STRATAL ORDER IN PERITIDAL CARBONATE SEQUENCES

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ABSTRACT: **Speculation on the depositional origins and geological significance of meter-scale cycles in peritidal carbonates is becoming an increasingly prominent facet of sequence stratigraphic theory, the understanding of which bears directly on their appropriateness as chronostratigraphic entities as well as their usefulness as records of periodic extrabasinal forcing during sediment accumulation. In spite of the generally wide acceptance of the stratigraphic importance and interpretational significance of meter-scale parasequences, little has been done to quantitatively document the stratigraphic nature of regularly recurring lithologic associations or to verify the predominance of such cyclicity in shallow-water limestone/dolostone sequences.**

In order to determine the statistical extents and stratigraphic scales of stratal order in such sequences, we have examined several long sections of peritidal carbonate both with respect to the presence or absence of Markovian lithologic transitions and with respect to the ''upward-shallowing'' character of lithofacies associations. In contrast to common wisdom, these measures of stratal order suggest that lithologic manifestation of meter-scale cyclicity is relatively uncommon. All of the several sequences deemed ''cyclic'' via qualitative inspection in fact contain relatively few intervals of demonstrable lithologic order, and even fewer exhibit any tendency for contained units to shallow upsection. In reality, most parts of most shallow-water carbonate sequences exhibit little more stratal order than would be apparent in random sequences of peritidal lithologies.

On the basis of these considerations, we suggest that discrimination of meter-scale cyclicity in epicratonic carbonates is perhaps more perceptional artifact than stratigraphic reality. Imminent and future efforts intended to fruitfully evaluate the importance of intrabasinal versus extrabasinal processes of sedimentation in shallow low-latitude settings should perhaps eschew more generic perceptions of periodic paleoclimatic forcing in favor of a less regimented view toward the importance of stochastic processes of carbonate accumulation.

INTRODUCTION

With relatively few exceptions (Kozar et al. 1990; Zeller 1964), sequences of shallow-water terrigenous and (especially) carbonate rocks have been interpreted as embodying upward-shallowing associations that reflect repeated reduction in relative water depth during sediment accumulation. Moreover, meter-scale carbonate cyclicity has been perceived as perhaps the dominant depositional motif on epicontinental platforms, and numerous examples of such apparent order have now been reported from a large number of regions that collectively represent a broad span of geologic time (e.g., Bond et al. 1991; Borer and Harris 1991; Crevello 1991; Elrick and Read 1991; Goldhammer et al. 1987, 1990; Goldhammer et al. 1991; Grotzinger 1986a; James 1984; Koerschner and Read 1989; McLean and Mountjoy 1994; Montañez and Osleger 1993; Osleger and Read 1991, 1993; Soreghan 1994; Yang et al. 1995).

With almost equally few exceptions (e.g., Cloyd et al. 1990; Ginsburg 1971; Goldhammer et al. 1993; Satterley and Brandner 1994; Satterley 1996a, 1996b), these associations have been interpreted as recording the influence of Milankovitch-band periodic climate change on global sealevel and attendant patterns of carbonate accumulation. Many recent studies have also suggested an intrinsic relation between meter-scale cycles and longer-term hierarchies of the ''sequence stratigraphic'' infrastructure that have been inferred from terrigenous passive-margin siliciclastic sequences. High-frequency meter-scale carbonate cycles (commonly referred to as ''fifth-order'' parasequences) are not infrequently suggested to comprise but one of several caste orders of sequence stratigraphic cyclicity, each driven by a range of periodic glacio-eustatic to tectono-eustatic processes.

Although rigorous quantitative evaluation of cyclical paradigms at grander scales of stratigraphic consideration is also perhaps overdue, herein we investigate several of the underlying suppositions concerning high-frequency order in peritidal carbonate sequences. Above and beyond questions concerning periodicity of accumulation, several features of such sequences suggest that perceptions of lithologic cyclicity are perhaps more subjective than is generally acknowledged. The most important of these is that most peritidal successions can as readily, if not more parsimoniously, be interpreted as comprising largely random assemblages of shallow-water lithologies (Wilkinson et al. 1996). In the following, we expand on this postulate of largely stochastic accumulation through application of several techniques of numerical analysis to data from several ''cyclic'' shallow-water sequences. These data are examined in order to explicitly evaluate the degree to which up-section lithologic transitions occur nonrandomly and to determine if shallower water units indeed do preferentially overlie units deposited at somewhat greater depths. The calculations are relatively straightforward, but discussion of several general aspects of peritidal sections and assumptions about their origins is necessary, inasmuch as they impact on the nature of the analyses and the interpretation of results.

Before addressing various aspects of stratal cyclicity, it is perhaps best to first define our usage of the word ''cycle'', and to comment on the consequences of this usage in discussions of stratigraphic order. The American Geological Institute Glossary of Geology (1973) defines a ''cycle'' as a group of rocks, the units of which occur in a certain order, and a ''cycle of sedimentation'' as a sequence of related processes and conditions repeated in the same order that is recorded in a sedimentary deposit. Both definitions require some degree of order (nonrandomness) in sequences of stratal elements deemed ''cyclic'', and it is this presence of order, or predictability of stratal recurrence, that we focus on here.

Stratigraphic ''order'' may be manifest as repeated patterns of either thickness and/or lithologic variation. Five-to-one bundling in generally monolithic Middle Triassic platform grainstones of northern Italy (Goldhammer et al. 1987, 1990) is perhaps the best example of epicratonic cyclicity defined largely on the basis of unit thicknesses. However, save the colloquial designation of ''meter-scale'', presumption of lithologic cyclicity in most other peritidal sequences is largely based on the perception of repeated ''shallowing'', a pattern of stratal order that should be manifest as distinguishable patterns of upsection lithofacies transition developed during the filling of available accommodation space. As such, inference of cyclicity in peritidal sequences as considered here is largely independent of scalar (thickness) properties of the stratal elements in question.

In a context of upsection stratigraphic variation in the lithology of peritidal carbonate sequences, and independently of any presumption of temporal periodicity of deposition, here we equate the term ''cyclic'' recurrence with compositional ''predictability''. It is this presence or absence of lithologic predictability manifest as stratal order that we primarily examine herein. It should also be noted that the presence of lithologic order alone makes no compelling argument for periodic accumulation. The question of cycle periodicity can be evaluated only by assuming some relation

JOURNAL OF SEDIMENTARY RESEARCH, VOL. 67, NO. 6, NOVEMBER, 1997, P. 1068–1082
1073-130X/97/067-1068/$03.00

between stratigraphic thickness and geologic time, and then proceeding with analysis of the resultant time series (e.g., Bond et al. 1991; Hinnov and Goldhammer 1991; Kominz and Bond 1990). Such approaches are now routinely employed in deeper-water sequences, where assumptions concerning secular variation in accumulation rate are perhaps more secure.

MARKOVIAN ORDER

Apart from questions related to thickness ordering among stratal elements and/or to secular periodicity of sediment accumulation, perception of lithologic cyclicity can be best evaluated by considering the frequencies with which any given lithology is succeeded vertically by another rock type present in the section. In a context of ''upward-shallowing cycles'', two questions are specifically posed here: (1) do component stratal elements exhibit nonrandom upsection transitions from one rock type to another? and, (2) do patterns of lithologic transition define trends readily interpretable as recording progressive decreases in water depth?

GENERAL APPROACH

Stratigraphic manifestation of lithologic cyclicity requires that sequences exhibit Markov-like properties; that is, that lithologic units of one type are generally followed by units of another type. In this context, it is therefore requisite to determine the degree to which the occurrence of any type of stratal element is, in a probabilistic sense, contingent on the lithologic composition of the preceding element. Such partial dependence is referred to as a Markov chain, and is conceptually intermediate between totally deterministic (perfectly ordered) and completely random stratigraphic sequences. General application of Markov chain analysis to sedimentologic problems has a relatively long history (e.g., Dacey and Krumbein 1970; Doveton 1971; Gingerich 1969; Krumbein and Dacey 1969; Krumbein and Graybull 1967; Miall 1973; Potter and Blakely 1968), and is a relatively simple yet insightful numerical technique for the discrimination of partial order among various lithologic elements; Davis (1986) and Swan and Sandilands (1995) contain outstanding summaries of the methodology employed in Markov chain analysis.

In practice, a transition frequency matrix is first tabulated, where integer counts of lithologic transitions (unit X to unit Y) are represented as rows of preceding (X) and columns of succeeding (Y) lithologic elements. From this frequency matrix, a transition probability matrix is calculated by dividing the total number of each transition type (a particular X to a particular Y) by its row total (the total number of transitions from a particular X to any of the possible succeeding Y lithologies). A marginal probability vector for each row is then determined by dividing row totals by the total number of transitions represented in the frequency matrix.

Because measured stratigraphic sections contain little more information than compositions and thicknesses of stratal elements that are lithologically distinct from underlying and overlying units, they rarely contain contiguous like elements. In other words, a particular lithology does not succeed itself, and diagonal terms in the transition frequency matrix are therefore zero. Sequences containing no transitions from a state to itself are referred to as embedded Markov chains. In these cases, it is then necessary to estimate the frequency with which each state does in fact succeed itself, even though such transitions would occur within some lithologically homogeneous unit and, as such, would not be discernible. This is done by employing the total number of each element type and an iteration routine to arrive at diagonal like-state transition frequencies. The approach simply presumes that numbers of like-lithology transitions are proportional to the numerical abundance of each rock type in the section; it is described in detail by Davis (1986).

Because a test of the null hypothesis of independence involves comparing observed transition frequencies with those expected in the absence of stratigraphic order, it is necessary to determine the transition frequency matrix that would be expected based only on the number of lithologic units of each type present in any section. This is done by calculating a matrix of expected transition probabilities from products of marginal probability vectors, and then multiplying each value in the expected probability matrix by its transition frequency row total; resultant values comprise a matrix of expected transition frequencies.

This expected transition frequency matrix can then be compared to the observed transition frequency matrix employing a Chi-squared (χ^2 test, wherein each matrix element (a particular X to a particular Y transition) is taken as a category with both an observed (O) and an expected (E) number of transitions. These are compared using the test statistic χ^2 calculated as

$$\chi^2 = \Sigma[(\mathrm{O} - \mathrm{E})^2/\mathrm{E}]$$

The test has $v = (m-1)^2$ degrees of freedom, where m is the number of states (lithologic types) represented in the matrix.

However, rather than determining if the critical value of χ^2 for some value of v is greater than this test statistic at some level of significance (and thereby rejecting the null hypothesis of independence), here we proceed to calculate that level of significance at which the χ^2 test statistic is equal to the critical value of χ^2 for a section containing m lithologic types. For each analysis, we determine the critical value of χ^2 at all integer significance levels as

$$\chi\alpha^2 = \mathrm{v}\left\{1 - \frac{2}{9}\mathrm{v} + \left[\mathrm{Z}\alpha\left(\frac{2}{9}\mathrm{v}\right)\right]^{1/2}\right\}^3$$

where Z is the normal deviate and α is the significance level at v degrees of freedom (e.g., Krumbein 1967). This approach yields that critical significance level at which the null hypothesis of independence can be accepted or rejected; higher values of α indicate a greater degree of transitional order among the population of stratal elements under consideration (Fig. 1).

STRATIGRAPHIC STABILITY

In a context of determining Markovian dependence within a stratigraphic sequence, it should be emphasized that virtually no real-world exposure of any significant length consists of randomly ordered lithologies. At almost any scale of consideration longer than several dozen stratal elements (e.g., Sadler et al. 1993), peritidal sequences exhibit upsection change, in either the dominance or the thickness of one or more particular rock types. Such upsection instability in the composition and/or size of stratal elements is commonly interpreted as recording ''third-order'' stratigraphic change (e.g., Goldhammer et al. 1994; Koerschner and Read 1989) and/or the development of ''grand cycles'' (e.g., Grotzinger 1986a, James 1984), the causes of which frequently are ascribed to longer-term change in sealevel and/or rate of subsidence. In fact, it is this intrinsic section-scale instability in stratal element thickness (and associated lithologic composition) that is widely utilized in the construction of ''Fischer plots'' (e.g., Read and Goldhammer 1988, Sadler et al. 1993), graphic constructions that associate cumulative deviation from mean cycle thickness with estimates of sequence age to deduce temporal change in rate of generation of accommodation space. Stratigraphic intervals containing thicker-than-average elements presumably record longer-term increase in global sealevel and/or regional subsidence rate.

The importance of stratigraphic instability to questions of Markovian dependency of lithologic transitions and the discrimination of higher-frequency cyclicity is that, at a scale of longer stratigraphic intervals, specific rock types and/or unit thicknesses may indeed be more closely associated in some parts of the sequence than in others. In essence, the outcome and interpretational value of Markov analysis is strongly scale-dependent. Imagine, for example, a sequence of several hundred lithologic elements, the lower half consisting of randomly alternating perhaps somewhat thicker subtidal and lower intertidal units, and the upper half containing randomly

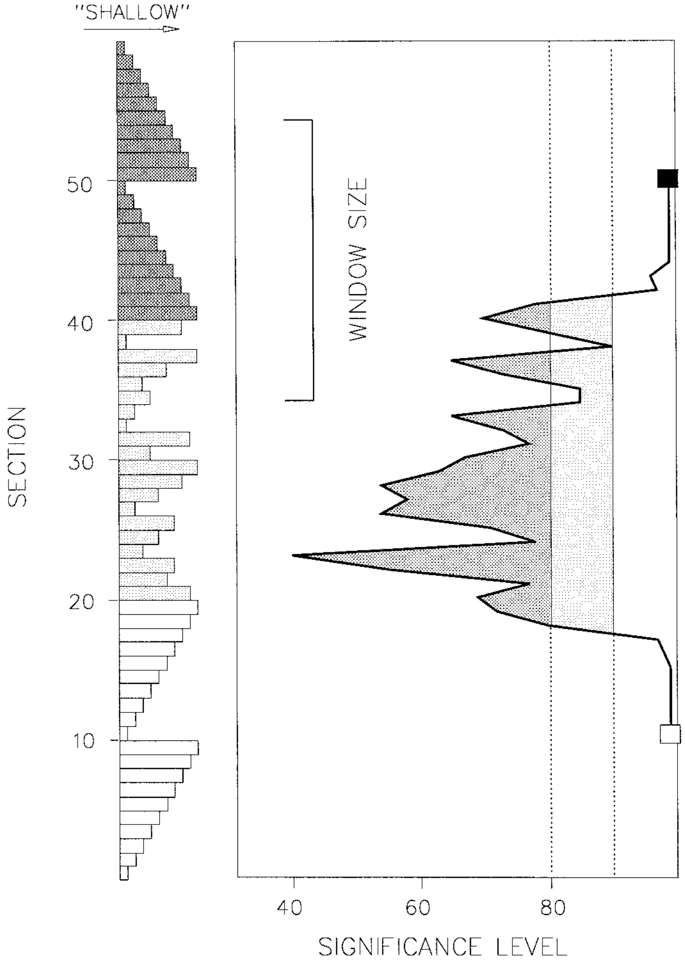

FIG. 1.—Embedded Markov chain analysis of a synthetic sequence consisting of 60 units comprising 10 discrete ''lithologies'' arranged as 2 upward-shallowing ''cycles'' of 10 units each (open bars), 20 randomly ordered units (lightly stippled), and 2 upward-deepening cycles of 10 units each (densely stippled). Significance levels (heavy line) requisite for the rejection of a null hypotheses of independence calculated with a moving window of 20 units (19 transitions each) from a lower window comprising units 1 to 20 (open box at 10 units) to an upper window comprising units 40 to 60 (filled box at 50 units). Note that a hypothesis of independence (randomness) is generally not rejected at an α of 80% (densely stippled) and is always not rejected at an α of 90% (lightly stippled) over the central interval of stratigraphic disorder.

ordered and perhaps somewhat thinner upper intertidal and supratidal units. Markov analysis of the entire interval would clearly allow for rejection of the null hypothesis of independence simply because certain lithologies occur together in the lower half while others are closely associated in the upper half. At a scale of the entire sequence, stratal elements indeed do exhibit some degree of order. Conversely, Markov analysis of either the lower or upper half of the sequence alone would yield relatively low values of critical significance. Here, hypotheses of independence are difficult to reject because units are not ordered within these shorter intervals. Because of this scalar dependence, any application of embedded Markov analysis over stratigraphic intervals of sufficient length to include long-term compositional variation will, by definition, exhibit some partial dependence between successive lithologies.

However, the issue we specifically address here is whether or not lithologic transitions also display some statistical dependence at a finer stratigraphic resolution. It is therefore necessary to calculate critical significance levels over a range of stratigraphic lengths (Fig. 2). To this end, we determine values of α within each sequence at window sizes (numbers of units over which the Markov analysis is run) from a maximum equal to the number of stratal elements in the entire section to a minimum window of several lithologic transitions.

Critical significance values (α) are plotted as points in X–Y space in which the X axis is the size of the window being evaluated, and the Y axis is the real stratigraphic midpoint of the particular window under consideration (Fig. 2). For any section containing N lithologic elements, by considering all possible window sizes down to some minimum length L, and shifting each window one element per calculation, it is possible to determine a large number of α values for any peritidal section. With respect to the total number (T) of possible solutions:

$$T = 0.5 * (N - L) * (N - L + 1)$$

If, for example, a peritidal sequence containing 60 elements (e.g., Fig. 1) is to be evaluated to a minimum window size of 5 elements, this approach yields 1540 values of critical significance. These values are readily contoured, yielding a surface of critical significance (α) in stratigraphic position/stratigraphic length space (Fig. 3).

We note here that in order for this approach to be of greatest significance in the evaluation of meter-scale cyclicity, it would be necessary to analytically ''step'' through sections at what ultimately become disconcertingly small window sizes. As with other χ^2 tests, each category (transition type) should have an expected frequency of at least five transitions (e.g., Davis 1986) and, at smaller window sizes, this would not always be the case. Although a window as small as several elements is at a scale comparable to that displayed by ''meter-scale'' cycles, the number of transitions encompassed by that window is also small and, as a result, the statistical significance of values of α become less secure. As a result, and depending on amount of lithologic variation in that interval, some smaller windows contain too few transitions to determine a value of critical significance. Moreover, because the precision of values of α determined at smaller window sizes is lower than those for longer intervals containing greater numbers of stratal units, it is not possible to appraise stratigraphic variation in α values with quite the same rigor that they were determined. We therefore abstain from drawing specific conclusions concerning the unequivocal presence or absence of stratal order at a scale of consideration finer than several dozen stratal elements.

However, and in spite of this limitation, resultant ''significance surfaces'' over these and larger window sizes are quite amenable to more qualitative interpretation in that variation in critical significance values closely reflects characteristic lengths of stratal order. If transitions in any segment of any sequence in fact do exhibit some probabilistic dependence, wherein the occurrence of any one type of lithologic element is related to the type of the preceding element, then the stratigraphic position, stratigraphic length, and statistical significance of such dependence becomes readily apparent (Fig. 3).

SHALLOWING ORDER

In addition to evaluating the absence or presence of order among lithologic transitions, in those parts of peritidal sections where a hypothesis of independence (randomness) can be rejected with some confidence (where critical significance levels are relatively high), incertitude still remains as to the degree to which these ''ordered'' sequences also exhibit trends wherein stratal elements of inferred greater depths of accumulation are overlain by units deposited in progressively shallower water. In theory, this question could be addressed by comparing differences between the observed and expected transition probability matrices. In the presence of shallowing order, one would expect a greater number of transitions from deep to shallow lithofacies than would be present in the absence of such order. In practice, however, such an approach is less than straightforward because section-scale instability may result in different depth-dependent stratal el-

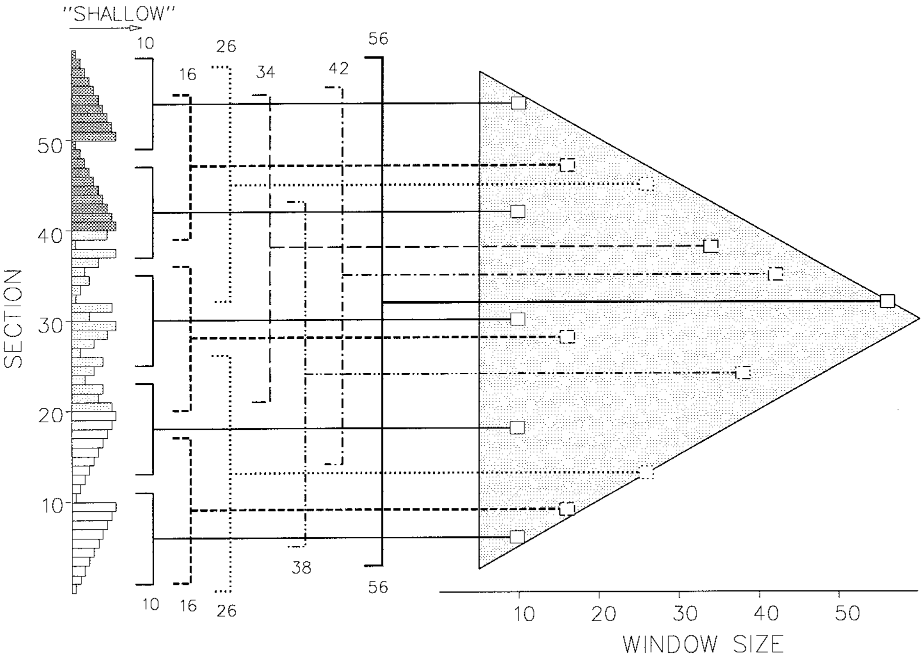

FIG. 2.—Schematic of multiple Markov analyses as a function of mean stratigraphic position (*Y* axis) and stratigraphic length (*X* axis). Model sequence as in Figure 1 showing 14 loci of determinations of critical significance (open rectangles) arbitrarily selected from 1540 possible nodes.

ements (lithofacies) predominating in different parts of a stratigraphic sequence. Moreover, even across sequence segments that accumulated under more-or-less equilibrium tectono-eustatic conditions, both absolute and relative abundances of different lithofacies may vary greatly. As a result of these factors, documentation of shallowing or deepening trends via comparison of differences between the observed and expected transition probabilities is, at best, a tenuous exercise.

GENERAL APPROACH

We have therefore formulated another metric to quantify tendencies of sequences of lithofacies to either shallow or deepen in stratigraphic successions. Unlike the calculation of critical significance levels from numbers of lithologic transitions via Markov analysis, distinguishing the presence or absence of shallowing tendencies is based on a determination of the number of contiguous stratal elements that occur within sequences that accumulated at successively greater or lesser water depths. The first step in this analysis is to assign each lithologic element to one of several categories of relative accumulation depth. These are then parsed into associations of presumably decreasing and increasing depths of deposition. For example, in a sequence of 20 elements as ABABDAECECDAEDEACEDB, where A→B represents an inferred decrease in water depth, the number of apparently shallowing (A→B A→B→D A→E C→E C→D A→E D→E A→C→E) and deepening (B→A D→A E→C E→C D→A E→D E→A E→D→B) transitions is 10 and 9, respectively. Any tendency for the sequence to shallow or deepen can therefore be simply expressed as the ratio of the number of shallowing transitions to the total number of transitions ($n-1$); in this case, the SI is 52.6%. In contrast, the same lithofacies elements could theoretically occur as ABCDEABCDEABCDEADEAE, and the number of shallowing (A→B→C→D→E A→B→C→D→E A→B→C→D→E A→D→E A→E) versus deepening E→A E→A E→A E→A transitions would yield a SI value of 78.9%. It is this ratio that serves as the basis for determining depth-dependent order within peritidal sequences (Fig. 4).

STRATIGRAPHIC SUBSTITUTABILITY

When applying this approach to real-world peritidal sequences, the least explicit step in analysis is the assignment of often rather specifically described lithologies to one of several categories of depth of accumulation. In and of itself, the exercise is qualitatively straightforward, inasmuch as virtually all ''environmental'' studies in carbonate sedimentology make at least some attempt at relating lithologic character to depositional setting. However, examination of lithologic successions in many ''cyclic'' sequences from a wide range of geographic localities and stratigraphic ages indicates that, in most cases, several rock types may occur at an equivalent position within any cyclic association. Such lithologic substitutability is perhaps a natural consequence of sediment heterogeneity (at comparable water depths) across regions of shallow-water carbonate accumulation.

Although we are unaware of any specific quantification of lateral sediment heterogeneity in modern settings, Gianniny and Simo (1996) have recently documented depth-related lithofacies substitutability in Middle Pennsylvanian shallow-water units of the Hermosa Group from the Paradox Basin in Utah that serves as an excellent case in point. Except for a predominance of coarser terrigenous units in nearshore nonmarine settings, and the possible restriction of fine organic-rich laminated muds to deeper perhaps anaerobic settings, virtually the entire suite of carbonate sediment types, ranging from coarse, wave-sorted grainstone to fine peloidal mudstone, and from cryptalgal laminite to biohermal boundstone, is interpreted to have accumulated at virtually all depths across a low-angle Carboniferous shelf system (Fig. 5).

In order to calculate shallowing indices for peritidal sequences, depth-specific substitutability therefore requires that each of the different lithologies in any section be numerically assigned to one of a smaller number of depth-dependent classes of lithofacies elements. During this stage of evaluation, we have relied almost exclusively on source reference assessments of accumulation depth, and on actual order of lithologic elements within reported ''upward-shallowing'' cycles, in order to assign each stratal unit to some depth-related group. For the purposes of discussion, we henceforth refer to individual beds of relative lithologic homogeneity as ''lithologies'' and to assemblages of depth-equivalent lithologies as ''lithofacies''. Whereas lithologic units are utilized in Markov analysis, it is these lithologic associations or lithofacies that are utilized in determining shallowing indices.

Finally, and much in the manner of Markov analysis and critical significance levels, indices of shallowing (SI) were also calculated within any sequence for window sizes ranging from that maximum size equal

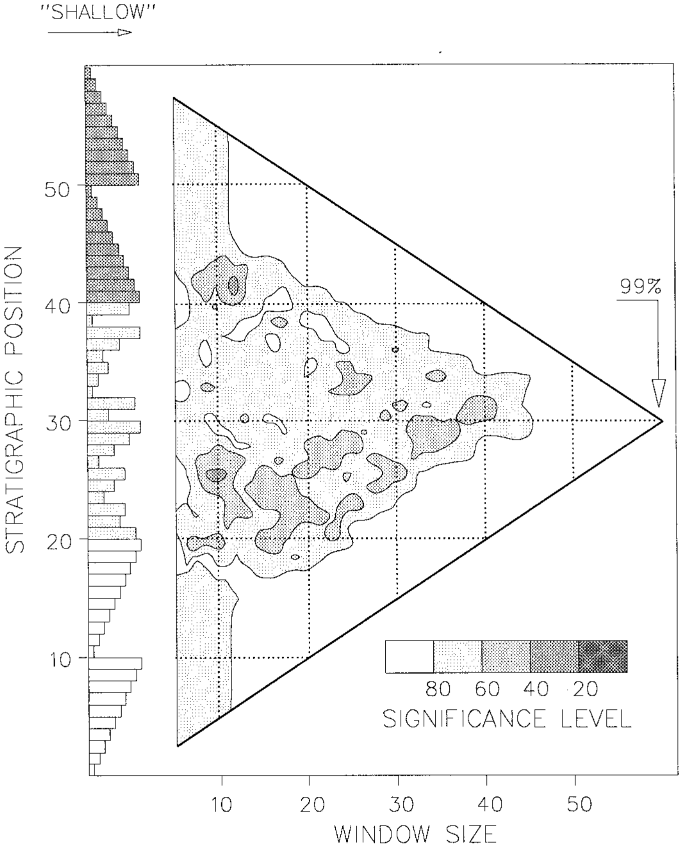

FIG. 3.—Results of embedded Markov analysis for the synthetic sequence in Figure 1, showing variation in 1540 values of critical significance α as a function of stratigraphic position and window length. Arrow at the triangle apex denotes the critical significance value for the entire section. Note that a hypothesis of independence (nonrandomness) for the entire sequence is rejected at an α of 99% but that, at progressively smaller window sizes, disorder becomes increasingly apparent across the central part of the sequence (at lower values of α, it is increasingly difficult to reject a hypothesis of independence; i.e., here, succeeding lithologies are not dependent on preceding lithologies).

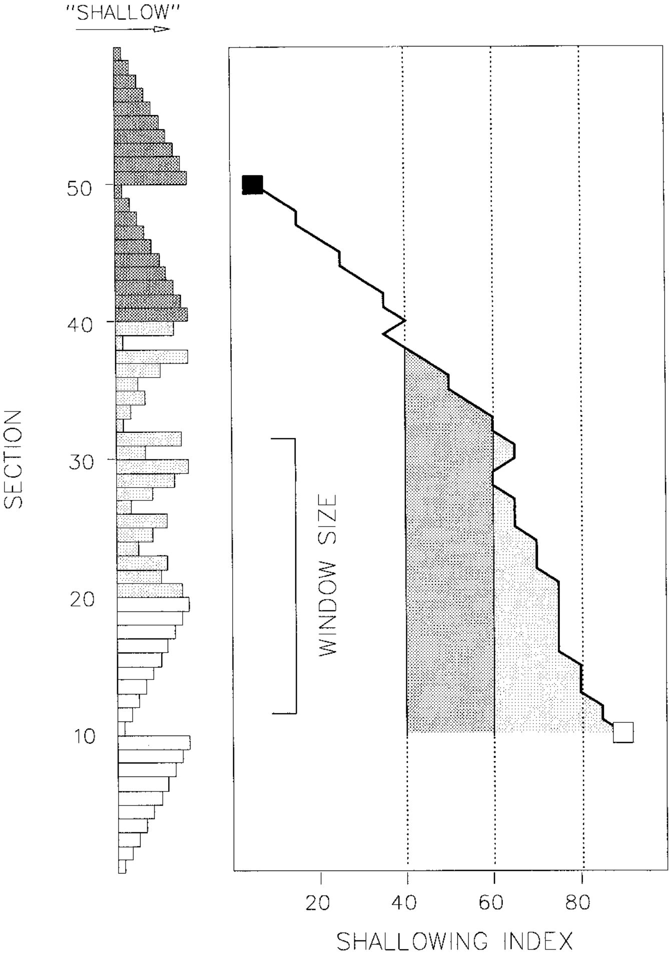

FIG. 4.—Shallowing analysis of a synthetic sequence as in Figure 1. Shallowing indices (heavy line) generally decrease from a lower window comprising units 1 to 20 (open box at 10 units) to an upper window comprising units 40 to 60 (filled box at 50 units).

to the number of depth-dependent lithofacies elements in the section to a minimum window of only several stratal elements. It should also be noted here that windows as small as several elements commonly contain few depth-related transitions. As a result, and depending on amount of lithofacies variation actually present in that interval, some smaller windows contain too few transitions to determine a statistically significant SI. However, over windows containing three or more lithofacies transitions, these values are also readily contoured, yielding a surface of shallowing index (SI) variation relative to different stratigraphic positions and interval sizes. The resultant surface is also amenable to qualitative interpretation in that variation in SI value closely reflects extents of shallowing or deepening over the stratigraphic intervals under consideration (Fig. 6).

One important difference between results of Markov chain analyses and shoaling index analyses is that the single, section-scale critical significance value (calculated for all lithologic transitions in the section) from Markov analysis need not bear any systematic relation to values determined at smaller windows over more localized parts of the sequence. Again consider the hypothetical sequence of randomly ordered subtidal and lower intertidal units in the lower portion, and randomly ordered upper intertidal and supratidal units in the upper portion. The single section-scale value of α at this maximum window size would also be at a maximum because any smaller window size would incorporate a greater proportion of either one or the other unordered halves of the sequence. Now consider another sequence, the lower half consisting of perfectly ordered deep subtidal to shallow subtidal to lower intertidal units, and the upper half containing perfectly ordered upper intertidal to lower supratidal to upper supratidal units. Here, the single section-scale value of α would be at a minimum because any smaller window size would enclose a greater proportion of either one or the other perfectly ordered hemisequences. Depending on stratigraphic stability and intrinsic scales of transition dependence, decreasing window size might well result in greater, lesser, or invariant values of α.

Conversely, shallowing indices are merely a measure of stratal order relative to inferred water depth and, as such, section-scale values of SI must reflect the aggregate value of all SIs of shorter intervals that could be perceived as being ''embedded'' in that longer sequence. Long sequences composed of shorter, upward-shallowing segments by necessity must also yield high SIs, while long sequences, composed of shorter but well-ordered upward-shallowing and upward-deepening segments, might well yield SI values that represent an intermediate average of more extreme indices of contained shorter intervals. In other words, and unlike levels of critical significance, SI values determined over larger window sizes represent only an average of the shallowing indices of contained segments. This difference between significance levels and shallowing in-

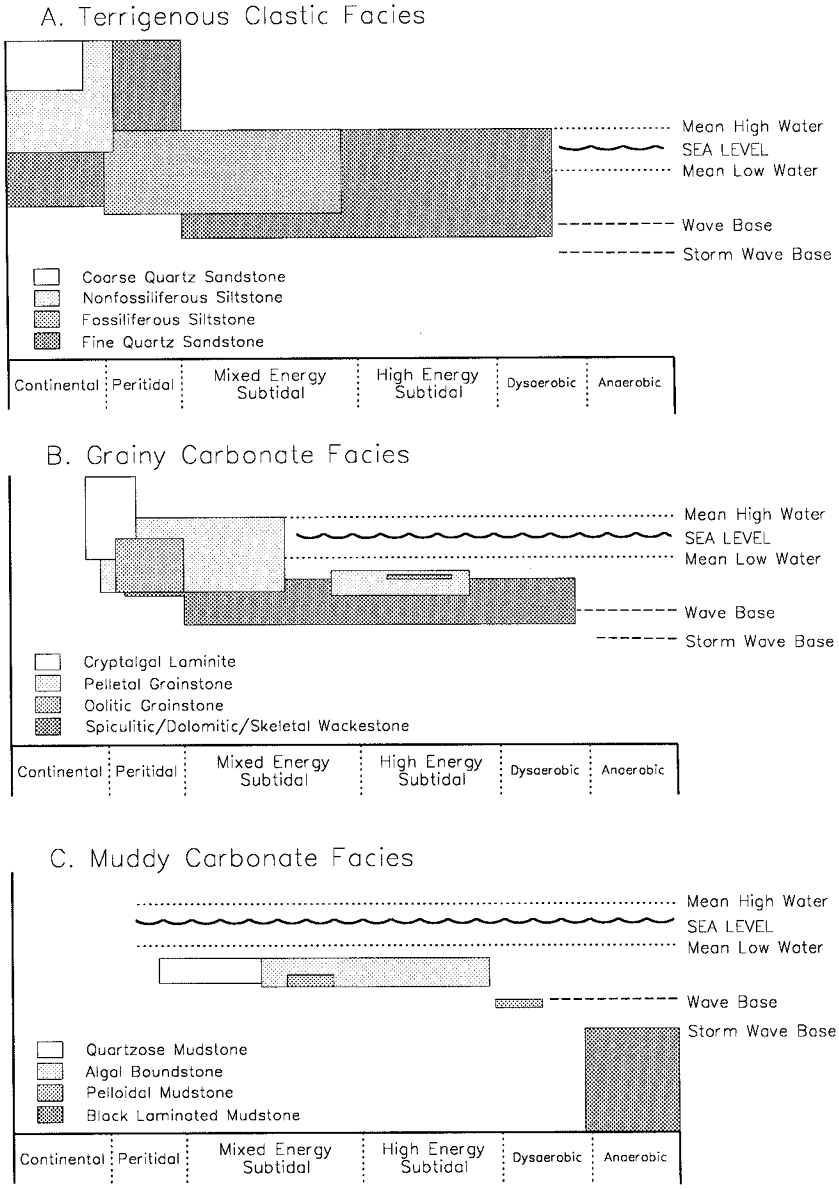

FIG. 5.—Lateral substitutability of depth-dependent sediment types across a low-angle Middle Pennsylvanian shelf during the accumulation of the Hermosa Group in the Paradox Basin of southeastern Utah; from Gianniny and Simo (1996). Note that, except for the coarsest clastic and finest organic-rich units, virtually all types of terrigenous siliciclastic and grainy to muddy carbonate lithofacies could potentially accumulate at virtually identical ranges in water depth and distance from shore.

dices becomes apparent when these measures are calculated for real-world peritidal sequences.

STRATAL ORDER

To evaluate the importance of meter-scale shallowing cyclicity in cratonic carbonates, we have determined the stratigraphic distribution of critical significance levels and shallowing indices for three peritidal sequences that have been interpreted as containing such stratal order. Because our primary focus is to determine the presence or absence of stratigraphic order in sequences perceived as ''cyclic'' in the current usage of the word, two recently described sections (Ordovician, Texas; Devonian, Alberta) are examined in addition to one sequence (Cambro-Ordovician, Virginia) from our own data. The two published sections were selected on the basis of the high quality of lithologic description and environmental interpretation. All three accumulated under ''greenhouse'' conditions in the colloquial sense of the term (e.g., Fischer 1984); lithologic evidence of prolonged subaerial exposure is generally lacking.

CAMBRO-ORDOVICIAN CYCLES, VIRGINIA

Extensive study of Cambrian and Ordovician sequences exposed throughout the south-central Appalachian region as reported by Koerschner and Read (1989) and Osleger and Read (1991, 1993) provides abundant data on the nature of early Phanerozoic platformal carbonate accumulation. Among the many peritidal exposures in this region, those of the Elbrook and Conococheague formations at Wytheville, Virginia, are unsurpassed. Within the entire 304 m-thick sequence, we distinguished 14 peritidal lithologies comprising a wide range of ''particulate'' carbonate rock types as grainstone, packstone, wackestone, and mudstone, but also containing a broad suite of boundstone lithologies as thrombolitic and stromatolitic buildups and cryptalgal laminite (Fig. 7).

Koerschner and Read (1989) provide excellent lithologic descriptions and interpretations of depositional setting for the upper 21 m of section exposed at this locality, and interpret this part of the sequence to contain 11 upward-shallowing lithologic associations consisting of (1) basal thrombolite and/or digitate bioherms, (2) carbonate clasts as flat-pebble conglom-

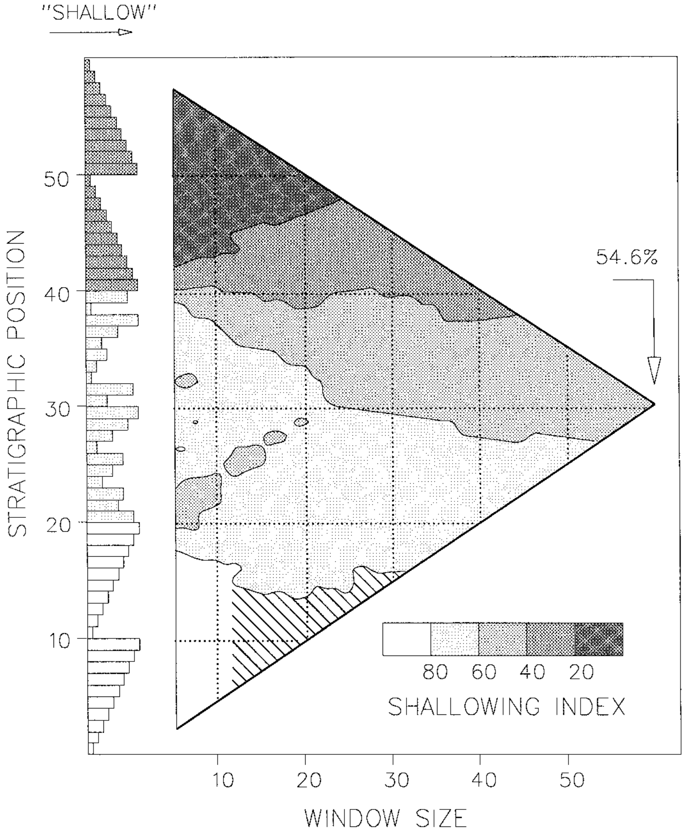

FIG. 6.—Results of analysis of the synthetic sequence in Figure 1, showing variation in values of the shallowing index (SI) as a function of stratigraphic position and window length. Arrow at the triangle apex denotes the SI value for the entire section. Note that while the entire sequence exhibits no tendency for units to comprise either shallowing or deepening associations (SI = 54%), at progressively smaller window sizes, upsection trends of upward shallowing, disorder, and then upward deepening become increasingly apparent. Diagonally ruled area is that region where critical significance values (Fig. 3) and shallowing indices are greater than 80%.

erate and/or oolitic/skeletal grainstone/packstone, (3) flaser-bedded carbonate sand and mud, (4) thickly laminated mudstone and/or wavy to domal stromatolites, and (5) cycle-capping cryptalgal laminite and/or breccia. It is these five groups of lithofacies that we utilize in calculating shallowing indices for the entire sequence (e.g., Fig. 7).

Long-term lithologic variation is manifest as subtle upsection change in the dominance of grainstone, microbialite, mudstone, and/or laminite that makes up most of the Wytheville section. Flaser-bedded grainstone, calcisiltite, and/or mudstone interpreted as recording generally subtidal accumulation, perhaps during long-term sealevel rise (e.g., Osleger and Read 1991), occur more abundantly in thickly bedded intervals, whereas cryptalgal laminites, perhaps deposited during long-term sealevel fall (e.g., Koerschner and Read 1989) exhibit somewhat greater predominance in more thinly bedded intervals. Trends of cumulative deviation from mean thickness for individual lithologic units and for shallowing ''cyclic'' lithofacies runs (Fig. 7) reflect the presence of two or three longer-term variations in mean element thickness. From our own observations, and as emphasized by Koerschner and Read (1989), the Wytheville sequence is also notable in that paleosols, caliche, karst features, and other evidence of vadose diagenesis are largely lacking. Save the common presence of desiccation cracks, and scarcer occurrences of minor stratiform breccias, these units largely lack evidence of prolonged subaerial exposure.

In contrast to interpretations of widespread shallowing cyclicity, results from Markov analysis reveal little affirmation of high-frequency order in this sequence. The section-scale level of critical significance is only 79% (e.g., Fig. 8A), and while similar levels of critical significance persist over the much of the central part of the sequence to smaller windows, significantly lower α values occur over most intervals smaller than about 80 stratal units. Exceptions to this generalization occur at elevations of about 120, 175, and 240 m, where somewhat higher α values suggest the presence of greater degrees of stratal order spanning intervals of several tens of meters. The persistence of elevated significance levels at longer stratigraphic intervals almost certainly reflects the presence of section-scale instability in the dominance of various lithologies at a scale of variation that is also apparent in plots of cumulative deviation from mean thickness (Fig. 7).

Shallowing indices for the entire sequence are 49.9% (Fig. 8B), and evince little tendency for contained lithofacies to comprise upward-shallowing associations. SI values are even close to 50% over the three shorter intervals of somewhat greater stratal order, and qualitative inspection suggests that they primarily span transitions wherein alternations of several lithologies are abruptly overlain by alternations of different rock types. In other words, much of this order is more closely related to high-frequency change in lithologic stationarity than to any obvious development of upward-shallowing stratal associations.

With the possible exception of several shorter intervals of elevated significance levels, neither Markov analysis nor calculation of shallowing indices reflect the widespread presence of meter-scale order or the dominance of upward-shallowing tendencies in the Wytheville section. Over stratigraphic intervals spanning less than several dozen stratal elements, lithologic units exhibit little more order than would occur in a randomly arranged sequence of peritidal units.

ORDOVICIAN CYCLES, TEXAS

A recent and notably detailed report of Lower Ordovician peritidal lithofacies successions is provided by Goldhammer et al. (1993), who describe and interpret a 283 m-thick section exposed in the Franklin Mountains of west Texas. This sequence contains 305 units, each of which Goldhammer et al. (1993) place into one of 12 peritidal lithologic categories. The lithologic units are also grouped into 115 upward-shoaling ''cycles'' which contain one or more of five depth-related lithofacies as (1) basal thrombolitic microbialite, (2) oolitic grainstone, digitate stromatolite, and/or heterolithic thin beds, (3) terrigenous sand and silt, thin wavy to graded beds, intraclastic grainstone, and/or burrowed skeletal to pelletal wackestone to grainstone, (4) wavy lenticular thin beds, and (5) wavy-bedded to flaser-bedded thin beds and cryptalgal laminite. We utilize these five groups of lithofacies in calculating shallowing indices for this sequence (e.g., Fig. 9).

Section-scale stratigraphic instability in the Franklin Mountains is present as three intervals with a greater abundance of relatively thin units dominated by reddish terrigenous sands and silts and desiccation-cracked planar laminite. Goldhammer et al. (1993) interpret these intervals as bounding several ''third-order'' eustatic sequences with thicknesses in the range of 60–140 m and durations of several million years (Fig. 9). This scale of lithologic variation is also apparent in plots of cumulative deviation from mean thickness. Like the Wytheville sequence and except for the presence of desiccation cracks and stratiform breccias, these exposures of the El Paso Group largely lack paleosols, caliche, karst features, and other evidence of prolonged subaerial exposure.

Markov analysis indicates a substantial amount of long-range order in this sequence; the full section α is 99% (Fig. 10A), and equally high values persist to smaller window sizes of about 50 stratal elements. Regardless of the origins of this ''third-order'' variation, its influence on stratal order is clearly apparent in the distribution of α values down to windows of some several dozen units in length. Moreover, similarly high significance levels persist to smaller window sizes over at least parts of the sequence, particularly at about 150 m from the base of the section (Fig. 10A). However,

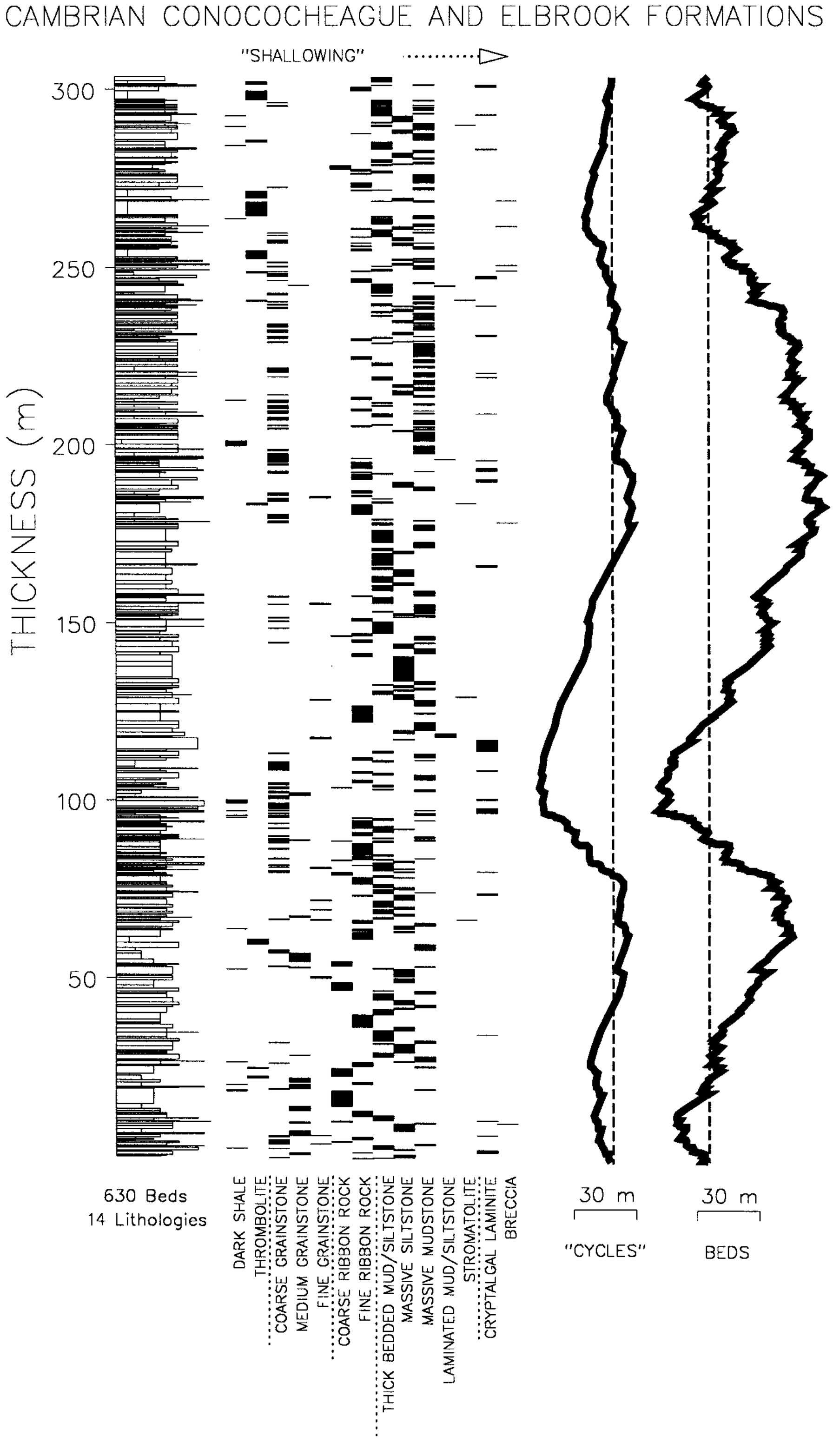

FIG. 7.—Section through the Cambro-Ordovician Elbrook and Conococheague Formations at Wytheville, Virginia. Shallowing "cycles" identified by Koerschner and Read (1989) in the upper 21 m of this sequence permit designation of five depth-related lithofacies groups (dotted lines) ranging from basal thrombolite to cycle-capping cryptalgal laminite and exposure breccia. The two curves show cumulative deviation from mean thickness (dashed lines) for the 176 cycles that could be delimited using these depth criteria, and for the 630 lithologic units that we distinguish in this sequence.

SI values indicate that even over this interval, component lithofacies exhibit little tendency to comprise "upward-shallowing" associations (Fig. 10B). The full-section SI is only 50.4%, and these values rapidly increase and decrease over intervals that are as long as several tens of elements in length. Moreover, visual comparison of lithologic compositions and thicknesses with the stratigraphic distribution of elevated α values suggests that much higher-frequency order is a direct manifestation of high-frequency change in lithologic stationarity. Elevated significance levels over the interval centered at about 150 m, for example, corresponds to the same interval where Goldhammer et al. (1993) place a major "sequence boundary" (Fig. 9); its establishment is of course based on an abrupt change in the thickness and lithology of peritidal units over that part of the Franklin Mountains

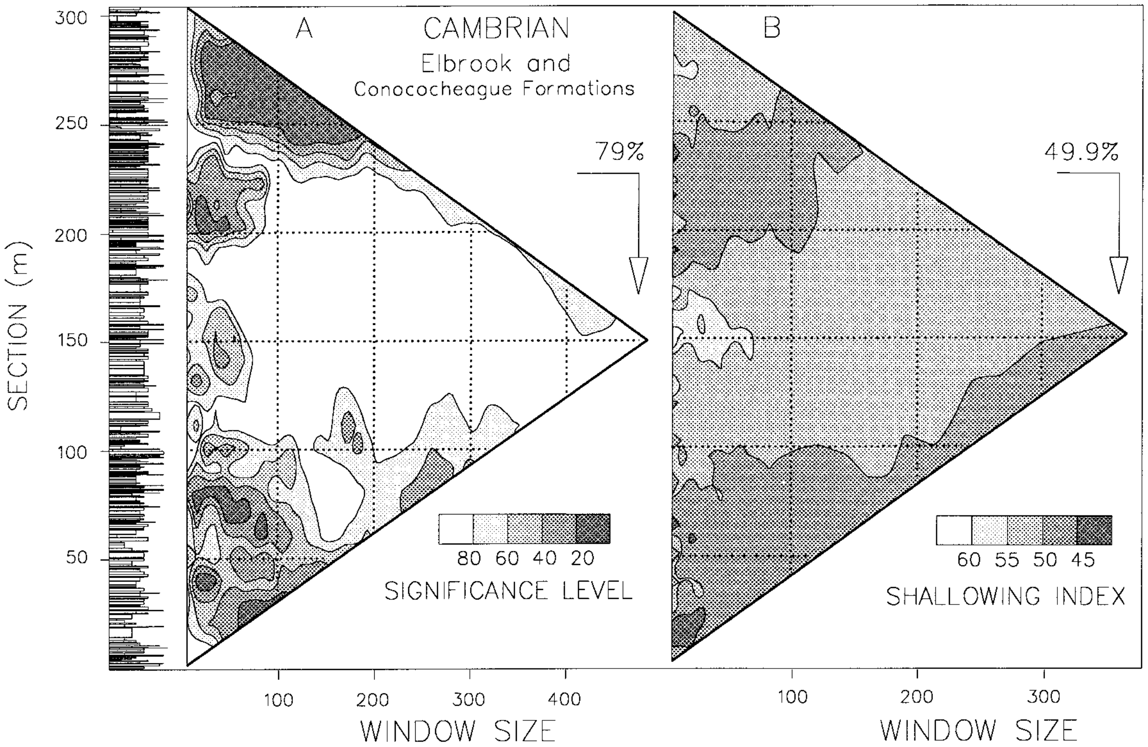

FIG. 8.—**A)** Significance levels and **B)** shallowing indices plotted as a function of mid-window stratigraphic position and window size (lithologic or lithofacies units) for the Cambro-Ordovician section in Figure 7. Significance levels are low toward the top and base of the sequence but somewhat higher over much of the central part down to a window size of about 50 units. Note that the section-scale significance level is only 79%, and that SI values indicate little tendency for stratal elements to comprise upward-shallowing associations.

sequence. At the ''meter scale'', there is evidently little tendency for these units to comprise upward-shallowing cycles.

DEVONIAN CYCLES, ALBERTA

McLean and Mountjoy (1994) report on meter-scale shallowing-upward parasequences in the Upper Devonian Flume platform and overlying Upper Cairn biostrome of the southern Canadian Rocky Mountains. Among the four sequences illustrated by McLean and Mountjoy (1994), thicknesses and compositions were tabulated from the 310 m-thick section exposed at Coronation Mountain (Fig. 11). This sequence contains 173 units, each belonging to one of eight distinct lithologies (basal dark dolomicrite, dark fossiliferous dolomicrite, calcisiltite, stromatoporoid floatstone/rudstone, calcareous *Amphipora* wackestone/packstone, dolomitic *Amphipora* wackestone/packstone, calcareous grainstone, and cryptalgal laminite) that are interpreted as comprising 61 upward-shoaling cycles. It is these eight groups that we utilize in determining shallowing indices (e.g., Fig. 11). Like the Cambrian and Ordovician sequences described above, longer-term stratigraphic instability is manifest as several upsection changes in the dominance of one or more component rock type, and plots of cumulative deviation from mean lithologic unit and shallowing run thickness exhibit alternations at a similar scale (Fig. 11). Like the Cambrian and Ordovician sequences described above, units at Coronation Mountain also lack lithologic evidence of prolonged subaerial exposure and/or vadose diagenesis.

Units within the Fairholme Group exhibit little apparent manifestation of ubiquitous high-frequency lithologic order. The full-section α is 93%, and becomes smaller and more variable values at smaller windows (Fig. 12). Intermittent persistence of some higher significance levels to smaller windows is at least in part related to section-scale instability manifest as alteration of thicker more subtidal and thinner more supratidal elements at scales spanning several tens of meters (e.g., Fig. 11). Units within the Fairholme Group also exhibit little apparent tendency to comprise shallowing lithofacies associations. The full-section SI is only 47.6%, and several intervals with somewhat elevated values of α in fact show a somewhat greater tendency for upsection deepening than shallowing. As with the Cambro-Ordovician section at Wytheville, Virginia, and the Lower Ordovician sequence in west Texas, the Upper Devonian succession at Coronation Mountain exhibits little stratigraphic order at scales less than several dozen stratal elements.

DISCUSSION

On the basis of embedded Markov and upward-shallowing analysis over a wide range of stratigraphic interval sizes, it appears that perceptions of widespread meter-scale shallowing cyclicity in these peritidal sequences are largely unfounded. Although longer-term ''third-order'' stratigraphic nonstationarity is indeed apparent in each of the three sequences, a similar degree of order cannot be demonstrated at the finer stratigraphic resolutions of ''fourth-order'' and/or ''fifth-order'' variation.

In addition to these sections, we have applied similar analysis to several other reportedly cyclic peritidal sequences. These include the Paleoproterozoic Rocknest Formation of Northwest Territories, Canada (Grotzinger 1986a, 1986b), Upper Cambrian platform carbonates of the Bonanza King Formation in the Nopah Range of the southern Great Basin, California (Montañez and Osleger 1993; Osleger and Montañez 1996), the Lower Ordovician Upper Arbuckle Group near Ardmore, Oklahoma (our data), the Ordovician El Paso Group exposed at Beach Mountain, Texas (Goldhammer et al. 1993), the upper Ordovician Kope and Fairview formations in northern Kentucky (Holland et al. 1997), the Lower Devonian Helderberg Group in central New York (our data), the Lower Mississippian Mission Canyon Limestone in west-central Wyoming (Vice and Utgaard 1995), and the Middle Pennsylvanian Hermosa Group exposed at Ross Canyon

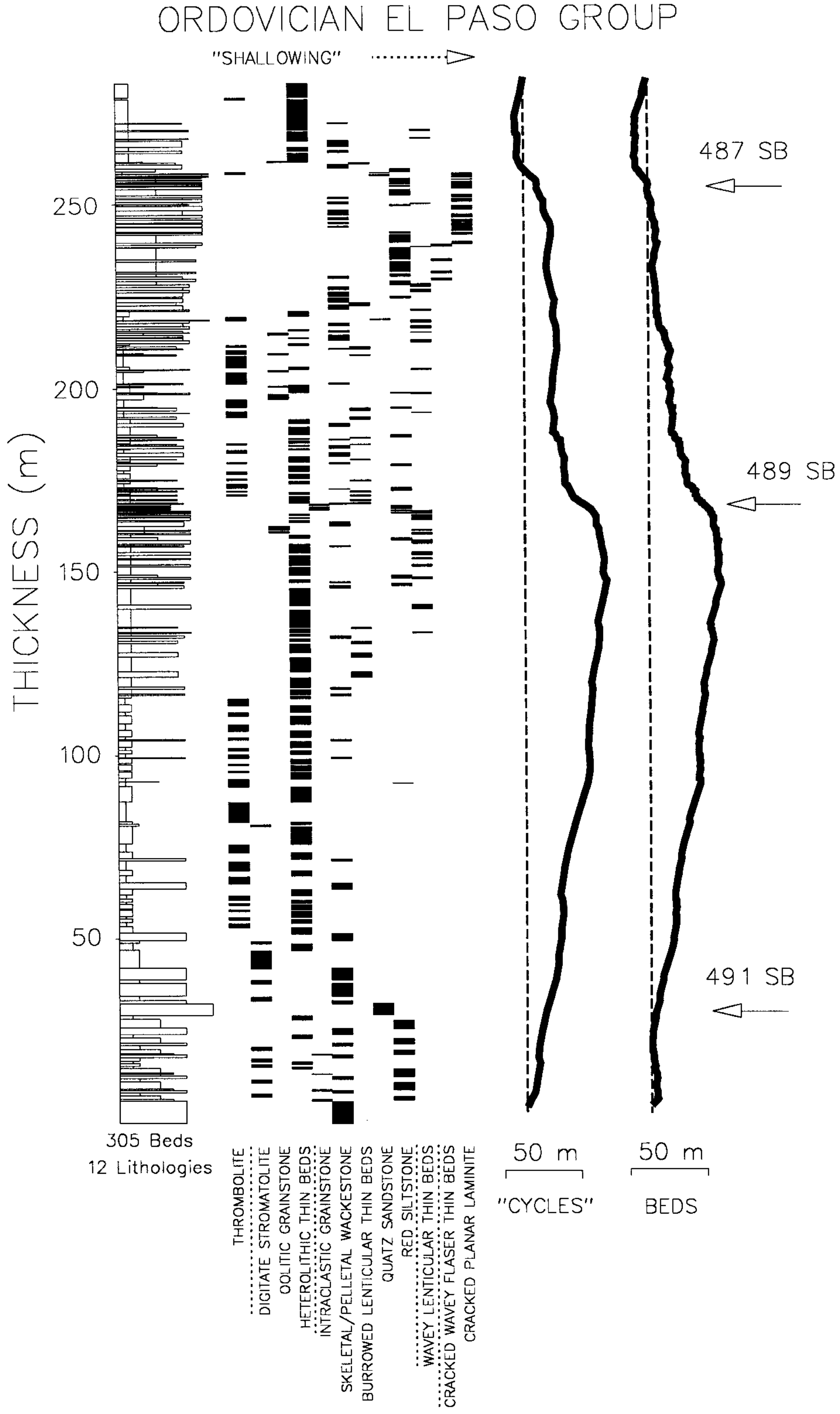

FIG. 9.—Section through the Ordovician El Paso Group from Goldhammer et al. (1993). Lithofacies within the 115 upward-shallowing "cycles" delineated by Goldhammer et al. (1993) allow for the identification of five depth-specific lithofacies groups (dotted lines) from basal thrombolite to cycle-capping desiccation-cracked laminite. Cumulative deviations from mean size (heavy lines) trend to the right across intervals containing elements that are thicker than average (dashed lines). Age (Ma) and stratigraphic location of three sequence boundaries identified by Goldhammer et al. (1993) are shown as the three arrows.

on the San Juan River near Mexican Hat, Utah (Gianniny and Simo 1996). Meter-scale shallowing cyclicity is no more apparent in these eight sections than in the three sequences discussed above. On the basis of these considerations, we conclude that categorical assertions of high-frequency shallowing cyclicity in peritidal carbonates are perhaps more deeply founded in subjective perception than in rigorous documentation of the actual existence of such order.

What then might be concluded from such examination of peritidal sequences? First and perhaps most importantly, it seems apparent that depositional processes across shallow carbonate platforms were not signifi-

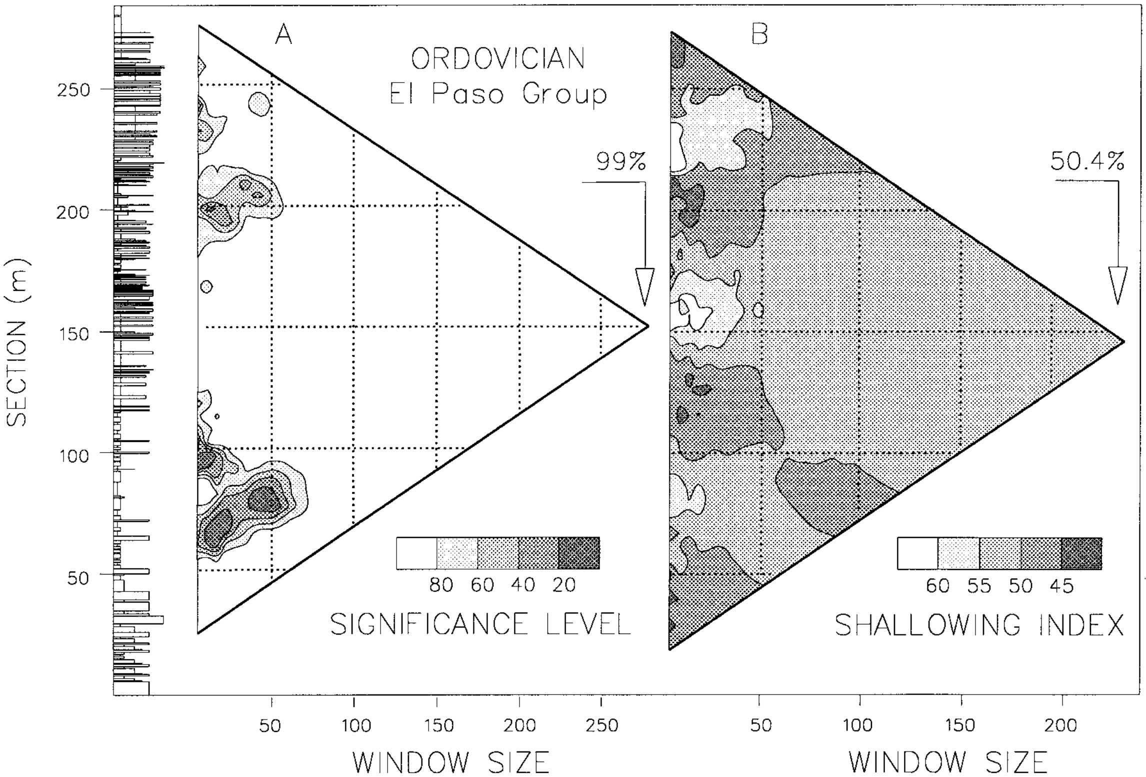

FIG. 10.—Stratigraphic distribution of **A)** critical significance levels and **B)** shallowing indices as a function of window size for the Ordovician El Paso Group section in Figure 9. Note that significance levels (degree of stratigraphic order) are high over most sequence intervals down to a window size of about 50 units, but that SI values indicate little tendency (sectional SI = 50.4%) for contiguous elements to ''shallow up''.

cantly unlike those now documented on more areally restricted Holocene counterparts. Resultant units comprise a continuum of grainstone to mudstone lithologies that range in size from lower practical limits of discrimination at perhaps a few millimeters, to those few units up to several meters in thickness. It is this high degree of lithologic variability over relatively short stratigraphic intervals that is perhaps the most characteristic feature of peritidal carbonate sequences. Embedded Markov analysis indicates that, at a typical scale greater than several dozen units, and up to several hundred units, these peritidal sequences may exhibit a high degree of stratigraphic order (critical significance levels approaching of 99%). This scale of variation is indeed a reflection of nonrandom change in the lithologic attributes of accumulated units, and very probably does record longer-term change in subsidence, sealevel, and/or the rate/intensity of depositional processes. In addition, such upsection instability, while perhaps not periodic, may well exhibit intrabasinal to interbasinal scales of correlation (e.g., Osleger and Read 1993).

Conversely, Markov and shallowing analyses strongly suggest that, at a scale of only several stratal elements, a similar degree of order is lacking in most parts of these peritidal carbonate sequences. Presumption of ''meter-scale'' shallowing cyclicity is simply not supported by the results of these numerical techniques. If high-frequency order is in fact not present in these sequences, how then is cyclicity commonly distinguished and, in its absence, what can be said about patterns of lithologic succession in peritidal carbonates? In the former case, it appears that cycle segregation is commonly based on the presence of some particular ''cycle top'' lithology such as exposure breccia and/or cryptalgal laminite that is interpreted as recording the near or complete filling of available accommodation space. By definition then, any overlying stratal unit must represent either a cycle base (if cyclicity is perceived as being purely upward-shallowing) or the basal transgressive portion of a regressive–transgressive couplet. If the occurrence of some near-exposure lithology alone is taken as sufficient evidence for the ''recognition'' of a cycle top, then it is a relatively straightforward exercise to designate shallowing cycles throughout almost any peritidal sequence containing a reasonable diversity of rock types. However, this exercise in and of itself yields no assurance that resulting ''associations'' are of any genetic significance. The stratigraphic length, lithologic constitution, and number of stratal elements that actually occur in real-world peritidal ''cycles'' are in fact often numerically indistinguishable from the number ''cycles'' which could be defined in random sequences of typical peritidal lithologies (e.g., Wilkinson et al. 1996).

Lack of meter-scale shallowing order in epicratonic sequences simply implies that facies successions are more or less random and that, depending on their abundance, any two lithologic elements of any inferred depth of accumulation are as likely to be in contact as any other. Such complexity does not necessarily mean that application of Walther's Law in peritidal carbonate sequences is invalid, only that the nature of lateral (and resultant vertical) transitions may be exceedingly complex. A similar lack of stratigraphic predictability has recently been discussed at some length by Ganiny and Simo (1996), who report that the 55 to 63 shallowing ''parasequences'' in the Hermosa Group near Mexican Hat, Utah, exhibit no less than 50 different lithologic successions. They conclude that this (lack of order) largely reflects a high degree of lateral facies substitutability and ''non-Waltherian'' lithologic transitions across the Middle Pennsylvanian Paradox Basin. Many other peritidal sequences evidently accumulated under similar circumstances.

In addition to apparent lack of stratal order, the Hermosa Group also contains no less than 25 paleosol horizons developed during subaerial exposure. What is really interesting about these surfaces is that they are nearly equally represented in a broad range of lithofacies types and inferred depths of accumulation (Fig. 13). Nearly identical paleosol distributions are ap-

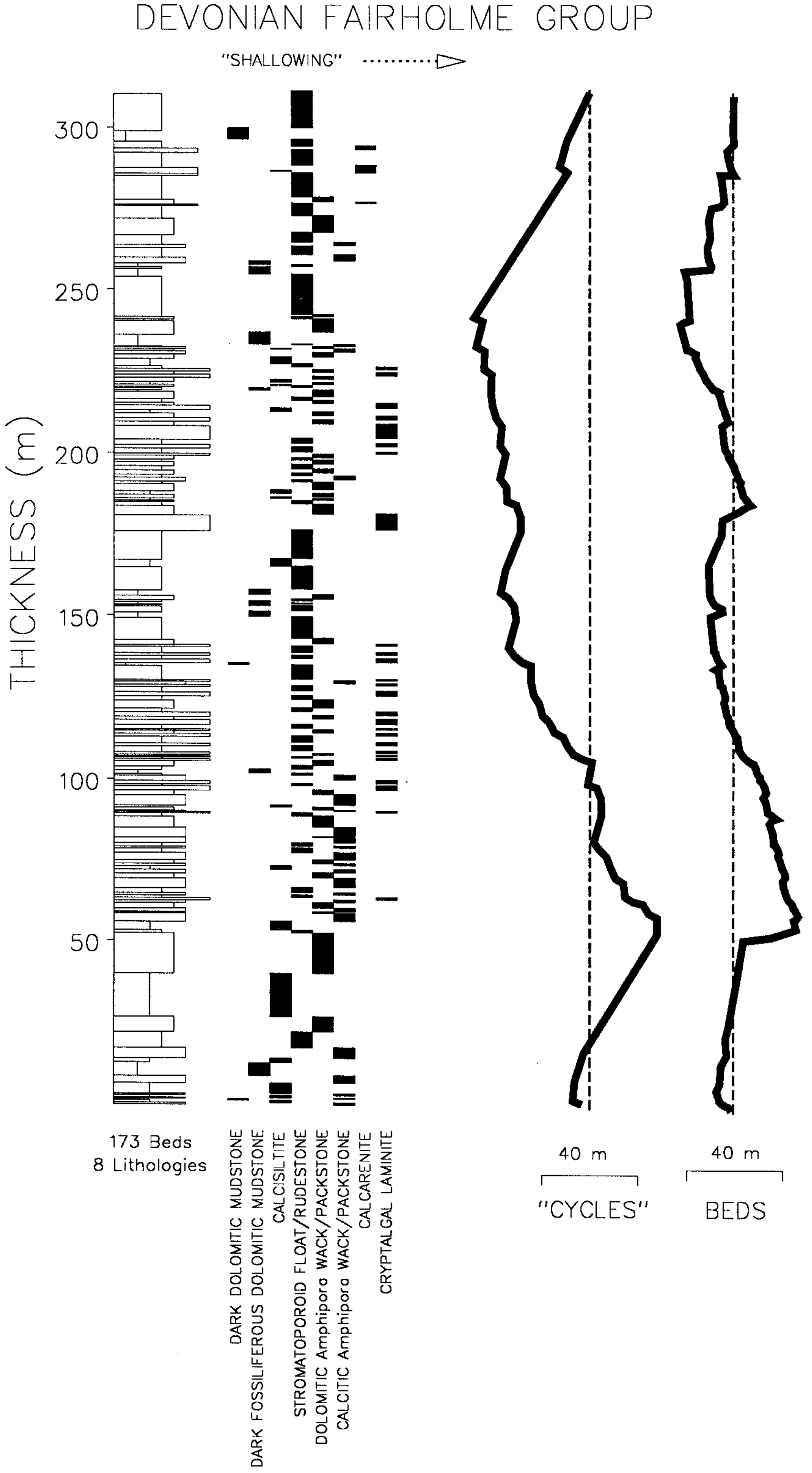

FIG. 11.—Section through the Devonian Fairholme Group at Coronation Mountain. McLean and Mountjoy (1994) report that this 310 m section contains 173 units composed of 8 distinct lithologies. Demarcation of 61 upward-shoaling cycles in this section allows for designation of five depth-related lithofacies groups ranging from basal thrombolite to cycle-capping cryptalgal laminite and exposure breccia. As in Figures 7 and 9, the two curves show cumulative deviation from mean thickness (dashed lines) for the 61 cycles identified by McLean and Mountjoy (1994), and for the 173 lithologic units that we identified in this sequence.

parent in Carboniferous platformal sequences in the Karatau Mountains of southern Kazakhstan (Lehmann et al. 1996) and to a lesser degree the Appalachian Basin (Al-Tawil and Read 1996). In all three of these "ice house" sequences, exposure horizons occur more or less indiscriminately throughout subtidal upper slope and platform margin, as well as platform-interior facies. In all three sequences it seems clear that shallowing of water prior to subaerial exposure (as a result of either eustatic or tectonic processes) was generally not recorded by the accumulation of lithologies at successively shallower depths.

Paleosol development on deep-water units of Carboniferous sections is of course directly analogous to lack of stratal order in the other peritidal sequences discussed above, in that all reflect an abrupt juxtaposition of

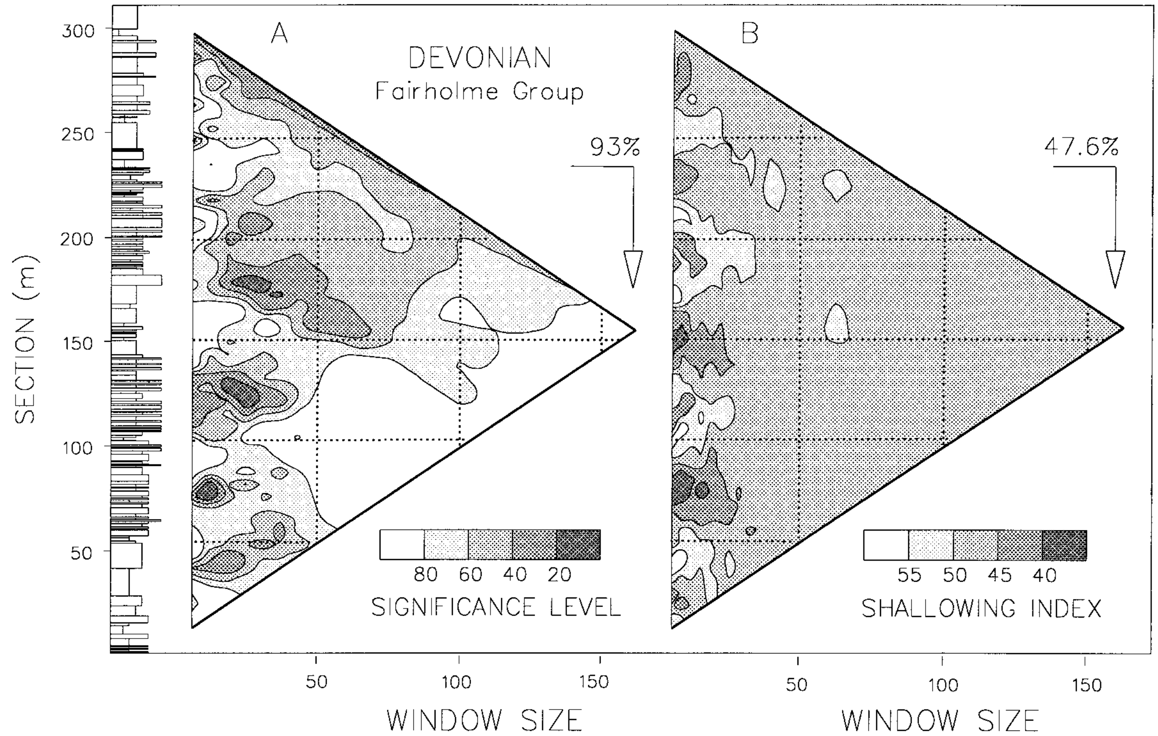

FIG. 12.—Stratigraphic distribution of **A)** critical significance levels and **B)** shallowing indices as a function of window size for the Devonian Fairholme Group in Figure 11. Significance levels and degree of stratigraphic order are variable but generally decrease with smaller window size. Shallowing indices reveal a greater tendency for associated lithofacies to deepen than to shallow upsection (sectional SI = 47.6%).

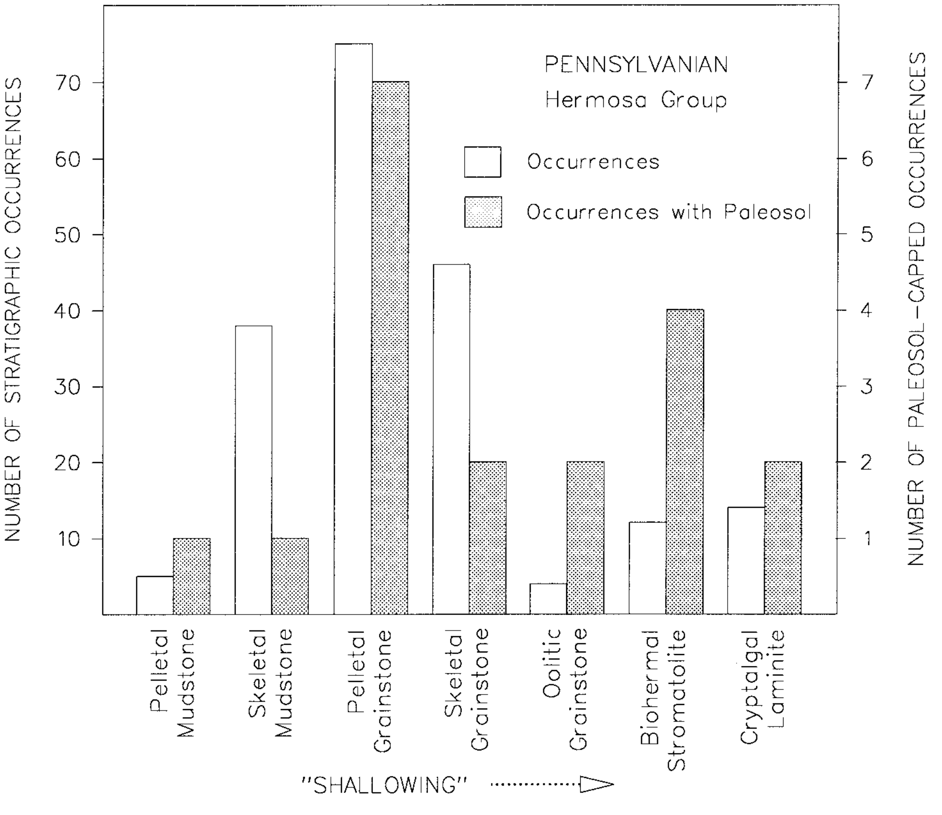

FIG. 13.—Number of stratal elements by lithology in the Middle Pennsylvanian Hermosa Group exposed at Ross Canyon on the San Juan River near Mexican Hat, Utah (open bars, left axis) and number of stratal elements by lithology capped by a subaerial exposure surface (stippled bars, right axis) from data in Gianniny and Simo (1996). Note that paleosols occur in general proportion to the abundance of each type of lithology, and bear little relation to inferred depths of accumulation.

units deposited at significantly different (negative in the case of paleosols) water depths, and that all exhibit a general absence of transitional lithologic states. Two explanations for this apparent lack of stratigraphic continuity or order are conceivable. First, it is at least plausible that relations between depths of peritidal carbonate accumulation and lithologic composition are much more complicated than is generally acknowledged. It is conceivable that most, if not all, of the entire compositional range of common peritidal lithologies has accumulated over nearly identical depth ranges. Regardless of lateral continuity of individual units, such lateral equivalence of lithofacies elements would readily result in a complex mosaic of lithofacies elements, all deposited within the same range of relatively shallow waters. Episodic exposure of such an unordered assemblage would therefore result in soil development over a wide range of rock types. Moreover, because all represent similar depths of accumulation, there would be no reason to anticipate the dominance of any specific facies tract laterally across the system or the presence of any particular motif of shallowing or deepening stratal order in resultant vertical sections.

Conversely, one might take the stance that lithofacies composition indeed does closely record relative depths of accumulation, but that relations between change in water depth and change in rock type are nonlinear. Presumably, any substantial decrease (or increase) in water depth might result in cessation of sediment deposition such that progressive regression (or transgression) is not (or is infrequently) recorded in stratigraphic sequences. The actuality of such ''unfilled accommodation space'' (e.g., Gianniny and Simo 1997) is conceptually analogous to that of ''lag time'' (e.g., Read et al. 1986) or ''lag depth'' (e.g., Goldhammer et al. 1990), a depositional lapse that has been frequently (but rather uncritically) invoked to explain a perceived absence of transgressive lithofacies in supposed shallowing meter-scale cycles. Although absence of cyclic order obviates any need for an explanations of hiatal transgression during formation, there is no compelling reason to also presuppose that change in water depth across carbonate platforms need be faithfully recorded by the lithologic composition of accumulated sequences. Lack of meter-scale stratal order merely suggests that peritidal carbonate sequences are ambiguous records of high-frequency sealevel change, be the magnitude of that variation periodic, episodic, or insignificant.

ACKNOWLEDGMENTS

We thank Robert Demicco, Robert Ginsburg, Robert Goldhammer, John Grotzinger, Lawrence Hardie, Linda Hinnov, Michelle Kominz, Dan Lehrmann, David Osleger, Fred Read, Peter Sadler, and Wan Yang for direct and benign assistance in discriminating some of the problems addressed herein, and as sources of continued motivation during the progression of these studies. Early drafts of the paper benefited greatly from reviews by Linda Albertzart, Clint Cowan, Gregor Eberli, Maya Elrick, Kelly Fuks, Michelle Kominz, Dan Lehrmann, David Osleger, and John Southard. Research on patterns of epicratonic carbonate accumulation is supported at the University of Michigan by National Science Foundation grant EAR-94-05551.

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Received 21 October 1996; accepted 14 June 1997.