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Cycle Anatomy and Variability in the Storm-Dominated Type Cincinnatian (Upper Ordovician): Coming to Grips with Cycle Delineation and Genesis[1]

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ABSTRACT

Although parasequence and sequence are scale-independent terms, they are frequently applied only to specific scales of cycles. For example, meter-scale cycles are commonly assumed to be parasequences or PACs. In the Upper Ordovician Kope and Fairview Formations of northern Kentucky, we examined a succession of 50 meter-scale cycles that have been variously interpreted as deepening-upward, shallowing-upward, or showing no relationship with water depth. Our analysis shows that these cycles, characterized by shifts in storm-bed proximality, are highly variable in their thickness and internal construction. Most cycles are best considered high-frequency sequences, because deepening-upward intervals are common, and many cycles contain evidence of abrupt basinward shifts in facies as expected at sequence boundaries. A minority fit the parasequence model of shallowing-upward cycles bounded by flooding surfaces. Larger, 20 m scale cycles are defined by systematic thickening and thinning trends of meter-scale cycles. However, meter-scale cycles do not display any systematic trends in cycle anatomy as a function of position within the 20 m cycles or position within the Kope and Fairview Formations. The high cycle variability and the lack of systematic stratigraphic organization with respect to longer-term cyclicity reflect either the irregularity of relative sea-level changes, the poor recording of sea-level changes in this deep-water setting, or the generation of these cycles by climate-induced cyclicity in storm intensity. These three mechanisms would generate similar patterns at the outcrop scale, so it is not possible at the present to distinguish between them.

Introduction

The parasequence and the sequence are currently the two most widely recognized types of sedimentary cycles. Parasequences have the more rigidly defined structure of the two and consist of a shallowing-upward cycle bounded above and below by marine flooding surfaces (Goodwin and Anderson 1985; Van Wagoner et al. 1990). In contrast, sequences can display a much wider variation in expression. Sequences are bounded by surfaces of subaerial exposure, or their correlative submarine erosion surfaces or correlative conformities, and may display a variety of water depth trends, depending on which systems tracts are locally present (Van Wagoner et al. 1990).

Both parasequences and sequences are defined only on the basis of their bounding surfaces and internal structure; time scales of formation and thickness of cycles are irrelevant in their definition (Posamentier and James 1993). This point has been underscored by the increasing recognition of high-frequency sequences (Mitchum and Wagoner 1991; Posamentier et al. 1992a), and by the realization that sequences can pass laterally into parasequences as rates of long-term accommodation increase (Van Wagoner et al. 1990; Mitchum and Wagoner 1991). Despite these demonstrations that thickness and time are not part of the definitions of parasequences and sequences, there remains a tendency by many workers to automatically consider meter-scale cycles to be parasequences, often with little critical evaluation of their internal structure or variability thereof.

This paper was generated as part of a larger study attempting to regionally correlate meter-scale cycles identified previously in the Kope and Fairview

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Formations of the type Cincinnatian (Hay 1981; Hay et al. 1981; Tobin and Pryor 1981; Jennette 1986; Tobin 1986; Jennette and Pryor 1993). As we began to identify cycles on the outcrop, we were struck by how poorly they consistently fit any particular model of cyclicity. In this paper, we examine the varying expression of cycles in the Cincinnatian that were previously interpreted as parasequences. On this basis, we argue that more critical evaluation of cycle variability is needed because of its implications for correlation, relative sea-level history, and, more fundamentally, the ways in which meter-scale cyclicity is interpreted.

Regional Background. The Kope and Fairview Formations are the lowermost formations in the type Cincinnatian (Upper Ordovician) and consist of a series of alternating shale and limestone beds. Storm deposition dominated in these units, as it did throughout much of the type Cincinnatian (Kreisa et al. 1981; Tobin 1982; Jennette and Pryor 1993). Based on storm bed anatomy, sedimentary structures, fossil morphologies, and taphonomy, as well as vertical and lateral facies relationships, the Fairview Formation has been interpreted as being deposited between fair-weather and storm wave base, with the Kope Formation deposited below the wave base of all but the most intense storms (Tobin 1982; Holland 1993; Jennette and Pryor 1993). The presence of abundant skeletal grains, coupled with the relative scarcity of micrite and the absence of ooids and peloids indicates temperate-type or cool-water limestone deposition, despite the 20°S latitude of Cincinnati during the Late Ordovician (Nelson 1988; Holland and Patzkowsky 1996). Both formations were deposited on a northward-dipping ramp along what is now the Cincinnati Arch and what was then the distal edge or peripheral bulge of the Appalachian Foreland Basin (Tobin 1982; Weir et al. 1984; Beaumont et al. 1988; Holland 1993; Jennette and Pryor 1993).

Cincinnatian Meter-Scale Cycles. Meter-scale sedimentary cycles have been recognized in the Upper Ordovician of the Cincinnati, Ohio, area for at least the past fifteen years. Hay (1981; Hay et al. 1981) recognized that, within the Kope Formation, 25–30 cm rippled grainstones were regularly spaced approximately every 2 m and were separated from one another by thick, shaly intervals (figure 1). She interpreted these thick grainstones as recording periodic clusters of intense storms.

At the same time, Tobin also recognized sedimentary cycles in the Kope Formation. Tobin and Pryor (1981) viewed these cycles as consisting of a basal intraclastic and bioclastic grainstone (Unit A), a middle bioclastic packstone and shale unit (Unit B), and an upper shale-rich unit containing rippled and hummocky siltstones (Unit C; Figure 1). Tobin and Pryor emphasized the upward bed-thinning of limestones and the sharp contact between the upper shale unit of one cycle and the overlying grainstone unit of the following cycle. They recognized vertical variability of the cycles, particularly in the local absence of the middle packstone-shale unit, and in the presence of apparently non-cyclic intervals in the Cincinnatian. Tobin and Pryor envisioned alternating clear and turbid water storm deposition as producing these cycles. The shale and siltstone unit was viewed as the rapid deposition of mud from one or more storms that generated an abrupt decrease in local water depth. The grainstone unit was deposited following the storm and represented clear water background conditions in the newly shallower water. The packstone-shale unit was deposited in deeper water than the grainstone unit as subsidence and compaction gradually lowered the seafloor.

Tobin (1982) later reevaluated the structure and interpretation of these cycles. He noted that the transition from the grainstone unit to the packstone-shale unit occurred in only 24% of the cycles, and he thereby redefined all of the cycles as consisting of a lower carbonate hemicycle (including his previous grainstone and packstone-shale units) and an upper shale hemicycle (equivalent to his shale-siltstone unit). The carbonate hemicycle was characterized by a low (<20%) shale content, and numerous thick and closely spaced bioclastic grainstones, packstones, wackestones, and calcisiltites. The shale hemicycle was characterized by a high (~70%) shale content and relatively thin siltstones, calcisiltites, and lime mudstones. Tobin reinterpreted the cycles as having been generated by fluctuating sediment supply under constant water depths, rather than by fluctuating eustasy or subsidence.

In a subsequent thorough and detailed study of storm deposition, Jennette (1986) and Jennette and Pryor (1993) described the same Kope cycles as consisting of a basal distal storm facies and an upper proximal storm facies. The distal storm facies included abundant shale, graded shale layers, hummocky to laminated siltstones and calcisiltites, and thin bioclastic packstones. The proximal storm facies included amalgamated, megarippled, intraclastic and bioclastic grainstones. Jennette and Pryor's cycles differed notably from Tobin's in that they coarsened upward, rather than fined upward, and in that the grainstone facies was abruptly overlain by the shale-rich facies, not vice versa as Tobin had argued. Jennette used the proximality concept of

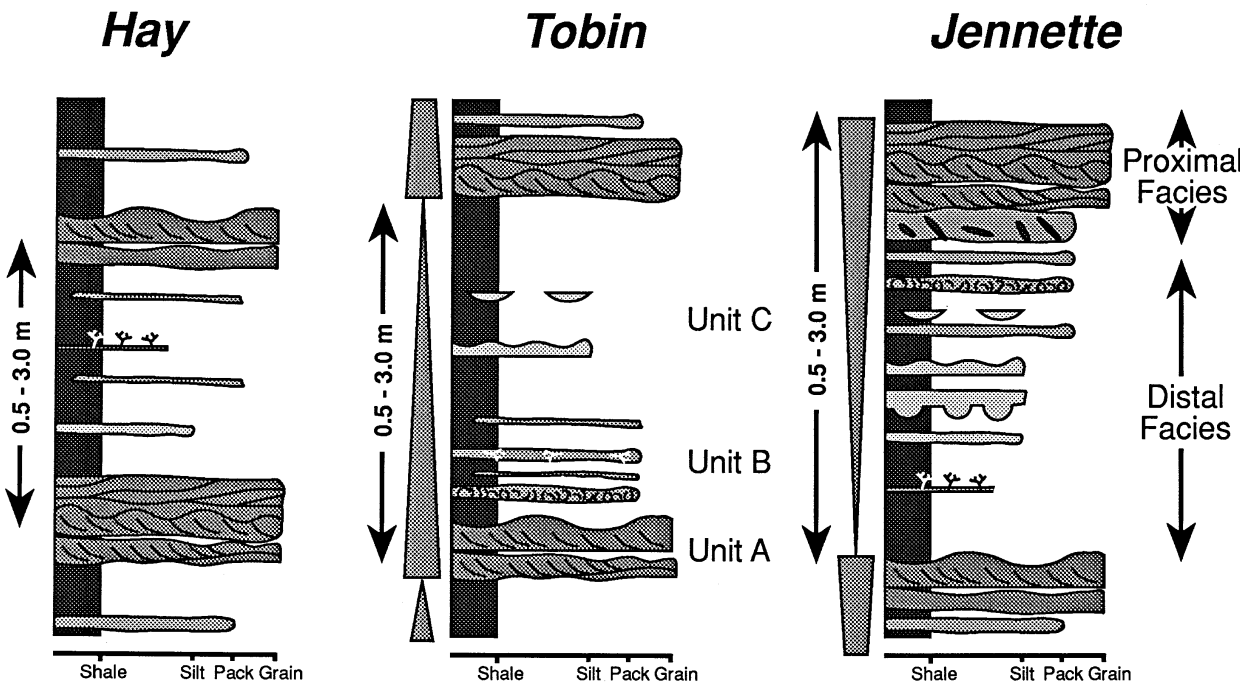


Figure 1. Previous models of Kope Formation meter-scale cycles. Hay noted the regular spacing of grainstone bundles. Tobin also recognized their spacing, but saw the cycles as deepening-upwards, as indicated by the triangles. Jennette viewed the cycles as shallowing-upwards. Tobin labeled three divisions of each cycle: Unit A is the basal series of amalgamated grainstones; Unit B is interbedded packstones and shale; Unit C is dominated by shales but contains rare calcisiltites. Jennette subdivided his cycles only into a proximal and a distal facies; his proximal facies corresponds roughly to Tobin's Unit A and his distal facies corresponds roughly to the combined Units B and C of Tobin.

storms (Aigner 1985) to argue that a gradual upward change from distal to proximal storm facies indicated a shallowing-upward cycle and that the abrupt upward switch from proximal to distal storm facies indicated a relative rise in sea level, which he attributed to glacioeustasy. Although he mentioned that some cycles show evidence of a more abrupt shallowing, Jennette emphasized the essentially continuous shallowing and the abrupt deepening in these cycles.

It is important to recognize that all of these workers examined many of the same outcrops and that they came to different conclusions about not only the mechanisms that produced these cycles, but also about the internal structure and definition of the cycles. In short, Hay saw a series of poorly defined limestone-shale alternations reflecting no change in water depth, Tobin originally saw a series of well-defined deepening-upward cycles but later considered the cycles to be less well structured, and Jennette saw a series of well-defined coarsening-upward cycles. This paper focuses on the internal structure of these cycles and characterizes their variability to understand how several workers could come to such different conclusions about the same rocks. The issue of cycle correlation, about which these authors also disagreed, adds still more complications and will be discussed in a future paper on methods of high-resolution correlation.

Methods

For this study, we measured an approximately 68 m composite section along the Ohio River, just east of Cincinnati (figure 2; locality descriptions are available from The Journal of Geology data repository). Roughly the lowest 10 m of the Kope Formation was covered and not measured; otherwise, the section spans the entire Kope Formation and the basal 8 m of the Fairview Formation (figures 3, 4). We marked the outcrop into 10 cm increments and described the rock type, sedimentary structures, trace fossils, and bedding continuity for all beds thicker than 5 mm, an unusually fine scale of measurement. The four outcrops that comprise the composite are spread over 0.5 km and were initially correlated to one another by reciprocal sightings with a telescopic hand level. These correlations were further refined by recognizing individual beds and bed successions in the stratigraphically overlapping portions of adjacent sections, such that we have assembled a complete section with no gaps

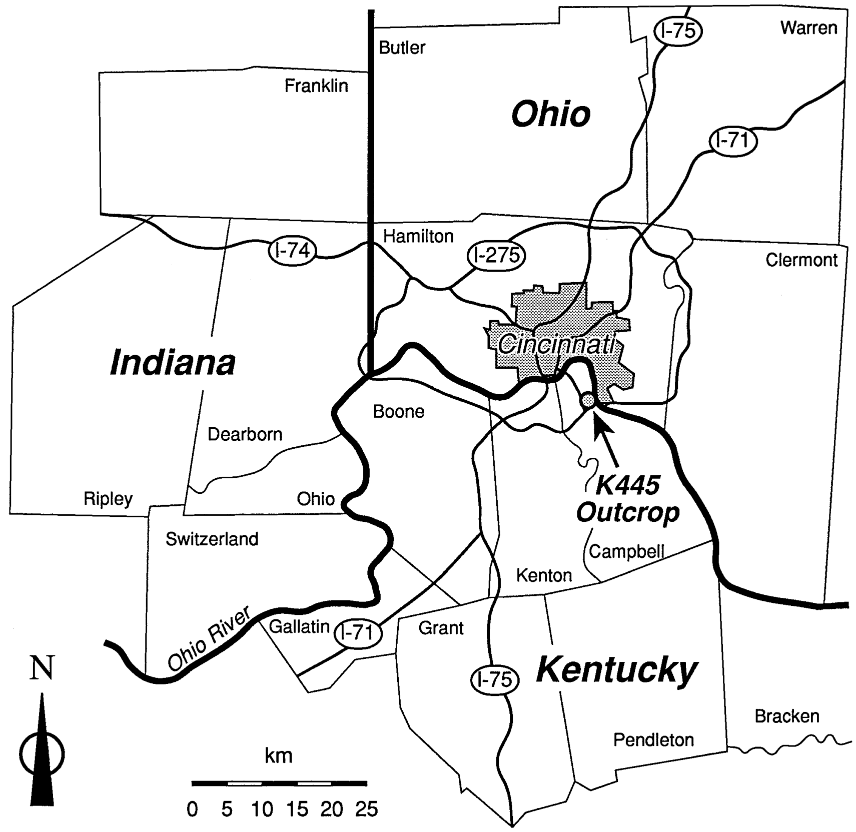


Figure 2. Location of measured section.

and no overlaps. Given the approximately 2 m.y. duration of the study interval (Holland and Patzkowsky 1996), the 50 meter-scale cycles recognized in this study average 40 kyr in duration.

Identifying Cycles. Several studies (e.g., Kreisa 1981; Brett 1983; Aigner 1985; Brett and Baird 1985; Myrow 1992) have documented the anatomy of storm beds in relation to storm proximality. Most of these authors have concluded that proximal storm beds are characterized by thick, skeletal grainstones containing megaripples, intraclasts, and amalgamation surfaces. Medial storm beds are typically thin skeletal packstones with or without a hummocky-to-rippled siltstone cap. Distal storm beds are usually planar-to-rippled siltstones, and ultradistal storm beds are simply graded or structureless mudstones. Grain size and bed thickness typically decrease in a distal direction. Although proximality reflects in part the strength and proximity of a storm, most of these workers have considered consistent vertical trends in storm beds to be more parsimoniously explained by changes in water depth, an assumption we adopt here as a working hypothesis, but also one that we will question below.

We initially picked cycles assuming a parasequence/PAC model of cyclicity, in which shallowing-upward cycles are bounded abruptly by sharp flooding surfaces, as did Jennette and Pryor (1993), and our cycles are similar to theirs. Flooding surfaces were identified by abrupt changes from proximal-to-distal storm beds; flooding surfaces are commonly recognized by an abrupt increase in the thickness of shale beds. In some portions of the column, we had difficulty recognizing sharply defined flooding surfaces and subsequently reevaluated our cycle picks until we were satisfied with the consistency with which we could recognize cycles. That cycles could not be picked reliably on our first attempt is an important point we will discuss below. Our prior expectations of cycle anatomy and thickness played a strong role in our cycle picks, another point we will discuss later in the paper. We would not be surprised if other workers would pick somewhat different cycles, particularly in certain intervals, and we would regard those different picks as a demonstration of cycle variability and its influence on the identification of cycles.

Generating the Cycle Database. To characterize cycle variability and to search for systematic vertical trends in cycle architecture, we measured several aspects of each cycle, starting with cycle thickness. Based on progressive changes in storm bed proximality, we measured the percent of each cy-

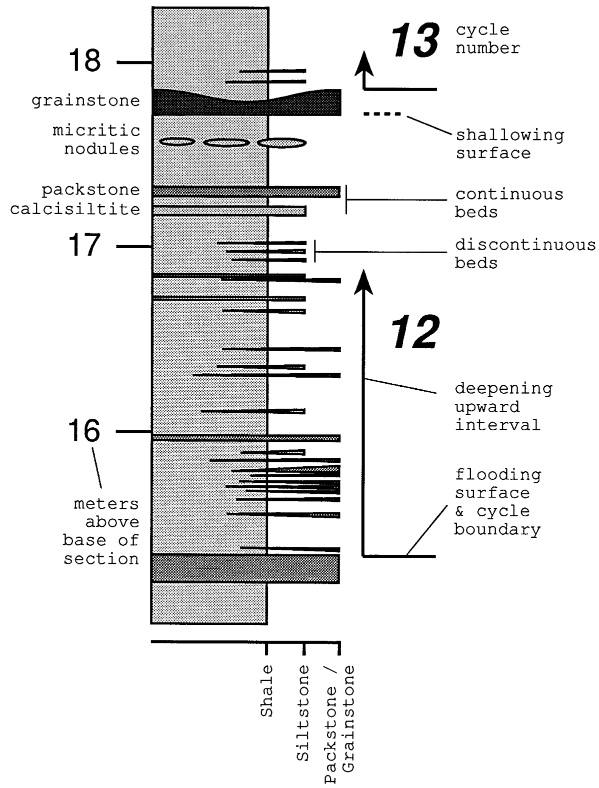


Figure 3. Key to measured sections. Deepening-upward intervals span the distance between the flooding surface/cycle boundary and what is interpreted as the deepest deposits within a cycle. The thickness of the proximal cycle cap (or micro-lowstand) is the distance between the shallowing surface and the overlying flooding surface. The shallowing-upward interval of a cycle corresponds to the remaining parts of the cycle, that is, the portion of the cycle between the deepening-upward interval and the proximal cycle cap. If these two divisions are absent in a cycle, the entire cycle is shallowing-upward. Continuous beds are beds that could be traced on the outcrop for at least 10 m laterally; discontinuous beds pinched out within 10 m. All lithologies are distinguishable in the section by gray tones; shales, siltstones, and packstones/grainstones are also distinguishable by how far to the right a bed extends.

cle's thickness that was: (a) shallowing-upward, (b) deepening-upward, or (c) represented by a sharp-based highly proximal cycle cap (figure 3). Not every cycle contained all three of these subdivisions. Because individual storms can vary in intensity, storm bed proximality does not simply reflect water depth, so we looked for clear proximality trends among several successive storm beds and did not base any depth interpretation on a single storm bed. Individual storm beds that contradicted an overall trend were considered to represent unusually strong or weak storms.

We also coded each cycle based on whether its shallowing or deepening occurred gradually, abruptly at a single surface, or in some combination of the two. We also recorded the shallowest and deepest facies present within each cycle. Finally, we recorded whether micritic nodules were present within each cycle because their rare occurrence suggested that they might indicate significantly unusual depositional conditions. These data were used subsequently for a multivariate stratigraphic comparison of cycle architecture (see below).

Cycle Variability

Meter-scale cycles in the Kope and Fairview Formations show considerable variability in several aspects, including the rate of shallowing and deepening, the shallowest and deepest facies present, the presence of minor within-cycle reversals in storm bed proximality, and overall cycle thickness.

Variability in Shallowing and Deepening. The parasequence model of cyclicity predicts a simple shallowing-upward cycle bounded by marine flooding surfaces (Van Wagoner et al. 1990). Despite the emphasis of some on transgressive deposits (Posamentier and Allen 1993; Arnott 1995), most workers have emphasized the simple shallowing-upward nature of parasequences. Some have suggested that non-shallowing-upward parasequences are rare if they exist at all and that transgressive lags are absent at parasequence boundaries except where they coincide with sequence boundaries or maximum flooding surfaces (Van Wagoner et al. 1990). Moreover, the shallowing that occurs within a parasequence is widely attributed to either progradation (e.g., Van Wagoner et al. 1990) or aggradation (e.g., Goodwin and Anderson 1985; Anderson and Goodwin 1990) under a relatively constant sea level. Parasequences have not been described as having abrupt decreases in water depth (Van Wagoner et al. 1990), a situation that would imply a relative fall in sea level (Posamentier et al. 1992b).

Most cycles in our study show evidence of a deepening-upward interval near their base rather than simply a marine flooding surface, as would be expected in a parasequence (figure 5; e.g., cycles 3 and 17 in figure 4). The deepening-upward interval is usually thin, and in the majority of cycles, it comprises <25% of the cycle thickness (figure 6; e.g., cycles 10 and 31 in figure 4). In a few rare cases, up to 75% of a cycle can record upward deepening (figure 6; e.g., cycles 9 and 11 in figure 4). In Tobin's (1982) model, meter-scale cycles are upward-deepening and consist of a basal amalgamated skeletal grainstone, a middle unit of skeletal packstones

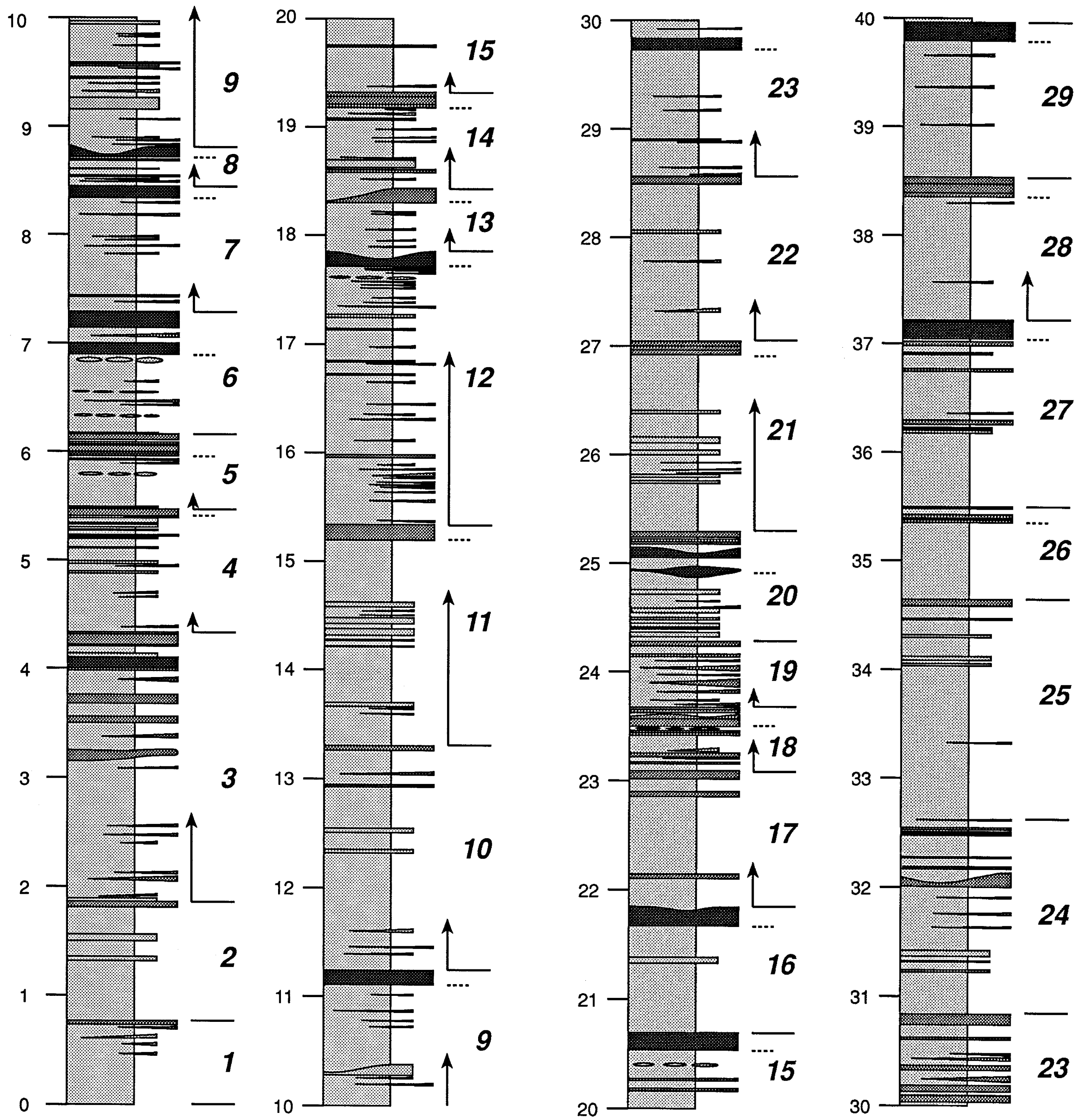
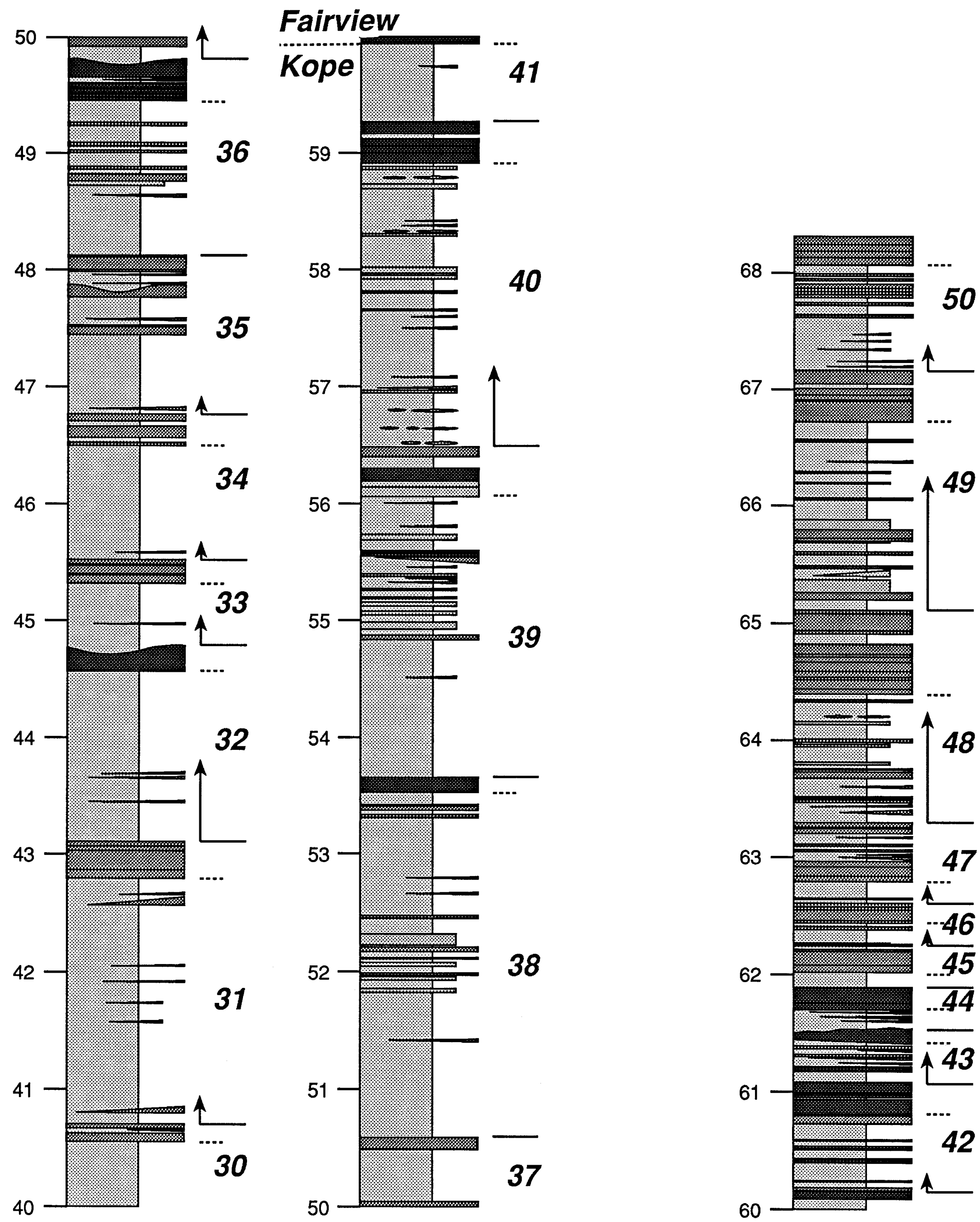


Figure 4. Measured section through most of the Kope Formation and the lower part of the Fairview Formation. Kope-Fairview contact lies at 59.9 m at the shallowing surface within cycle 41 and represents a third-order sequence boundary between the C1 and C2 sequences (Holland et al. 1993; Holland and Patzkowsky 1996). See figure 3 for key to section.

and laminated calcisiltites, and an upper unit dominated by shale. Our results suggest that, although deepening-upward intervals are common, most cycles are not mostly deepening-upward as predicted by Tobin's model. On the other hand, the majority of the cycles do not have a simple flooding surface as would be expected in Jennette's parasequence model.

Most cycles contain a thick shallowing-upward interval, with 70% of the cycles containing smoothly shallowing-upward intervals comprising over half of the cycle thickness (figure 7; e.g., cycles 10 and 39 in figure 4). Jennette's ideal model of Cincinnatian meter-scale cyclicity considered these cycles to be shallowing upward, a conclusion supported (but modified below) by our study. The find-



ing of widespread thick shallowing-upward intervals argues against Tobin's deepening-upward model of cyclicity.

The plurality of cycles display an abrupt shift from distal to highly proximal storm beds rather than simply a smooth progression from distal to proximal storm beds, as would be expected in a parasequence (figure 8; e.g., cycles 32 and 49 in figure 4). We call these abrupt shifts shallowing surfaces because they represent the opposite pattern of a flooding surface (cf. SDS or sea-level drop surface of Brett et al. 1990a). The interval between this shallowing surface and the following flooding surface typically represents <25% of the total cycle thickness. Storm beds within this interval are characterized by an amalgamated series of crinoidal, phosphatic grainstones separated by numerous cross-cutting erosional surfaces (Jennette and Pryor 1993). Cross-bedding is common as are megaripples with crests spaced approximately 1–2 m. Shale intraclasts are also common, particularly near the base of the set of grainstones. Fossil preservation

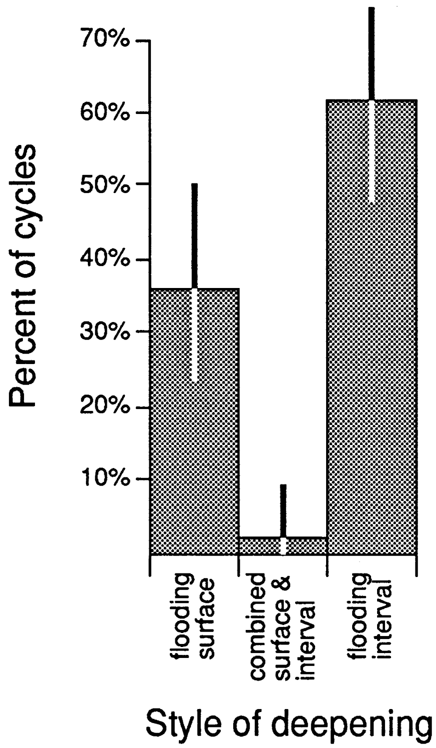


Figure 5. Percentage of all Kope and Fairview cycles containing flooding surfaces, flooding intervals, or a combination of a flooding surface and a flooding interval. A combination of the two would be reflected, for example, by an abrupt shift to distal storm beds, followed by a continued shift to even more distal storm beds. Upper and lower 95% confidence limits are shown by the black and white bars, respectively, and were calculated using the method of Raup (1991).

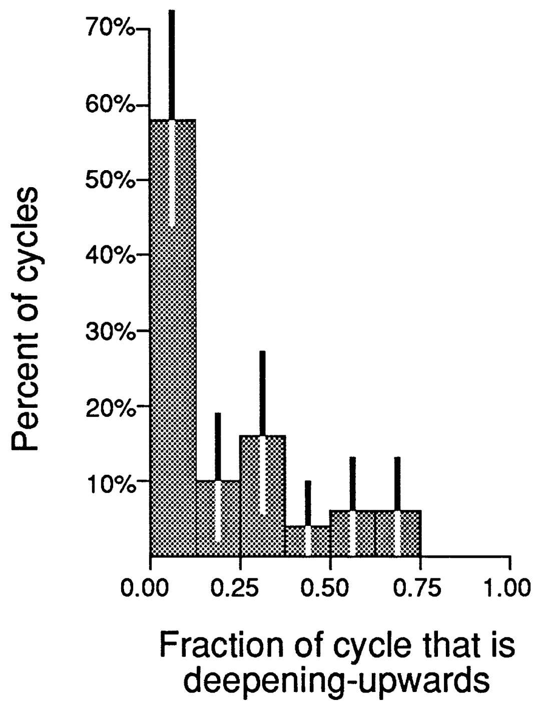


Figure 6. Percentage of cycles for which a given fraction of the thickness of a cycle records a deepening-upwards, with 0.0 corresponding to a cycle lacking any deepening-upward interval (that is, all deepening occurs at a flooding surface) and 1.0 corresponding to a cycle that is entirely deepening-upward, which is also bounded by flooding surfaces. Black and white bars: upper and lower 95% confidence limits, respectively.

in these beds is almost always poor with extensive breakage and abrasion; most bioclasts are comminuted.

We interpret these shallowing surfaces and their abrupt shifts to highly proximal storm beds as representing a basinward shift of facies in response to a relative fall in sea level. As relative sea-level fell, storm wavebase was lowered such that successive storms eroded the bottom but deposited little if any sediments. Once the ramp approached equilibrium with the newly lowered storm wave base, accumulation resumed in the form of highly proximal storm beds. Shale intraclasts at the base of these beds indicate that sea-floor erosion was extensive and sufficient to exhume compacted shales. The presence of intraclasts, the relatively coarse grain size and lack of micrite, as well as the common cross-bedding and megaripples further attest to the relatively high shear stress conditions under which these beds were deposited. The abundance of crinoidal and phosphatic grains and the highly frag-

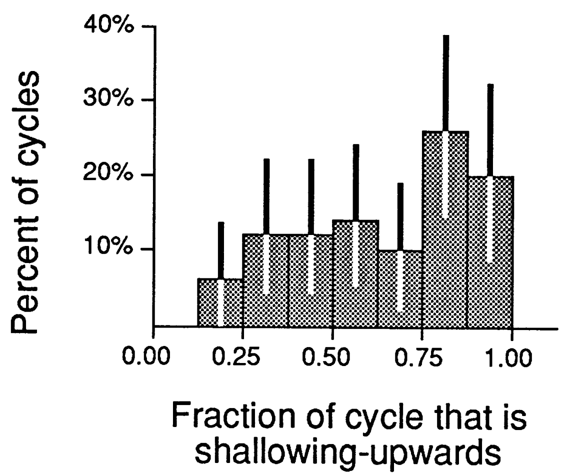


Figure 7. Percentage of cycles for which a given fraction of the thickness of a cycle records a shallowing-upward, with 0.0 corresponding to a cycle lacking any shallowing-upward interval and 1.0 corresponding to a cycle that is entirely shallowing-upward. Black and white bars: upper and lower 95% confidence limits, respectively.

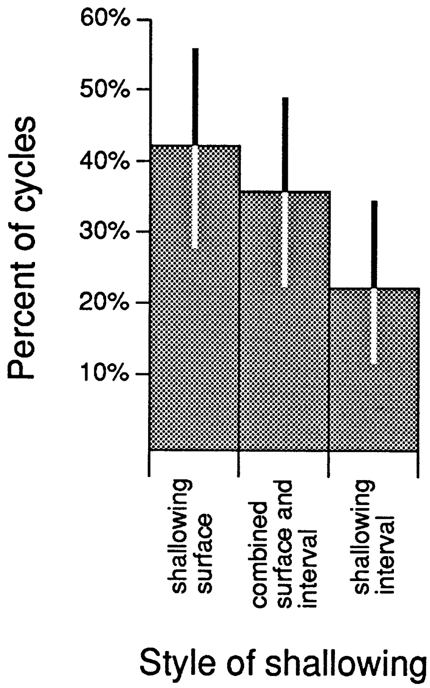


Figure 8. Percentage of all Kope and Fairview cycles containing shallowing surfaces, shallowing intervals, or a combination of a shallowing surface and a shallowing interval. A combination of the two would be reflected by a gradual shift to more proximal storm beds, followed by an abrupt shift to even more proximal storm beds, for example. Black and white bars: upper and lower 95% confidence limits, respectively.

mented and abraded nature of the bioclasts indicates prolonged reworking and enrichment in abrasion-resistant and dissolution-resistant grains. The numerous erosional surfaces within these beds indicates that this interval represents multiple events and is not interpretable as a single severe storm.

Jennette and Pryor (1993) also recognized the presence of these abrupt shallowings, and likewise argued that they represent small, relative falls in sea level. We interpret this abrupt basinward shift in facies to represent the lowstand systems tract of a meter-scale cycle, with a sequence boundary at the shallowing surface (the base of the proximal storm beds) and a transgressive surface at their top. Because these lowstand systems tracts are so much smaller than most lowstands previously described—excepting Posamentier et al. (1992a)—and because the basinward shift in facies is small relative to the overall width of the carbonate ramp, we will refer to these sharp-based grainstones intervals as micro-lowstands (cf. RLS or relative lowstands of Brett et al. 1990a).

Several cycles display minor depth reversals within an overall shallowing or deepening trend. For example, cycle 11 contains a bundle of hummocky siltstones near 14.5 m that has several potential interpretations (figure 4). This mid-cycle bundle of storm beds could mark the top of a cycle that did not shallow completely to a packstone or grainstone cap. Alternatively, it could represent a minor small-scale shallowing superimposed on an overall deepening trend, as suggested by the thick shales overlying and underlying this bundle. Finally, this bundle could represent only a cluster of stronger than normal storms and not signify any depth change. Such mid-cycle bundles are relatively common (e.g., cycles 21, 31, and 38 in figure 4), and we treated them as smaller-scale cycles within the meter-scale cycles, to be conservative in the number of cycles we recognized.

In short, Kope-Fairview cyclicity is more complex than a parasequence model would predict in that most cycles are not simply shallowing-upward cycles bounded by flooding surfaces. The presence of flooding surfaces, shallowing surfaces, deepening-upward intervals, shallowing-upward intervals, and micro-lowstands in many of the Kope-Fairview cycles suggests that these cycles are best considered to be high-frequency sequences (Mitchum and Wagoner 1991), in that they have a sequence structure, yet are components of a larger depositional sequence (i.e, the C1 sequence of Holland and Patzkowsky 1996). Aigner and Bachman (1992) reached a similar conclusion for the meter-scale cycles of the Triassic Muschelkalk.

Variability in Shallowest and Deepest Facies. Both Tobin and Jennette characterized successive Cincinnatian cycles as having similar facies at their shallowest and deepest extremes. Again, we find wide variability in the facies present at the extremes of each cycle.

The inferred shallowest facies present in each cycle is represented by amalgamated or intraclastic grainstones in one-half of all the cycles (figure 9). The amalgamated grainstone facies clearly represents a complex multi-event history of storm-induced erosion, winnowing, and redeposition. Each storm event left only a thin bioclastic grainstone welded to the grainstone lag of a previous storm. The thin nature of each of these grainstone lags, coupled with the irregular amalgamation surfaces that bound them, suggests that some depositional events may have been entirely eroded away during particularly severe storms. The shallowest facies in the remaining one-half of the cycles are bioclastic grainstones or packstones interbedded with thin shales. The presence of shale interbeds indicates less overall erosion at each storm event and sug-

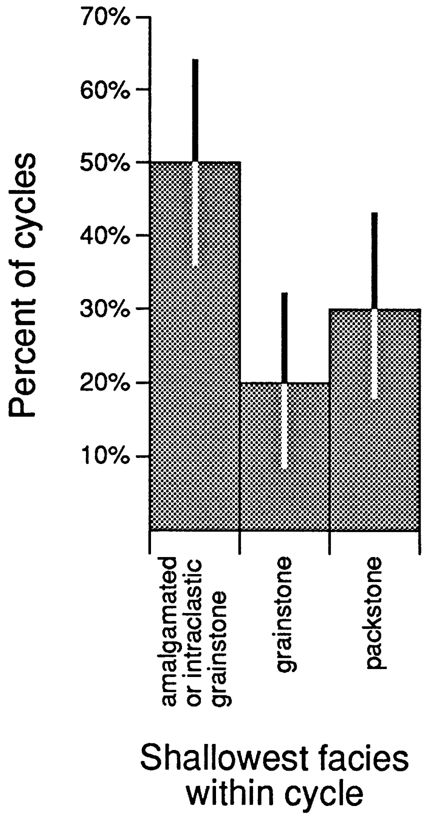


Figure 9. Percentage of all Kope and Fairview cycles in which a given facies represents the shallowest facies attained within the cycle. Amalgamated or intraclastic grainstones represent the most proximal (shallowest) facies and packstones represent the most distal (deepest) facies that occur as the shallowest part of a cycle. Black and white bars: upper and lower 95% confidence limits, respectively.

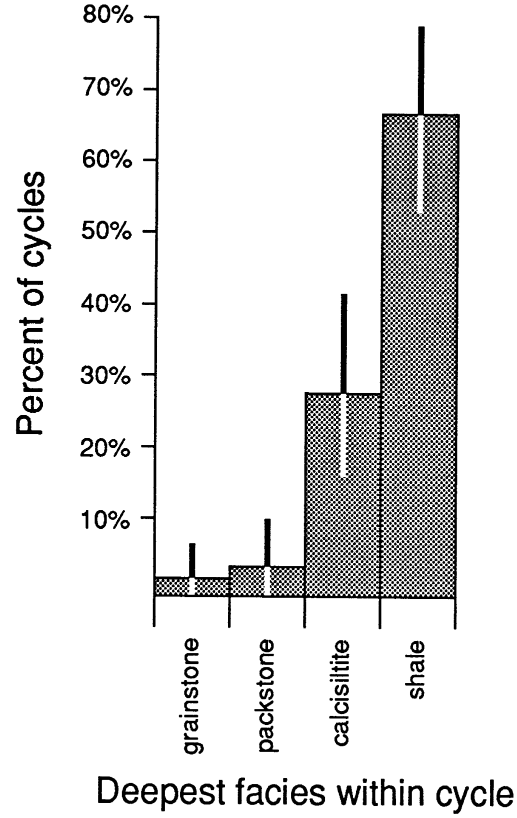


Figure 10. Percentage of all Kope and Fairview cycles in which a given facies represents the deepest facies attained within the cycle. Grainstones represent the most proximal (shallowest) facies and thick shales (>30 cm) represent the most distal (deepest) facies that occur as the deepest part of a cycle. Black and white bars: upper and lower 95% confidence limits, respectively.

gests a higher overall stratigraphic completeness within these facies. Both Jennette and Tobin indicated that every cycle was bounded by amalgamated grainstones, a feature that we recognize much less frequently than they did. As the majority of our cycles agree with their picks (compare our figure 4 to Jennette and Pryor's [1993] figure 3), the recognition of wider variability in the shallowest facies probably reflects the fact that we were specifically examining cycle variability, whereas Tobin and Jennette were likely looking for unifying common themes in these cycles and were perhaps willing to consider variations in cycle anatomy as noise.

The deepest facies of each cycle is by far most frequently represented by an interval of at least 30 cm of shale (figure 10; e.g., cycles 25, 34, and 39 in figure 4). These shaly intervals are commonly divisible into smaller graded mudstone beds and obrution deposits that blanket thin shelly pavements (cf. Brett and Baird 1986; Brett et al. 1990). Because of these features, we interpret these shaly intervals as a series of ultradistal mud tempestites. Although mudstone is the most common deepest facies within these cycles, not all cycles contain this mud-dominated facies, as Tobin's model suggests. Approximately 33% of all cycles deepen just to a laminated siltstone-shale facies, a packstone-shale facies, or in a few cases, a grainstone-shale facies. Thus, the Cincinnatian cycles also show variability with respect to shallowest and deepest facies.

Variability in Cycle Thickness. Kope and Fairview meter-scale cycles show a modal cycle thickness of approximately 1 m (figure 11). Infrequently, individual cycles may be >0.5 m thick or >3 m thick (e.g., cycles 38 and 43–46 in figure 4). The unimodal distribution and positive skewness of these cycles has been widely recognized in many carbonate cycles. Drummond and Wilkinson (1993, 1996) have argued that this distribution reflects an underlying exponential distribution of cycle thicknesses, assuming that thin cycles have been under-

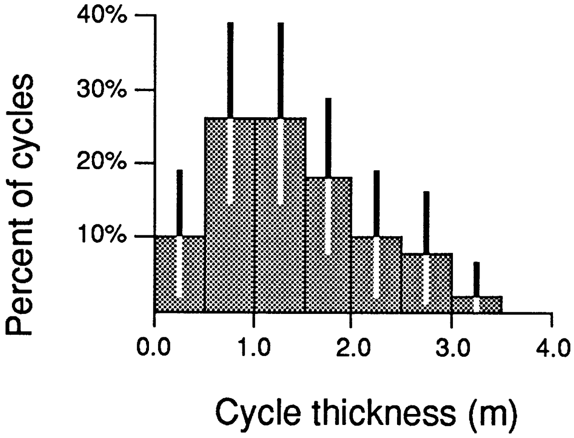


Figure 11. Frequency of cycle thickness as a percentage of all Kope and Fairview cycles. Mean cycle thickness is 1.37 m. Black and white bars: upper and lower 95% confidence limits, respectively.

recognized. They further argue that such an exponential distribution indicates stochastic (non-periodic) sediment accumulation. However, non-periodicity in deposition does not preclude sedimentary cyclicity; cycles could form in response to a stochastic or non-periodic forcing agent (Goldhammer et al. 1993).

Vertical Trends in Cycle Thickness and Anatomy

Thickness and Fischer Plots. Jennette and Pryor (1993) used Fischer plots to examine stratigraphic trends in cycle thickness, although Fischer plots are more typically used for peritidal cycles where relative sea level is thought to have a more direct control on cycle thickness. In this way, they were able to recognize parts of several fourth-order cycles, each of which was roughly 20 m thick. We performed a Fischer plot analysis of our cycles primarily to identify systematic variations in cycle thickness, which may or may not be related to relative sea level in these deep subtidal deposits. Our Fischer plot reveals two complete 20 m cycles and portions of two others (figure 12; Holland et al. 1993). Each 20 m cycle begins with several thicker-than-average meter-scale cycles (e.g., cycles 9–12, 21–25, 38–40), producing an upward trend on the Fischer plot. The remaining meter-scale cycles within each 20 m cycle are either average or below-average in thickness, producing a plateau or a fall on the Fischer plot.

The base of the Fairview Formation represents an abrupt decrease in mean cycle thickness, and in addition, marks the beginning of a series of condensed, proximal storm-bed cycles. Many of these cycles are difficult to recognize because of their thinness, and because of the minimal contrast between their deeper-water facies consisting of interbedded skeletal packstones, grainstones, and shales, and their shallower-water facies consisting of amalgamated grainstones. This formational contact represents an abrupt basinward shift in facies (Holland 1993; Jennette and Pryor 1993; Holland and Patzkowsky 1996). This shift can be recognized updip in the biostratigraphically equivalent Garrard Siltstone (Holland and Patzkowsky 1996; Pope and Read 1997), an unusual siliciclastic siltstone for the type Cincinnatian that was deposited in marginal marine environments. Thus, this abrupt shift is interpreted as a third-order sequence boundary.

The presence of clearly definable 20 m-scale cycles and a third-order sequence boundary on the Fischer plot indicates systematic vertical changes in cycle thickness. One might expect these 20 m-scale cycles to display similar vertical changes in their anatomy as well, but they do not.

Lack of Trends in Cycle Structure. We used several multivariate ordination techniques, including polar ordination, principal components analysis, and factor analysis to look for coordinated behavior between several cycle characteristics (figure 13) and to search for stratigraphic trends in the structure of these cycles. As described earlier, we analyzed, for each cycle, the fraction represented by deepening, shallowing, and the micro-lowstand, whether the flooding and shallowing were abrupt or gradual, the deepest and shallowest facies present, the presence or absence of micritic nodules, and the cycle thickness. None of the analyses produced any consistently interpretable relationship between the variables, nor any stratigraphic pattern in cycle anatomy that corresponds to the 20 m cycles revealed by the Fischer plot. As a typical example, the results of one of our polar ordination analyses are shown in figure 13 and table 1. All of our multivariate analyses indicated somewhat different associations between the variables, which we interpret to represent weak associations between any of the variables. Weak intervariable associations are further confirmed by low (<0.50) Pearson correlation coefficients among the variables.

Correlations with the original variables are the primary means for interpreting the significance of particular variables to each of the three polar ordination axes (table 1). Positive values on axis 1 correspond to cycles that have, in decreasing order of importance, micritic nodules, thick deepening-upward intervals, shallowing surfaces, and grainstones as their shallowest facies; negative val-

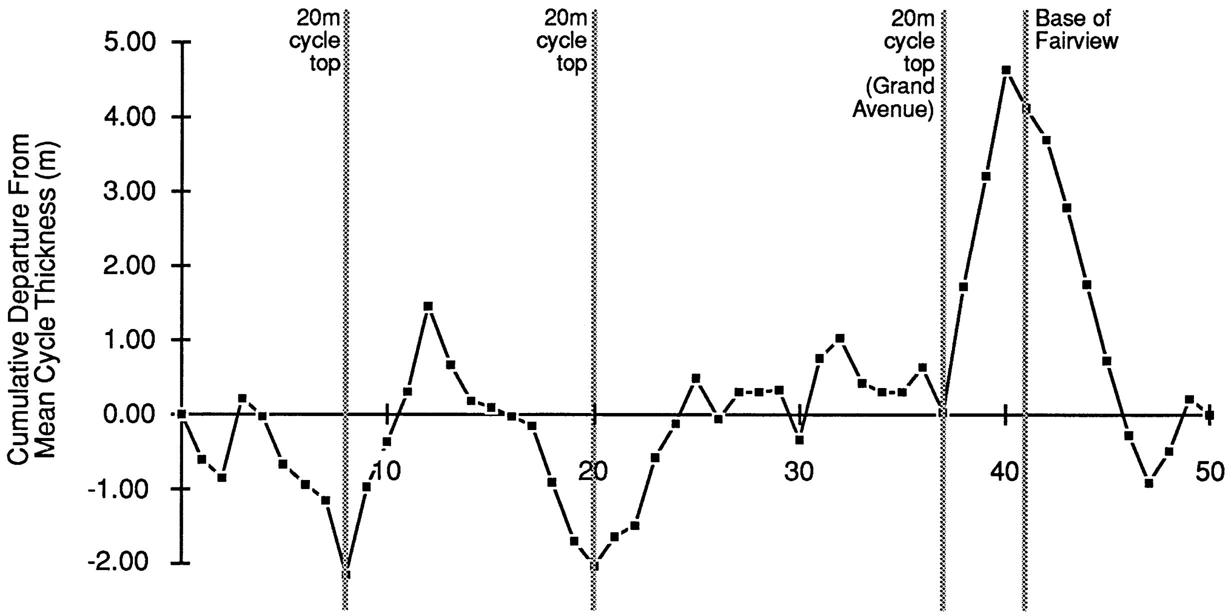


Figure 12. Fischer Plot of Kope and Fairview cycles. Plot does not include the triangles illustrating cycle thickness as in most Fischer plots, but only tracks the cumulative departure from mean cycle thickness. Positive slopes represent a succession of thicker-than-average cycles and negative slopes represent a succession of thinner-than-average cycles. Note that the 20 m cycles are initiated with several thicker-than-average cycles, followed by several average to thinner-than-average cycles. Two complete 20 m cycles are present (cycles 9–20, 21–37). The second 20 m cycle is capped by a prominent limestone band known as the Grand Avenue Member. The trend of decreasing cycle thickness in the first nine cycles records the end of a partial 20 m cycle and the trend of rapidly increasing cycle thickness in cycles 38–40 records the beginning of a partial 20 m cycle. A third-order sequence boundary at the base of the Fairview Formation truncates the fourth 20 m cycle and is marked by an abrupt decrease in cycle thickness.

ues would indicate cycles with the opposite attributes. Positive values on axis 2 correspond to cycles that have, in decreasing order of importance, flooding intervals rather than simple flooding surfaces, relatively thick micro-lowstands, shallowing surfaces, and grainstones as their shallowest facies. Positive values on axis 3 indicate cycles with flooding intervals, thick shales as the deepest facies, and relatively thin or absent micro-lowstands.

A plot of the first three polar ordination axes versus stratigraphic position (figure 13) fails to reveal any consistent pattern in axis scores for the unusually thick meter-scale cycles that occur near the bases of the 20 m cycles nor any distinctive signature for the highly proximal cycles (43–47) that occur at the base of the Fairview. The values for both of these unusual cycle types lie within the range of variation of all of the cycles for each of the axes, suggesting that the variables we analyzed are not well-correlated with one another or with cycle thickness. These results suggest that whatever is producing cycle variability has little to do with cycle thickness or long-term patterns of stratigraphic accumulation.

Several patterns are visible on this plot, and these might prove to be useful as correlation tools. First, Axis 1 shows a clear up-section decrease in variability within the Kope Formation. Second, a possible bundling of four to five meter-scale cycles is visible on axis 1 and axis 3 within the third 20 m cycle (cycles 20–37). Finally, spikes formed by several cycles (e.g., 6, 40, and 48 on axis 1) might also be correlatable to other outcrops, a possibility that we will test in subsequent analyses.

Discussion

Preconceived Expectations and Cycle Picks. Throughout this study, we were struck by the difficulty of consistently identifying cycles. Different members of our research team would pick slightly different cycles, and individual members would pick slightly different cycles on subsequent attempts. Given this, we suspect that other people might also pick cycles somewhat differently than we did. We were also impressed by the extent to which Hay, Tobin, and Jennette could look at the same outcrops and come to such different conclu-

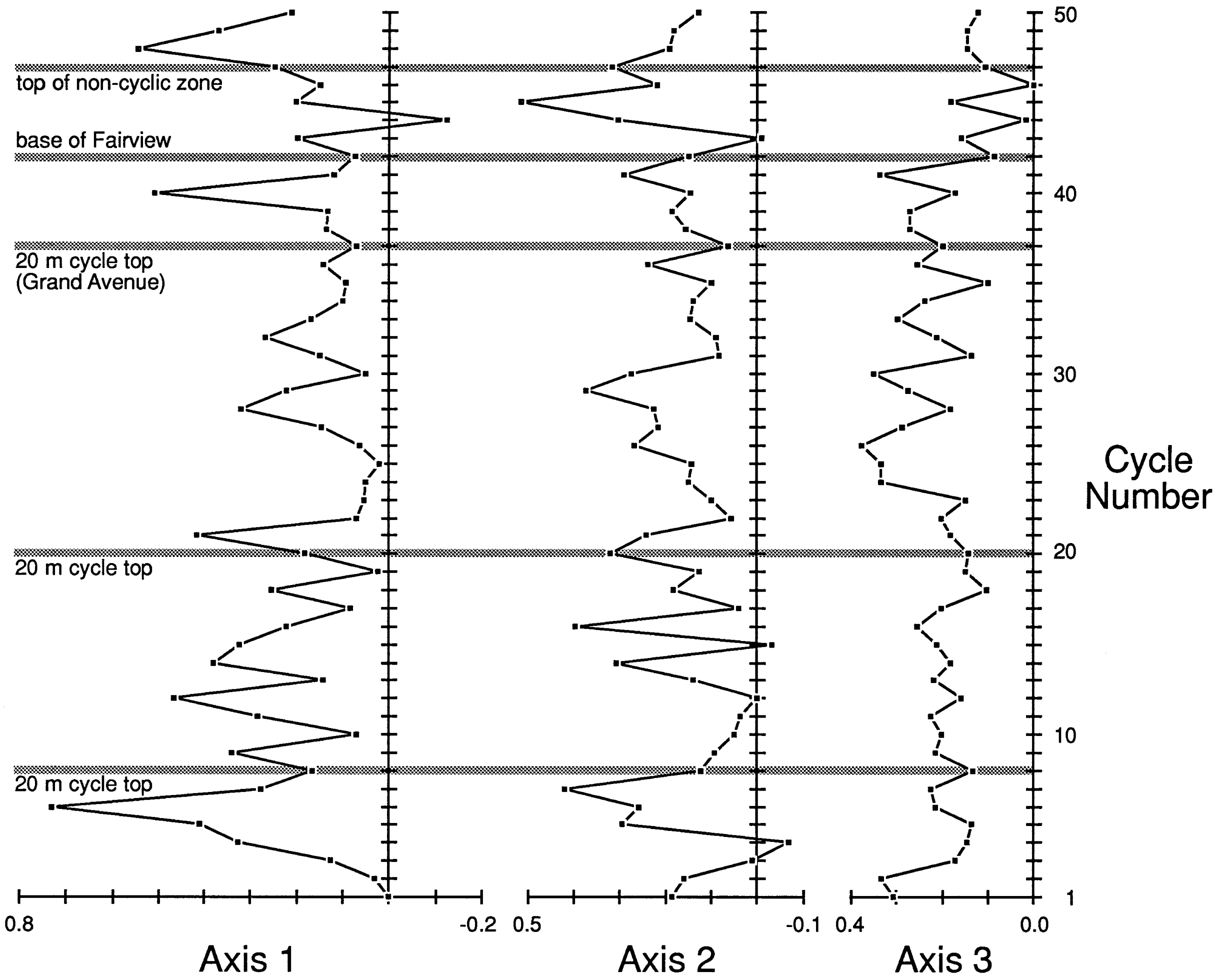


Figure 13. Plot of cycle coordinate values for the first three axes of a polar ordination of Kope and Fairview meter-scale cycles. Note lack of consistent trend on any of the three axes with respect to the 20 m scale cycles that were recognized by repeated changes in meter-scale cycle thickness. A similar lack of pattern with regard to the 20 m cycles was found using different combinations of variables, different ordination techniques, and different cycle picks. Variables in analysis include cycle thickness, deepening-upward proportion of cycle, micro-lowstand proportion of cycle, flooding surface vs. interval, shallowing surface vs. interval, deepest facies, shallowest facies, and presence of micritic nodules. The quantified Dice coefficient was used to calculate the distances among samples (Sepkoski 1974).

sions about the structure of the cycles. Finally, we could not help but notice the variability of the cycles and the number of exceptions we could find to the general cycle models of Jennette and Tobin. We believe that the root of these observations lies both in our preconceptions about cyclicity and in the inherent variability of these cycles.

Our preconceptions exerted a powerful and not always immediately recognized force on our cycle calls, both in regard to cycle thickness and cycle anatomy (cf. Zeller 1964). Where cycles were well-defined on the outcrop (e.g., cycles 28–32 in figure 4), they were typically around 1–2 m thick. Where we tried to identify cycles that were not so obvious, we assumed implicitly that the cycles should be about the same thickness. In intervals where cycles proved to be much thicker, we found ourselves tending to look ever more carefully for a cycle boundary where we would expect one based on thickness alone. Where the cycles were much thinner, we were often reluctant to recognize them as such for fear of overinterpreting such a thin interval of rock. Our team still disagrees as to whether cycles 43–47 are real or not, and this interval is locally known as the "non-cyclic interval," Jennette and Pryor (1993) were similarly stymied and treated this interval as one cycle on their measured section and as four cycles on their Fischer plot.

Preconceptions of cycle anatomy likewise played a role in our cycle picks. Because we were

Table 1. Correlations between Variables and Polar Ordination Axes

Variable	Axis 1	Axis 2	Axis 3
Micritic nodules (+: nodules absent)	−.691	.209	.154
Deepening fraction (+: thicker deepening intervals	.643	−.309	−.208
Shallowing surface vs. interval (+: shallowing interval)	−.511	−.462	−.136
Shallowest faces (+: deeper-water facies)	−.491	−.419	.482
Flooding surface vs. interval (+: flooding surface)	.268	−.588	−.610
Micro-lowstand fraction (+: thicker micro-lowstand interval)	.050	.523	−.420
Cycle thickness (+: thicker cycles)	.208	−.333	.184
Deepest facies (+: deeper-water facies)	−.004	−.133	.612

most familiar with Jennette's work and the parasequence model of meter-scale cycles, we focused initially on single, sharp flooding surfaces to define the tops of cycles. We also initially overlooked the deepening-upward intervals so clearly developed at the bases of some cycles (e.g., cycles 7 and 10 in figure 4); once we became aware of these clear examples, we found other examples throughout the section. In short, our eyes had to become tuned to see the variability in cycle anatomy.

Why Are These Cycles Poorly Defined? Sequence stratigraphy has succeeded in large part because its predictions of a highly structured stratigraphic record have been confirmed in numerous case studies. Once we recognized that some of the meter-scale cycles fit a typical parasequence model, whereas others were more easily interpreted as high-frequency sequences (Van Wagoner 1991), complete with deepening-upward and shallowing-upward intervals, as well as micro-lowstands, we expected to see coordinated changes in cycle construction within each 20 m cycle and within the entire study interval. In particular, we expected meter-scale cycles to change in their anatomy if the 20 m cycle represented a longer period relative fluctuation in sea level (figure 14; Van Wagoner et al. 1990; Goldhammer et al. 1993). For example, meter-scale cycles deposited on the rising limb of a longer-period relative fluctuation in sea level would be expected to have enhanced flooding surfaces and suppressed relative falls in sea level, leading to a classical shallowing-upward, flooding surface-bounded parasequence. Meter-scale cycles deposited on the falling limb of a longer-term cycle would be expected to have enhanced falls, favoring the formation of shallowing surfaces and micro-lowstands. Cycles formed during long-term stillstands would be expected to have some intermediate architecture. However, our multivariate analyses revealed no such coordinated changes among meter-scale cycles, suggesting that their variability does not fit the pattern expected from superimposed cycles of relative sea level. The variability in these cycles may represent several different phenomena: the poor recording of fluctuations in relative sea level, the accurate recording of an irregularly changing relative sea level, climatic fluctuations as recorded in storm beds, or random variations in storm intensity.

Deposition of subtidal mixed carbonate-siliciclastic sediments may poorly record fluctuations in relative sea level because of a decreased sensitivity to sea-level changes in deeper-water settings. Numerous studies have demonstrated that non-cyclic intervals in deep subtidal carbonates frequently represent a failure to record relative sea-level fluctuations because cyclicity is well-developed in correlative shallow subtidal to peritidal carbonates (Markello and Read 1981; Elrick and Read 1991; Elrick 1995). Grotzinger (1986) argued that what appears to be random interbedding of non-cyclic facies may have been driven by relative sea-level fluctuations and that such apparently random interbedding represents poorly formed or incompletely developed cyclicity. The presence of "non-cyclic" zones (e.g., cycles 43–47) and the presence of mid-cycle bundles of storm beds (e.g., cycles 11 and 21) may be examples of poorly developed or incomplete cyclicity in the Kope and Fairview Formations or may reflect "noise" imposed by random variations in storm intensity.

Alternatively, the variability and irregularity of Kope-Fairview cyclicity may indicate an accurate recording of highly irregular relative sea-level fluctuations. Goldhammer et al. (1993) demonstrated several striking differences between carbonate cycles modeled using a sinusoidal relative sea-level history versus a sea-level history generated by smoothed random fluctuations. Cycles generated by a high-frequency sinusoidal sea level show systematic and predictable trends in cycle thickness and facies composition, such as progressively thicker and more subtidally-dominated cycles during the rising limb of the long-term sea-level and progressively thinner peritidal-dominated cycles during the falling limb of the long-term sea level (cf. figure 14). Cycles generated by smoothed random fluctuations in sea level superimposed on a long-term sinusoidal sea level display cycle thick-

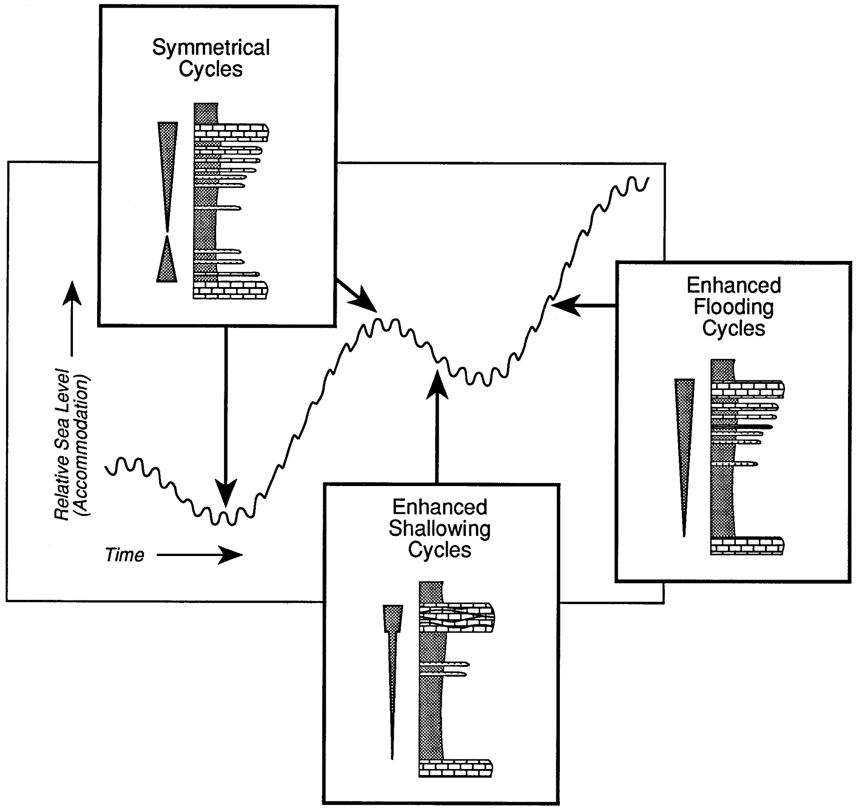


Figure 14. Schematic drawings of expected variations in cycle anatomy as a function of longer-term relative sea-level history. Meter-scale cycles forming during a long-term relative rise in sea level should exhibit enhanced rises and subdued falls. Cycles forming during a long-term relative fall should show the opposite effect. Cycles forming near the crest or trough of a long-term relative fluctuation in sea level should not have either their rises or falls enhanced or subdued.

ening and deepening on the rising limb and cycle thinning and shallowing on the falling limb of long-term sea level, but with much more cycle variability. For example, anomalously thick or thin cycles frequently interrupt overall thinning or thickening trends. Likewise, anomalously deep- or shallow-water cycles disrupt long-term shallowing or deepening trends. Many cycles generated by the smoothed random fluctuations in sea level do not simply shallow upward as in parasequence but have significant deepening-upward intervals at their base. Many of these patterns are reflected in Kope and Fairview cycles. Fischer plots indicate overall thickening and thinning trends, but these trends are interrupted in places by anomalously thick or thin cycles. Multivariate analyses indicated no systematic connection between longer-term cycles and meter-scale cycle anatomy in terms of asymmetry, presence of a micro-lowstand, facies, etc. Deepening-upward bases are common in the Kope and Fairview cycles, similar to the smoothed random fluctuation model of sea level.

A third possibility for cycle variability is that the vertical changes in storm bed proximality record cyclically changing storm intensities over time, not changing water depth. One potential test of this hypothesis is to examine the updip correlatives of the Kope and Fairview Formations; if these cycles reflect storm intensity, no peritidal cyclicity should be present updip. Testing of this hypothesis awaits our completion of high resolution correlations in the Kope and Fairview Formations, which will be presented elsewhere. Alternatively, storm intensity may have varied randomly, not cyclically, such that what we and others describe as cyclicity is merely an illusion. The spacing of the grainstone-rich intervals and the intercalation of shale-rich zones between them may be enough to give the appearance of cyclicity where none exists. If these fluctuations in storm intensity are indeed random rather than cyclic, it does not diminish the usefulness of these "cycles" in correlation, as Jennette and Pryor (1993) have shown that they can be correlated confidently for at least 20 km.

A final source of cycle variability may be the unusual detail with which we measured sections, where all beds thicker than 5 mm were described. Beds thinner than 2 cm record much of what we recognize as cycle variability, and ignoring these beds would cause these cycles to look much more similar to one another (Holland et al. 1996).

Implications. The presence of highly variable cycles has several implications for applying sequence stratigraphic principles in the Kope-Fairview and elsewhere. First, because not all cycles contain a sharp flooding surface or shallowing surface, establishing precise surfaces of correlation may not always be possible for every cycle; that is, not every cycle will contain a surface that can be accurately correlated to adjacent sections. Thus, extremely high-resolution correlations (i.e., less than the scale of a meter-scale cycle) may not be possible without distinct flooding and shallowing surfaces. Additional methods of correlation are required to establish high-resolution time lines. Promising methods include coenocorrelation techniques and the use of faunal events such as epiboles (Cisne and Rabe 1978; Brett et al. 1990b; Dattilo 1996).

The variability of cycles itself may offer an additional tool for correlation in that the vertical changes in cycle anatomy may be sufficiently laterally persistent to allow correlation. For example, the presence of a shallowing surface, a thick deepening-upward interval, or a mid-cycle bundle of storm beds may be sufficiently distinctive to allow a given cycle to be correlated regionally. Whether or not these properties can be recognized and correlated regionally will be tested in the next phase of this study.

Similar amounts of cycle variability have been noted in other studies (e.g., Elder et al. 1994; Brett and Baird 1986; Brookfield and Brett 1988), and this variability was found to vary both laterally and vertically. Brett and Baird (1986) noted that shallowing-upward cycles tend to occur in areas close to sediment sources. They also found that cycles in distal areas tend to show greater amounts of cycle variability, and they attributed this to the greater role of random events, such as unusually intense storms.

With few exceptions, existing models of sedimentary cyclicity have used superimposed sine waves of relative sea level to generate cycles (e.g., (Grotzinger 1986; Read et al. 1986; Elrick and Read 1991; Osleger and Read 1991; Goldhammer et al. 1993). Such cycles represent an ordered extreme of the stratigraphic record, often recreate the stratigraphic record to a first approximation, and serve as a useful learning tool. However, sine wave models fail to recreate the finer structure of the observed stratigraphic record. Future modeling efforts should focus on random walk or chaotic models of sea-level change as a comparison to the simpler sine wave models. The inability of simple sine wave models to closely duplicate the stratigraphy observed in peritidal settings and storm-dominated shelf settings suggests that relative sea level may have a much more complicated history than a series of sine waves. As it is affected by numerous factors (see discussion in Revelle 1990), relative sea level might be expected to follow a random walk or chaotic history.

Finally, as Posamentier and James (1993) have argued, parasequences and sequences are not scale-dependent. This study underscores that some meter-scale cycles may be better described by a sequence model than a parasequence model. This conclusion should not be surprising, as the sequence model allows a much greater diversity in cycle expressions than does the highly specific parasequence model. For example, a sequence model of cyclicity is able to accommodate the variably deepening-upward and shallowing-upward components of Kope-Fairview cycles, as well as the abrupt basinward shifts in storm bed proximality.

Conclusions

1. Meter-scale cycles in the Upper Ordovician Kope and Fairview Formations have been described previously as both deepening-upward cycles and as shallowing-upward parasequences. Our studies indicate that Kope-Fairview cycles are more highly variable than recognized previously. Many meter-scale cycles contain evidence of flooding surfaces, abrupt basinward shifts in facies (shallowing surfaces), shallowing-upward intervals, and deepening-upward intervals. Thus, they are most easily described as high-frequency sequences, although some clearly conform to a parasequence model. In general, the anatomy of meter-scale cycles should be closely examined to determine whether they fit a parasequence or PAC model as is generally assumed. Kope-Fairview meter-scale cycles demonstrate that the smallest scale of cycles present in an area may be high-frequency sequences, not parasequences.

2. Larger-scale cycles, on the order of 20 m thick, are recognized by consistent thickening and thinning trends in Kope-Fairview meter-scale cycles. However, the internal anatomy of Kope-Fairview meter-scale cycles shows no consistent stratigraphic pattern with regard to 20 m cycles or to the overall Kope and Fairview Formations. Such nonsystematic variability suggests variously (1) that relative sea-level history was erratic and cannot be treated as a few superimposed sine waves, (2) that regular relative sea-level changes were poorly recorded in this offshore setting, (3) that these cycles are driven by climatic cycles or random variations in storm intensity, not relative changes in sea level, or (4) that others have oversimplified cycle anatomy.

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