Stratigraphic Resolution and Perceptions of Cycle Architecture: Variations in Meter-Scale Cyclicity in the Type Cincinnatian Series[1]

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ABSTRACT

Previous analyses of meter-scale cyclicity have de-emphasized thin beds within investigated stratigraphic intervals. Here, we analyze the effect of excluding relatively thin beds on cycle delineation and interpretation in the type Cincinnatian Series. Whereas inclusion of all strata suggests wide variation in cycle architecture, systematic culling of thin beds decreases this variability considerably, in part by removing much of the evidence for intervals of deepening that are important components in more than half the meter-scale cycles recognized here. Thus, cycles in the culled data conform more easily to a parasequence model, in that a greater plurality exhibit a simple shallowing-upward motif, raising the concern that the exclusion of thin beds in other analyses might similarly oversimplify the perceived signal of cyclicity.

Introduction

During the past fifteen years, the science of stratigraphy has been energized anew by a proliferation of studies on stratigraphic cyclicity. While a variety of cycle models have been proposed to explain stratigraphic patterns in particular field areas, a common methodological practice, regardless of the model proposed, has been the exclusion from stratigraphic interpretations of relatively thin beds that were illustrated in accompanying depictions of lithologic sequences at individual localities. For example, in papers that delineated Punctuated Aggradational Cycles (PACs), Goodwin and Anderson (1985, 1988) presented columnar sections that schematically suggest substantial fine-scale stratigraphic variability within individual PACs. Similarly, as part of their investigation into the complexities of cycle variation in the Lower Ordovician of west Texas, Goldhammer et al. (1993) provided measured sections that delineated individual cycles only at the subfacies level. Although their depictions of individual sections indicate stratigraphic variation at the level of individual beds within particular subfacies, the possible bearing of these relatively thin beds on the accompanying delineation of intervals that they classified as fifth-order cycles is not clear. In these studies, as well as others where cycles encompass more than a single bed, it is difficult to determine whether individual delineation and consideration of all beds, regardless of thickness, would have altered perceptions of cyclicity. It is possible that potentially complex stratigraphic signals have been oversimplified to the extent that a more ''monotonous'' stratigraphic repetition of a particular cycle model emerges than would be warranted if all the data were included. Further, the extent of this problem is not clear because published stratigraphic sections are commonly drafted at a coarser level of resolution than the actual field measurements. Some authors may well be aware of fine-scale stratigraphic variations but may have simply been unable to draw such variation given the space constraints of publishing. Thus, stratigraphic sections drawn at a coarse scale are not necessarily evidence of a failure to recognize fine-scale stratigraphic variation.

In the type Cincinnatian Series, it appears that previous investigations of meter-scale cyclicity have overlooked the data available in relatively thin limestone beds contained within shale-dominated intervals (see below). For an ongoing investi-

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gation of high resolution stratigraphy and cyclicity in these strata, we have been collecting and analyzing lithologic and faunal data at an unusually fine stratigraphic scale, in which all beds thicker than 5 mm were described separately. Here, we present a comparison of stratigraphic patterns exhibited by the raw data at a single locality to a culled version of the data that lumps thin beds with surrounding, thicker lithologies, to evaluate directly the effects of excluding thin beds on cycle architecture.

Parasequences and Sequences: Anatomy Versus Scale

Before commencing with the central analyses of this paper, we want to clarify the terminology used herein. Two types of cycles form the core of sequence stratigraphy, and they are distinguished on the basis of their internal anatomy (Van Wagoner et al. 1990; Van Wagoner 1985; Posamentier and James 1993). Parasequences are shallowing-upward cycles bounded by flooding surfaces, across which inferred water depths increase abruptly. They are contrasted with sequences, which are sedimentary cycles bounded by unconformities, surfaces of subaerial exposure, or their correlative surfaces. Sequences contain a series of systems tracts defined by stratigraphic position, bounding surfaces, and gross trends in water depth. They can display a wider range of water depth histories and may contain not only shallowing-upward intervals and flooding surfaces, but also deepening-upward intervals and surfaces of abrupt shallowing.

In many cases, meter-scale cycles exhibit a parasequence structure, whereas larger-scale cycles commonly exhibit a sequence structure. Perhaps for this reason, many researchers have conflated scale with structure, and have tended to view *all* meter-scale cycles as parasequences and *all* larger-scale cycles as sequences. However, the explicit original intent of these terms was to characterize cycle anatomy rather than scale (Van Wagoner et al. 1990, p. 5; also see cogent discussion in Posamentier and James 1993, p. 8ff). Therefore, we use the terms parasequence and sequence in reference only to the internal anatomy of cycles, independent of their scales (Holland et al. 1997).

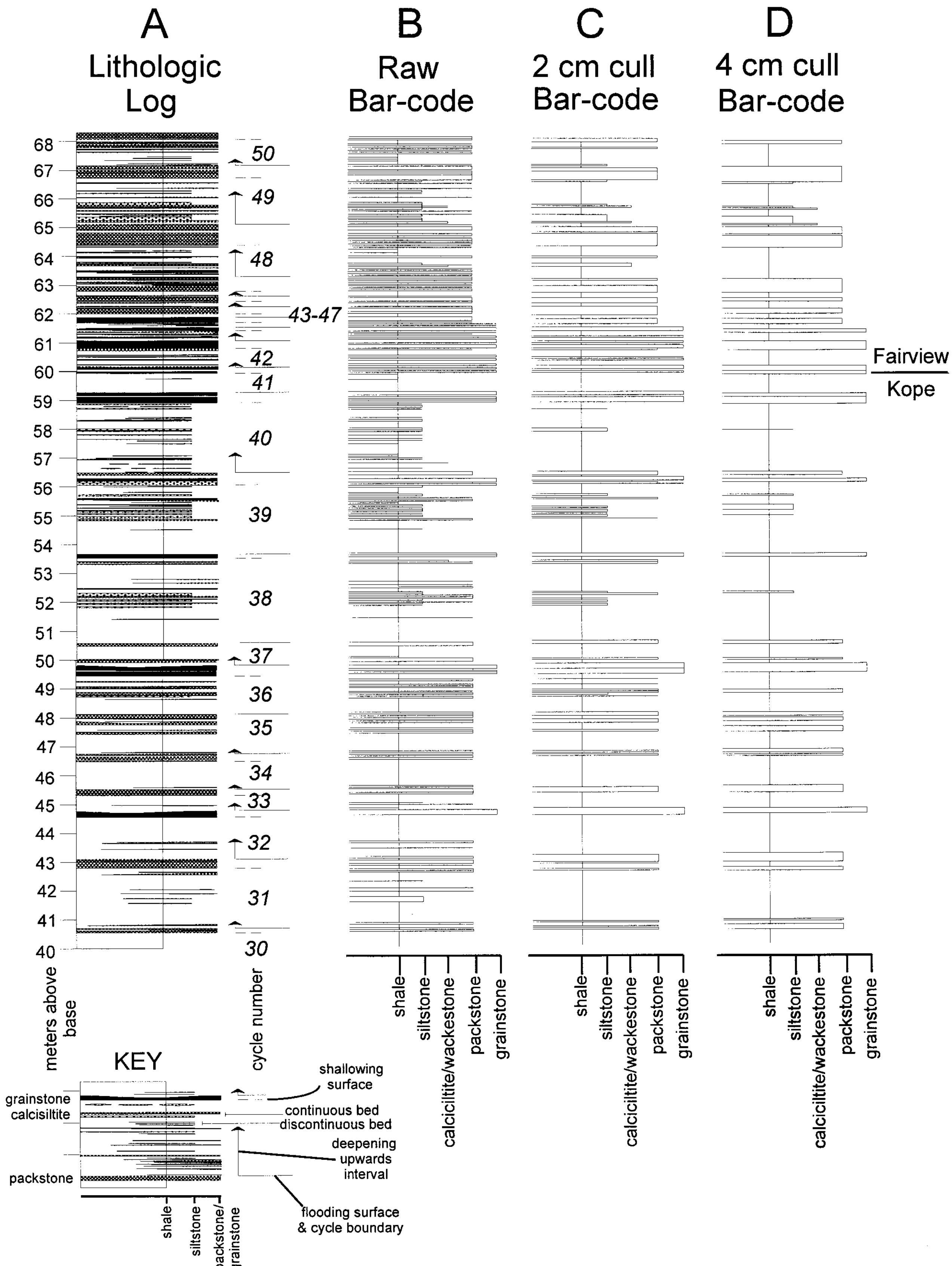
Stratigraphy at the Study Locality

This investigation focuses on a 68 m composite section in Campbell County, northern Kentucky along the Ohio River, just east of Cincinnati, Ohio. The section spans all but the lowest 10 m of the Edenian Kope Formation, plus the basal 8 m of the overlying Maysvillian Fairview Formation. The raw stratigraphic pattern was described in detail by Holland et al. (1997).

The Kope and Fairview formations are composed of alternating limestones and shales deposited on a northward-dipping carbonate ramp that received considerable siliciclastic mud and silt derived from eastern sources uplifted during the Taconic Orogeny. The region was subject to appreciable storm activity; storm-deposits are major features of these and other Cincinnatian strata (Kreisa et al. 1981; Tobin 1982; Jennette and Pryor 1993). The upward transition from the Kope to the Fairview is associated with a marked decrease in siliciclastic content relative to carbonate (figure 1). The siliciclastic content of three-foot intervals measured by Ford (1967) averaged 86% in the Kope, but only 64% in the Fairview.

Meter-scale cyclicity within the study interval has been recognized and variously interpreted by several workers. Most recently, Jennette and Pryor (1993) evaluated inter- and intracycle stratigraphic patterns on the basis of storm-deposit proximality (e.g., Aigner 1985). Shallowing-upward trends, for example, are indicated by an upward transition from rippled calcisiltites to skeletal packstones to highly reworked and amalgamated crinoidal grainstones, all of which are accompanied by an upward thinning of shales between storm beds; thus the percentage of mud within and between limestones decreases upward. Jennette and Pryor argued that Kope and lower Fairview cycles exhibit consistent, repetitive patterns indicative of gradual shallowing, followed by abrupt deepening prior to initiation of the next cycle. On this basis, they suggested that the meter-scale cycles were fifth-

Figure 1. Comparative stratigraphic patterns in the upper Kope and lower Fairview Formations, based on fieldwork at a composite outcrop in Campbell County, Kentucky, located just south of the Ohio River, in the vicinity of the intersections of Kentucky State Route 445 and Kentucky State Route 8, and Interstate-275 (see Holland et al. 1997 for a more complete description). Only the upper 28 m of the 68 m composite section are illustrated here. *A:* Lithologic log of the raw stratigraphic data; *B:* Bar-code rendition (see text) of the raw stratigraphic data; *C:* Bar-code rendition of the data following culling of beds less than or equal to 2 cm in thickness; *D:* Bar-code rendition of the data following culling of beds less than or equal to 4 cm in thickness.



A
Lithologic Log
B
Raw Bar-code
C
2 cm cull Bar-code
D
4 cm cull Bar-code
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59
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47
46
45
44
43
42
41
40
meters above base
cycle number
50
49
48
43-47
42
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33
32
31
30
Fairview
Kope
shale
siltstone
calcisiltite/wackestone
packstone
grainstone
KEY
grainstone
calcisiltite
packstone
shallowing surface
continuous bed
discontinuous bed
deepening upwards interval
flooding surface & cycle boundary
shale
siltstone
packstone/grainstone

order parasequences, stacked into parasequence sets. However, inspection of stratigraphic sections presented by Jennette and Pryor (e.g., figures 3 and 13 of Jennette and Pryor 1993) indicates, in itself, that their interpretation oversimplifies the stratigraphic signal. Thinner limestone beds that Jennette and Pryor recognized in the illustrated sections were significant components of the lower 50 to 75% of most delineated cycles. Along with interbedded shales, these thin limestone beds were considered, collectively, to represent the ''distal'' facies of individual cycles (figure 4 of Jennette and Pryor 1993). Systematic stratigraphic variation within this facies, possibly indicative of sea-level fluctuation, was apparently not addressed.

In our bed-by-bed analysis of the study interval (Holland et al. 1997) we found a more complex pattern at the meter scale than that envisioned by previous workers (figure 1*A*), based on a more detailed delineation of storm facies. Our distal, or deepest-water, facies consists of repeated, thin (1–3 cm) terrigenous mudstone beds that collectively comprise a relatively thick (30 cm or more) shale. In more proximal, or shallower-water settings, thin rippled and cross-laminated calcisiltites are present within these shales and are followed by thin skeletal packstones and shales in yet shallower-water settings. Finally, in the most proximal, shallowest-water settings, amalgamated and cross-bedded crinoidal grainstones with minor shale partings are present.

Most cycles do not contain the entire suite of facies. For example, *shallowing-upward intervals* are not always capped with a crinoidal grainstone and instead may exhibit all or part of the following upward succession: (a) a thick, basal shale; (b) shale with interbedded, thin calcisiltites; (c) shale with calcisiltites and thin packstones; and (d) shale with thicker, laterally continuous packstones. What does typify all such intervals, regardless of which facies they contain, is a gradational stratigraphic transition from relatively distal to more proximal facies, with intermediate facies also present. *Deepening-upward intervals* are characterized by the reverse trend, suggesting a gradual shift from proximal, shallow-water facies to deeper-water distal facies.

Cycle boundaries or *flooding surfaces* are distinguished by abrupt shifts from proximal to more distal storm facies. These are indicated by the absence of intermediate facies, as when shales with calcisiltites directly overlie amalgamated crinoidal grainstones. In most cases, cycle boundaries are marked by abrupt increases in shale content. We also recognized *shallowing surfaces,* marked by abrupt shifts from deeper-water or distal storm facies to shallower-water or proximal storm facies, as where a series of skeletal packstones with minor shale abruptly overlies a thick shale interval. These shallowing surfaces represent abrupt, basinward shifts in facies, and we correspondingly interpreted them as sequence boundaries (cf. Posamentier et al. 1992; Van Wagoner 1995, p. 181ff and his figure 40). Subaerial exposure is not indicated at these boundaries, but is inferred to occur in updip settings.

As an illustration of cycle delineation and characterization, several of the aforementioned features can be recognized in figure 1 by focusing on cycle number 49, located near the top of the illustrated interval. The base of this cycle is marked by a flooding surface, characterized by an abrupt transition from a band of skeletal packstones with minor shale interbeds that cap the underlying cycle, to a mixed interval of thinner packstones, shales, and calcisiltites. Moving upward within cycle number 49, shale intervals become thicker, whereas limestones beds become thinner and laterally discontinuous, indicating a deepening-upward interval. Near the top of the cycle, there is an abrupt return to thicker, closely spaced, and laterally continuous packstones, indicative of a shallowing surface. The cycle terminates with the next flooding surface.

The scale of figure 1 makes it difficult to readily observe all the features relevant to our delineation of every cycle. Interested readers are encouraged to consult figure 4 of Holland et al. (1997), where individual beds are more easily discerned in an expanded version of the illustrated section.

Cycle anatomy in the study interval displayed much more variation than suggested by previous workers. For example, more than half of the 50 meter-scale cycles that we recognized exhibited deepening-upward intervals (figure 2*A*), rather than simply flooding surfaces, as predicted by the parasequence model (Van Wagoner et al. 1990). Overall, the patterns of shallowing and deepening within the cycles are highly variable, suggesting that the cycles are best interpreted not as parasequences, but as high-frequency sequences (see Mitchum and Van Wagoner 1991; Holland et al. 1997). The use of the term *high-frequency* underscores that these sequences are smaller in scale than is conventionally acknowledged, albeit that scale plays no part in the definition of a sequence.

Culling of Thin Beds

To test our hypothesis that the exclusion of thin beds from the raw data would substantially alter the extent of perceived cycle variability, we used

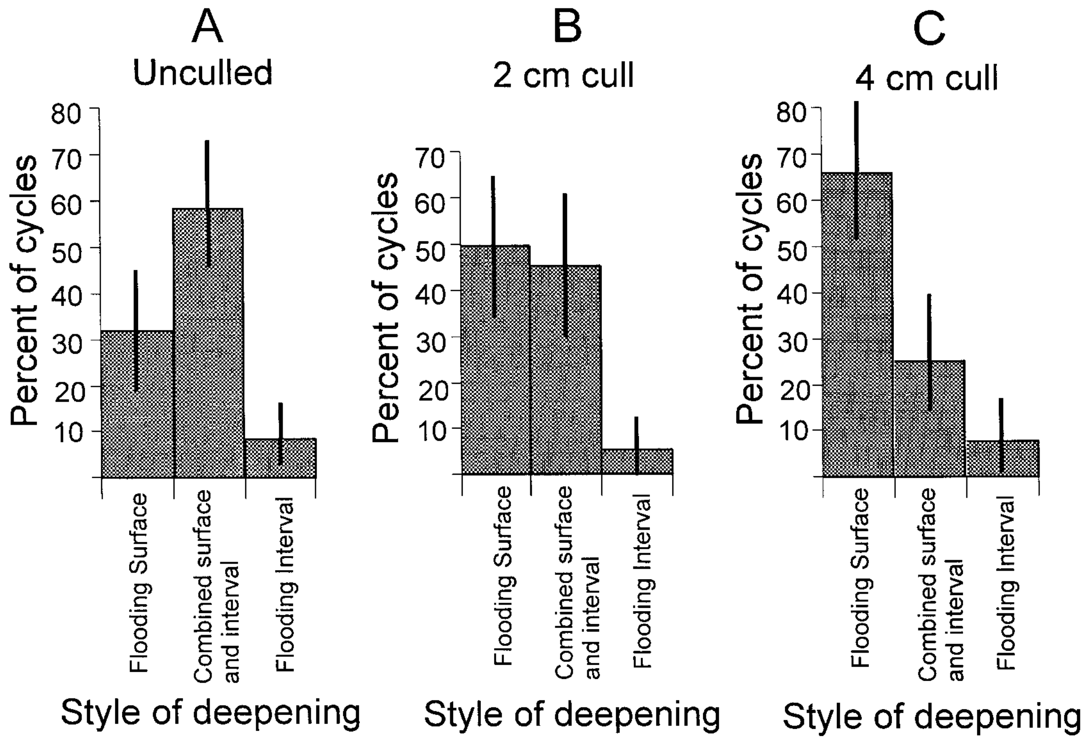

Figure 2. Comparison of styles of deepening exhibited by meter-scale cycles in the study interval. Error bars are 95% confidence intervals about the percentages (Raup 1991). *A:* Unculled data ($n = 50$); *B:* Beds less than or equal to 2 cm culled ($n = 42$); *C:* Beds less than or equal to 4 cm culled ($n = 39$).

an elementary culling technique. First, we constructed a computerized rendition of the lithologies and bed thicknesses in our stratigraphic section; this rendition is referred to herein as a "bar-code" (figure 1*B*). We then culled beds less than or equal to 2 cm in thickness by converting these beds to the same lithologies as those of the surrounding, thicker intervals in which they were contained; this culled version of the bar-code is illustrated in figure 1*C*. Finally, we conducted an additional culling of beds less than or equal to 4 cm in thickness (figure 1*D*). Typically, though not always, the culling exercise resulted in the loss of thin limestone beds within relatively thick, shale-rich intervals. In some instances, however, thin shale partings were lost from limestone-dominated strata.

This treatment of culling does not necessarily imply that all researchers ignore or fail to notice thin beds. Researchers performing a coarse scale of analysis might simply regard thin beds as part of a facies. For example, a researcher attuned to fine-scale variation might describe the location, thickness, and composition of thin limestone beds within an overall shaly unit, but a researcher focusing on coarse-scale patterns might simply see a shaly facies containing a variety of thin limestone beds. In an extreme case, a particularly cavalier researcher might only notice the shale and overlook the limestone beds entirely.

The effect of the initial 2 cm culling, as well as the more extensive 4 cm second pass, is a much-simplified stratigraphy. At first glance, it actually appears as though it might be easier to "see" individual cycles within the culled sequences than in the raw data. This is apparent when comparing the raw and culled bar-codes for the stratigraphic interval depicted in figure 1 (the upper 28 m of the composite section). For example, the three cycles at the very top of the section in the Fairview Formation (cycles 48, 49, and 50), which are easily discernible in the field because of differential weathering of shale and limestone beds, are not easily recognized in this graphical rendition (figure 1*A*,*B*), given the plethora of relatively thin beds that dominate this and other portions of the raw section. In contrast, these cycles are readily apparent in both culled versions (figure 1*C*,*D*).

Closer inspection, however, reveals that this apparent improvement is simply a graphical illusion. In fact, when we reanalyzed the culled versions through the entire study interval, using the criteria for cycle delineation and characterization described earlier (see also Holland et al. 1997), we could find evidence for only 42 cycles in the 2 cm culled version and 39 in the 4 cm culled version, in contrast to 50 cycles that we recognized in the raw data. For example, note the merging of cycles 43–47 into a single large cycle in the culled versions. Thus, our ability to delineate cycles is compromised by the loss of thin beds.

More importantly, the loss of thin beds dramatically alters our perceptions of cycle architecture. In figure 1, this can best be seen by observing, in several cycles (e.g., numbers 38, 40, and 48), the almost complete loss of discrete, thin limestone and calcisiltite beds, and the ''coalescence'' of thicker limestones that had previously been separated by thin shale interbeds. Among other things, this results in significant changes to perceived styles of deepening (figure 2) since, in several instances, what are recognized as deepening-upward intervals within cycles in the unculled version lose much of their ''texture'' and become simple flooding surfaces in the culled version. Throughout the entire study interval, some 68% of the cycles in the unculled data exhibit either a deepening-upward interval exclusively, or discrete flooding surfaces within broader intervals of deepening (figure 2*A*). By contrast, this is true of only 50% of cycles in the 2 cm culled version (figure 2*B*) and 33% of cycles in the 4 cm culled version. As described earlier and in Holland et al. (1997), the recognition of deepening-upward intervals is an important line of evidence in our interpretation of these meter-scale cycles as high-frequency sequences, in that deepening-upward cycle bases have not typically been recognized in parasequences. Thus, a clear effect of culling in this instance is to alter perceived cycle architecture to the extent that the plurality of cycles resemble parasequences, rather than high-frequency sequences (see earlier section, Parasequences and Sequences: Anatomy Versus Scale).

Discussion

The delineation of cycles in any stratigraphic sequence is, to some extent, a subjective exercise. We readily concede that other workers might not have recognized precisely the same cycles that we detected. However, we note that most of the cycles delineated here are the same as those recognized by previous workers (e.g., Jennette and Pryor 1993), and we are therefore confident that our initial cycle picks are repeatable. The recognition of deepening-upward intervals is based on the same objective criteria of storm bed proximality by which others have recognized shallowing-upward successions (Aigner 1985; see earlier discussion), and can be applied to the culled data, the raw data, and on the outcrop (Holland et al. 1997). Our delineation of patterns in the culled data resulted in perceptions of cycle architecture that, while at odds with our interpretations of the raw data (e.g., figure 2), were more in line with interpretations of meter-scale cycles as parasequences in most other studies, in that the percentage of cycles exhibiting discrete flooding surfaces increased significantly as a consequence of culling. Moreover, within our study interval, thin beds comprise the clear majority of the limestone beds contained within the more distal portions of meter-scale cycles (figure 1*A*,*B*). Even in the absence of the culling experiment presented here, this dominance suggests intuitively that the exclusion of thin beds from consideration as individual entities in analyses of cyclicity will lead inevitably to oversimplification of the perceived stratigraphic signal.

Because there is no inherent reason to believe that the Cincinnatian Series is unique with respect to the issues addressed here, our results lead to the concern that analogous, perhaps inadvertent, omission of the information contained in relatively thin beds might compromise the interpretation of signals preserved in strata elsewhere, in instances where cycles extend beyond the confines of individual beds. Most notably, because facies analysis necessarily subsumes a certain amount of fine-scale variation (Walker 1992), the analysis or presentation of stratigraphic data at the facies level, rather than bed-by-bed, will tend to favor the recognition of flooding surfaces, rather than flooding intervals. At a relatively coarse scale of analysis, many apparent flooding surfaces that indicate no deposition during transgression may actually record a depositional signal and slower rates of transgression that could only be detected with a bed-by-bed analysis. This calls into question the apparent pervasiveness of parasequences in the stratigraphic record, given their current definition, which recognizes only discrete flooding surfaces at the boundaries between them.

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