much the same manner as in the case of a sea-level driven sequence (Figure 1), for which the age of the unconformity immediately post-dates the maximum rate of fall in sea level. The sediment flux driven simulation (Figure 2) is extremely similar to the sea-level driven example (Figure 1).

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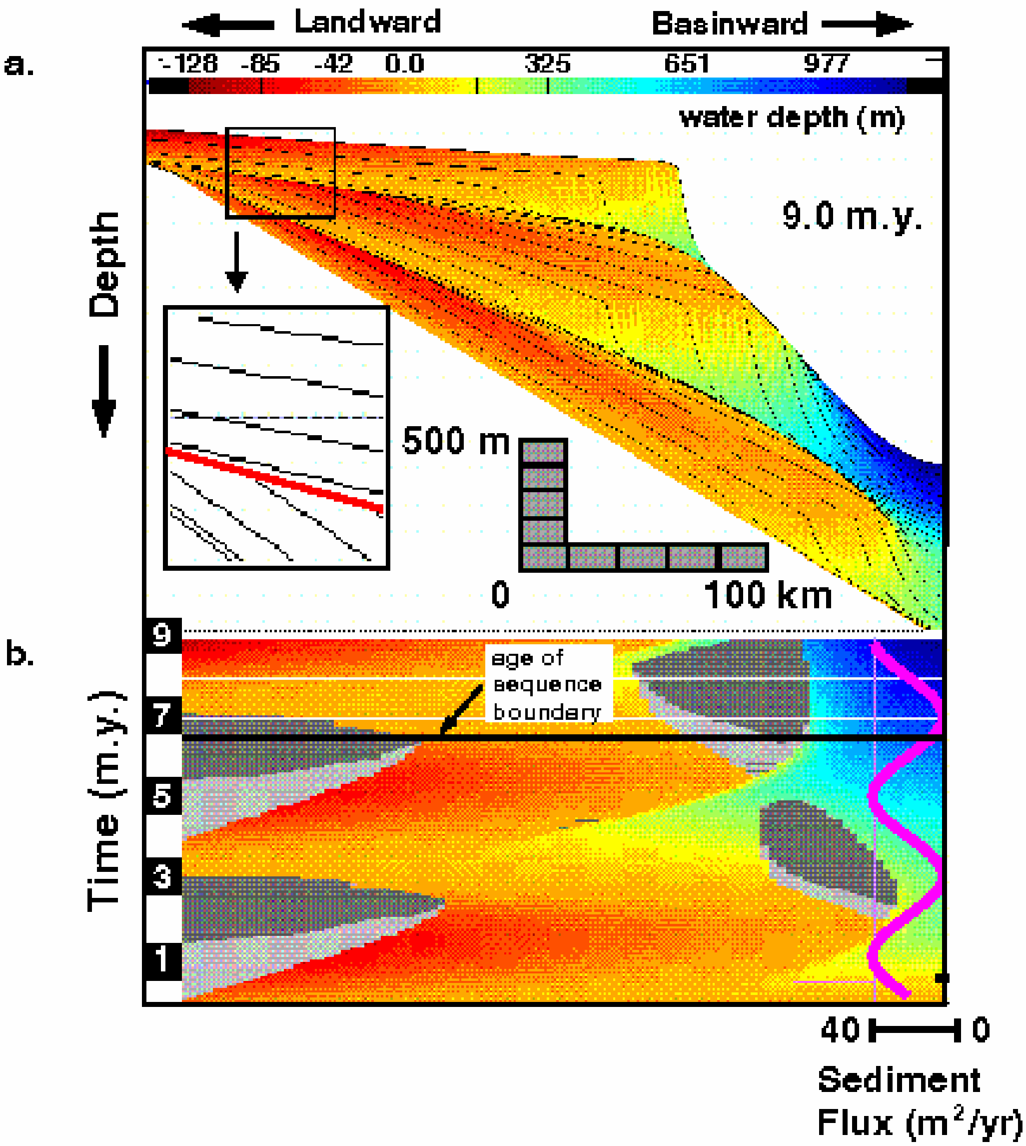

Figure 2: The generation of sequences by variable sediment supply. Simulation is identical to Figure 1 except eustatic sea-level does not change, but sediment supply does. A) Lithostratigraphy; B) Wheeler Diagram illustrates that unconformities are formed during times of decreasing sediment supply. Note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

This illustrates the complexity of the baselevel concept. Variable sediment supply, coupled with constant subsidence, naturally results in stacked depositional sequences. Galloway (1989) emphasizes that certain depositional sequences are driven by delta-lobe switching, rather than eustacy. STRATA (Figure 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) have shown that variable subsidence also can generate stratigraphic sequences, but we do not explore this here.

Carbonate Stratigraphy

Carbonate sedimentation fundamentally differs from clastic sedimentation because most carbonate sediments are produced within, rather than external to, the sedimentary basin. Therefore, carbonate sediment generally does not experience 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 shallow 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 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 last 2 billion years 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; 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 (Figure 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).

Figure 3: The Milroy Member of the Middle Ordovician Loysburg Formation (Mark Patzkowsky for scale, lower right). Four of the six measured carbonate cycles are visible and their tops are delineated with dashed lines. The darker rock is the subtidal facies; the 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, Pa..

In Figure 4b we present a forward model of this outcrop. We impose a long term eustatic sea-level change with an amplitude of 2.0 meters and a period of 0.725 m.y. (see red curve on Wheeler Diagram, Figure 4b). On top of this we impose a high frequency oscillation of 1.75 meters 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 5,000 years in carbonate production following complete shallowing to sea level. (lag depth rather than lag time, or a combination of both, is possible with STRATA).

Figure 4 Mpeg Movie
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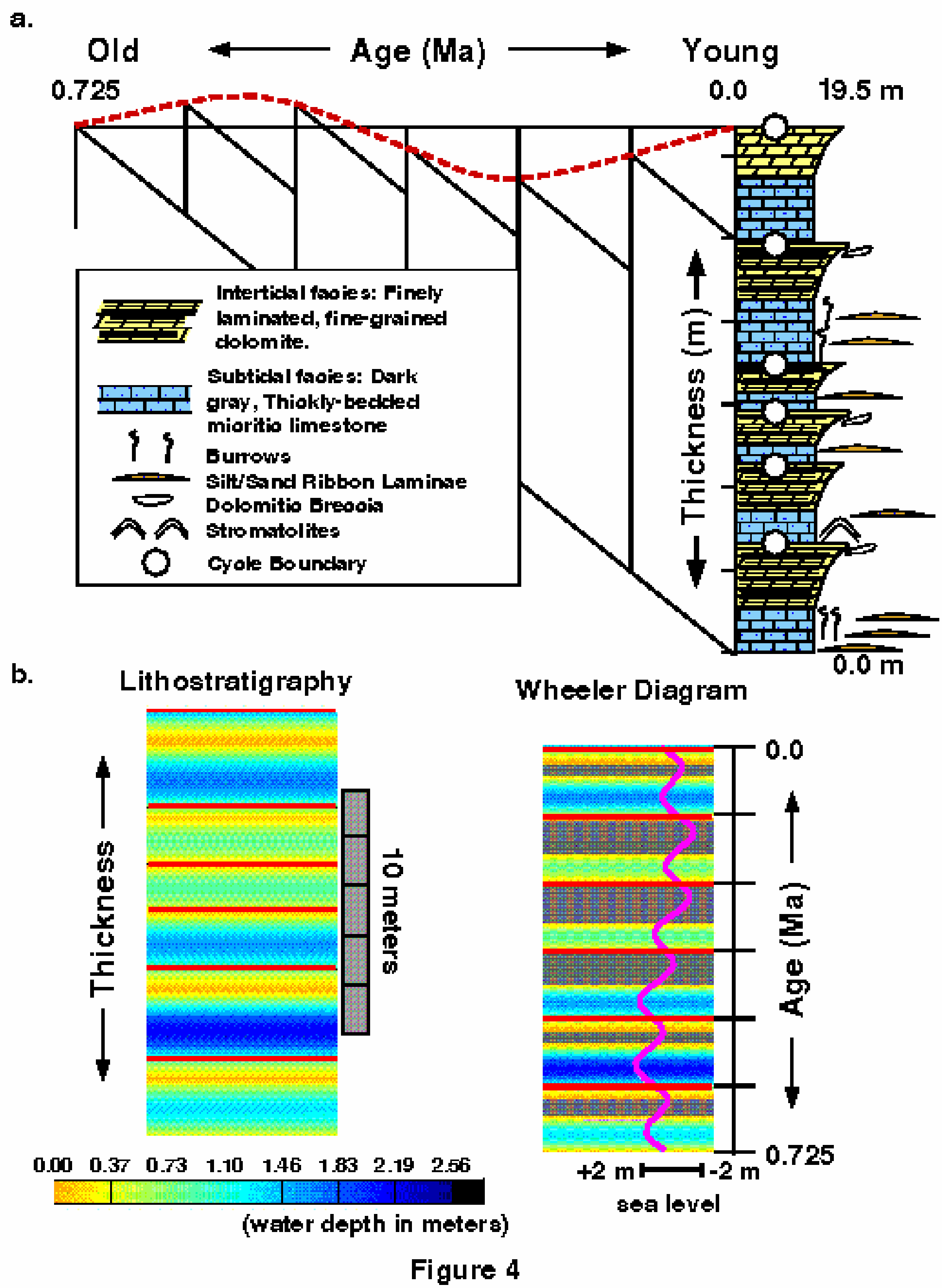

Figure 4: A) Fischer plot (left) and measured section of Milroy Member (right). B) Lithostratigraphy (left) and Wheeler Diagram (right) simulated by STRATA. Red horizontal lines mark 0.12 m.y. intervals which correspond to the cycle durations. Gray zones are disconformities. Parameters used illustrated in Table 1. The 0.725 m.y. duration of this section was calculated by dividing the thickness of these rocks (19.5 meters) 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 (6).

Figure 4b illustrates 6 modeled shallowing upward cycles. 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 (dark blue) than thinner cycles. All of the modeled cycles asymmetrically shallow upward as is observed in the outcrop. The Wheeler diagram (Figure 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 corresponds 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 these hiatuses may be preferentially partitioned within the rock record as a function of sea-level change (however, see below and Figure 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 only varying by one meter and sedimentation can always keep up with sea-level.

Cycle Bundling

As a last example, 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 which arise solely from the interaction between differential subsidence and sediment production (Figure 5); 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 years 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 m.y 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.

Figure 5 Mpeg Movie
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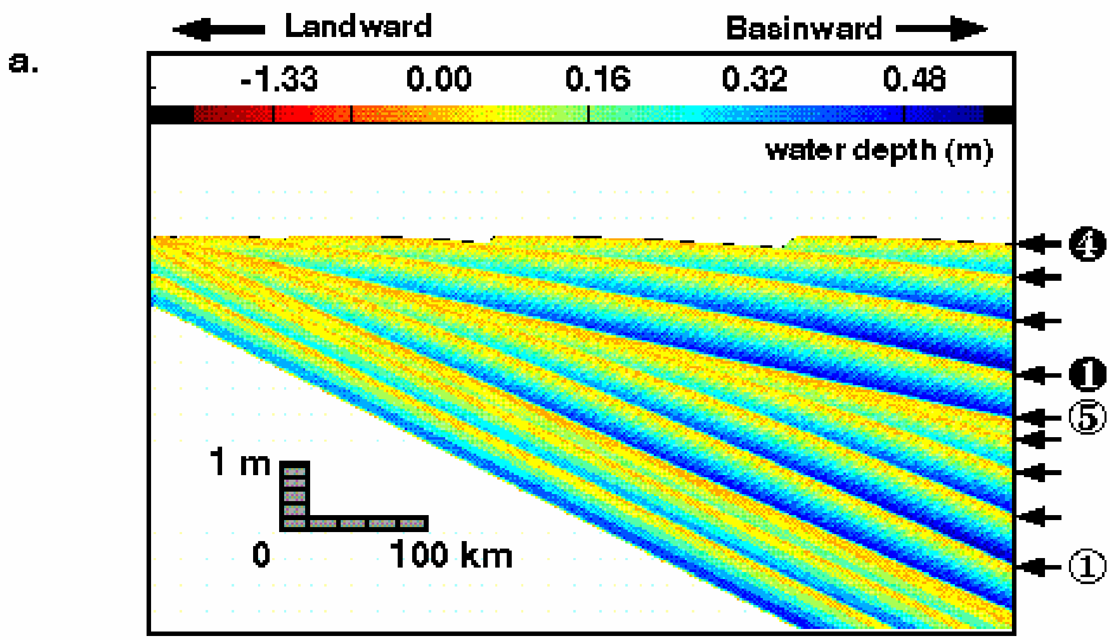

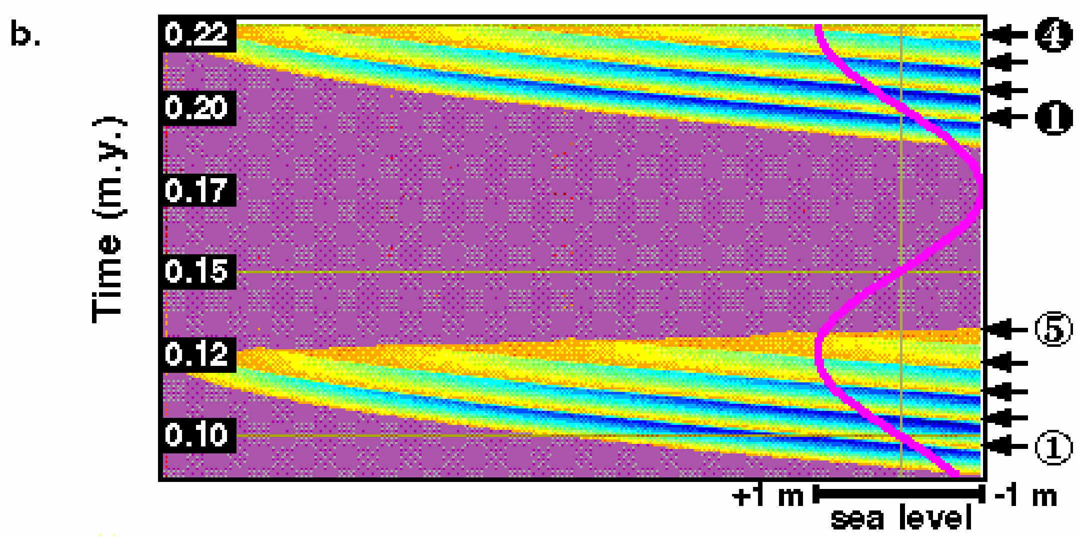

Figure 5: A) Cycle bundling as a result of "autocyclic" sedimentation dynamics. A 0.1 m.y. sea-level oscillation with a one meter amplitude is imposed on a subsiding basin. 5 cycles (labeled '1' to '5') are formed during

rising limb of 0.1 m.y. sea-level change (5th 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 7,000 year lag time before it begins again; fortuitously, 5 to 1 cycle bundling is produced. B) 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 base, during maximum rate of rise of long term sea level. Parameters used illustrated in Table 1.

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 (Figure 5b). In contrast, the high frequency cycles are unrelated to eustatic sea level and are diachronous, crossing time lines from right to left (Figure 5b).

Discussion

We have presented examples from clastic and carbonate sedimentation to 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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