Sediment supply versus storm winnowing in the development of muddy and shelly interbeds from the Upper Ordovician of the Cincinnati region, USA[1]

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Abstract: Shell-bed development can be a product of complex sedimentological and biological factors. The Upper Ordovician sediments near Cincinnati, Ohio constitute a succession of thinly interbedded shelly carbonates and mudrocks. Despite years of study, the development of Cincinnatian shell beds and metre-scale cycles has, until recently, been attributed solely to storm reworking. This "storm-winnowing model" treats shells as passive sedimentary clasts, ignoring other factors of shell-bed development. A recently proposed alternative is Brett and Algeo's idea that these shell beds grew during long periods of normally low sedimentation, while most mud accumulated during brief periods of high sedimentation. Under this "episodic starvation model," any storms would winnow pre-existing muds and shell beds alike. We tested both models in the Edenian–Maysvillian (early to mid Katian) strata of the Cincinnati region by compiling observations on their petrologic, taphonomic, and paleoecologic characteristics. The storm-winnowing model does not explain several observed features that the episodic starvation model does, including (*i*) storm-related sedimentary structures in mudrocks *and* limestones; (*ii*) lack of a sufficiently fossiliferous precursor deposit to winnow; (*iii*) deep-water faunas in grainstones; (*iv*) mixed taphonomic conditions of shell-bed fossils; (*v*) ubiquitous discontinuity surfaces; (*vi*) carbonate concretion horizons; (*vii*) unwinnowed shell beds; and (*viii*) micrite in packstones. Episodic starvation is a superior explanation because it explains all of these features and allows for the complex interplay of other environmental and biological factors that contribute to shell-bed growth. It may also be applicable to other deposits, previously interpreted as tempestites.

Résumé : La formation de lits coquilliers peut être le résultat de facteurs sédimentologiques et biologiques complexes. Les sédiments de l'Ordovicien supérieur des environs de Cincinnati, en Ohio, constituent une succession de roches coquillières carbonatées et d'argilites finement interlitées. Bien qu'elle ait fait l'objet de longues années d'étude, la formation des lits coquilliers et des cycles métriques cincinnatiens était, jusqu'à tout récemment, attribuée au seul remaniement par l'action des tempêtes. Ce modèle de « triage par l'action des tempêtes » considère les coquilles comme étant des clastes sédimentaires passifs et ne tient pas compte d'autres facteurs influant sur la formation des lits coquilliers. Le modèle récemment proposé par Brett et Algeo voulant que ces lits coquilliers se soient formés pendant de longues périodes de sédimentation normalement faible et que la plupart des argilites aient été déposées pendant de brèves périodes de forte sédimentation constitue une autre explication possible. En vertu de ce modèle de « privation épisodique », toute tempête se traduit par le triage des lits tant argileux que coquilliers. Nous avons testé l'application de ces deux modèles aux strates edeniennes–maysvillienne (Katien précoce à moyen) de la région de Cincinnati en compilant des observations relatives à leurs caractéristiques pétrologiques, taphonomiques et paléoécologiques. Le modèle de privation épisodique prédit plusieurs des caractéristiques observées que le modèle de triage par l'action des tempêtes n'arrive pas à expliquer, dont les suivantes : (*i*) des structures sédimentaires associées à l'action des tempêtes tant dans les argilites *que* les calcaires; (*ii*) l'absence d'un dépôt fossilifère suffisamment riche préalablement au triage; (*iii*) des faunes d'eau profonde préservées dans des grainstones; (*iv*) les conditions taphonomiques mixtes dont témoignent les fossiles des lits coquilliers; (*v*) l'ubiquité de surfaces de discontinuité; (*vi*) des horizons de concrétions carbonatées; (*vii*) des lits coquilliers non triés; et (*viii*) de la micrite dans des packstones. La privation épisodique est donc le meilleur des deux modèles parce qu'il explique toutes ces caractéristiques et intègre l'interaction complexe d'autres facteurs environnementaux et biologiques qui participent à la formation de lits coquilliers. Il pourrait également s'appliquer à d'autres dépôts précédemment interprétés comme étant des tempestites.

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Introduction

The analysis of shell-bed-rich successions, including the common interbedded shelly limestones and siliciclastics (Parsons et al. 1988; Dattilo 1993; Taylor and Brett 1996; Li and Droser 1999; Finnegan and Droser 2008), has become increasingly sophisticated. Kidwell (1986*a*, 1991*a*) explored such systems and concluded that the shell-bed limestones might form when shell accumulations were not diluted by other sediments. She also helped explain how the accumulation of hardparts affected benthic community succession with the concept of taphonomic feedback (Kidwell and Jablonski 1983; Kidwell 1986*b*). Recent work has also emphasized the role of biological processes in shell-bed development (e.g., Copper 1997; Tomašových et al. 2006*a*).

The abundantly fossiliferous Upper Ordovician of the Cincinnati region is among the best documented examples of such an interbedded succession (Tobin 1982; Diekmeyer 1990, 1998; Jennette 1986; Jennette and Pryor 1992, 1993; Holland 1993; Feree 1994; Dattilo1994, 1996, 1998, 2004*a*, 2004*b*; Holland and Patzkowski 1996, 1997; Holland et al. 1997, 2001*a*, 2001*b*; Miller 1997; Hughes and Cooper 1999; Barbour 2001; Brett and Algeo 2001*a*, 2001*b*; Drummond and Sheets 2001; Kohrs 2001; Miller et al. 2001; Sumrall et al. 2001; Webber 2002, 2004, 2005; Kirchner and Brett 2003; Hunda et al. 2006; Kohrs et al. 2008; McLaughlin and Brett 2007; Brett et al. 2008). In light of the well-preserved fossils and decades of intensive study, it is surprising that, until recently, virtually all Cincinnatian shell beds have been interpreted as tempestites, formed primarily by storm winnowing (e.g., Tobin 1982; Jennette and Pryor 1993; Holland et al. 2001*b*). This "storm-winnowing model" invokes active concentration of shells by erosional reworking and active bypassing of sediments (see Kidwell 1986*a*). The result is that shells are seen as passive clasts rather than the products of ecological processes.

A recently proposed alternative (Brett and Algeo 2001*b*; Dattilo 2004*b*; Brett et al. 2008) is that Cincinnatian shell beds grew in situ during long periods (decades to millennia) of normal, relatively low terrigenous input and that thick intervals of fossil poor siliciclastic muds were deposited as smothering blankets during periods of relatively high sediment input. This "episodic (sediment) starvation model" invokes passive concentration of shells by a mild sediment starvation (see Kidwell 1986*a*), which requires that shell beds formed by biological processes. It also encourages consideration of other environmental and biological factors, which may have enhanced or inhibited the growth of benthic communities.

In this paper, we discuss and test the predictions of both models against observed characteristics of microfacies, beds, and depositional cycles in the Cincinnatian. We argue that many paleoecologic, taphonomic, and sedimentologic features of these rocks cannot be adequately explained by the storm-winnowing model, but are consistent with the episodic starvation model. Thus the ubiquitous "tempestites" of the Cincinnatian Ordovician, and perhaps other similar successions, are more storm *influenced* than storm *generated*. Ultimately, we hope that this paper will encourage others to explore and debate the complexity of shell-bed genesis in these rocks.

Geological setting and paleogeography

The focus of this study is the interval of the Kope, Fairview, and Bellevue strata in outcrop and subsurface sections in the "tri-state" region of Ohio, Indiana, and Kentucky, USA (Figs. 1, 2). These units form the C1 and C2 sequences of Holland and Patzkowski (1996) in the lower part of the Cincinnatian Upper Ordovician section. They are of Edenian and early Maysvillian (approximately middle Katian; see Bergström et al. 2006) age.

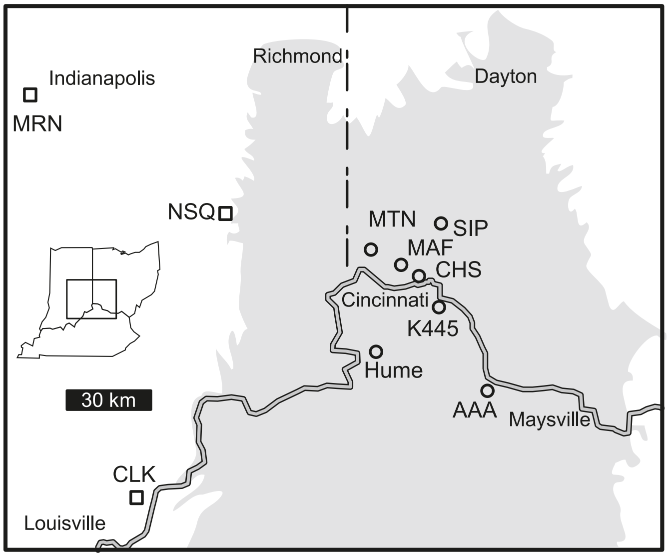
The C1 locally comprises the deep-subtidal Kope Formation (Holland et al. 2001*b*; Brett and Algeo 2001*b*). The C2 sequence includes the shallow-subtidal Fairview Formation (Diekmeyer 1998), the arguably deeper subtidal Miamitown Shale (Dattilo 1996), and the nearshore Bellevue Member. Local depositional strike was roughly northeast–southwest with deeper facies to the northwest and shallower facies to the southeast. These sediments also display metre-scale cycles (Hay et al. 1981; Tobin 1982; Jennette and Pryor 1993; Holland et al. 1997; Miller et al. 1997), which are each composed of a shale-dominated hemicycle and a limestone-dominated hemicycle. They range in thickness from 1 to 3 m with an estimated average period of about 40 thousand years(Holland et al. 1997).

Most models of shell-bed genesis previously applied to Cincinnatian strata (e.g., Cumings 1908; Bucher 1917, 1919; Rich 1951; Fox 1962; Scotford 1965; Weiss et al. 1965) have acknowledged the importance of three factors: (*i*) terrigenous sediment supply, (*ii*) storm or event winnowing, and (*iii*) hardpart production by benthic communities. If modern-day climatic systems are similar to those of the Ordovician, then the position of the area, between 20° and 25° south latitude, combined with the orientation of the continent at that time (Scotese 1990; Fig. 3.), would have made the area susceptible to large numbers of tropical storms.

Most of the terrigenous sediment that was deposited in the Cincinnati area during the Ordovician was derived from the rising Taconic Mountains to the east (Keith 1989; Pope and Read 1997; Ettensohn 1992; Ettensohn et al. 2002). The Taconic Foredeep, within which deep-water turbidites of the Martinsburg Formation were deposited, probably served as a barrier to sediment transport. Between the Martinsburg Foredeep and the Lexington Platform, shallower water siliciclastic sediments of the Reedsville Formation constitute a wedge that thins as it grades westward into the carbonate-rich Kope, Fairview, and Bellevue strata (Fig. 3).

This westward increase in carbonate content suggests some sediment starvation to the distal basin; a conclusion born out by the paleogeography. Coarser sediments shed from the Taconic highlands would have been trapped gravitationally behind the forebulge. Detrital clays drifting into the foreland basin would have flocculated on contact with salt water and settle out long before reaching the Reedsville, Kope, and Fairview depositional areas. Long-range transport (200–600 km to the areas of the Reedsville, Kope, and Fairview formations, and yet another 200 km to central Indiana) would have, therefore, been impossible. Given this barrier, the question is not simply how both silt and clay reached this area, but how they might have been delivered with approximate 40 000 years periodicity. Although this periodicity suggests a strong influence of orbital forcing, the

Fig. 1. Regional map of the Ordovician outcrop area around Cincinnati in Ohio, Indiana, and Kentucky showing drill cores (squares) and outcrop sections (circles). Ordovician outcrop shaded. Drill cores: MRN, Marion County core, Indiana core 494; NSQ, Newpoint Stone Quarry core, Decatur County, Indiana core 279; CLK, Clark County core, Indiana core 332. Ohio outcrop sections: MTN, Miamitown; MAF, Mount Airy Forest; CHS, Rice and Gage Street; SIP, Sharonville Industrial Park. Kentucky outcrops: K445, series of outcrops along Kentucky highway 445 and interstate highway 275; AAA, series of outcrops near Holsts Creek.



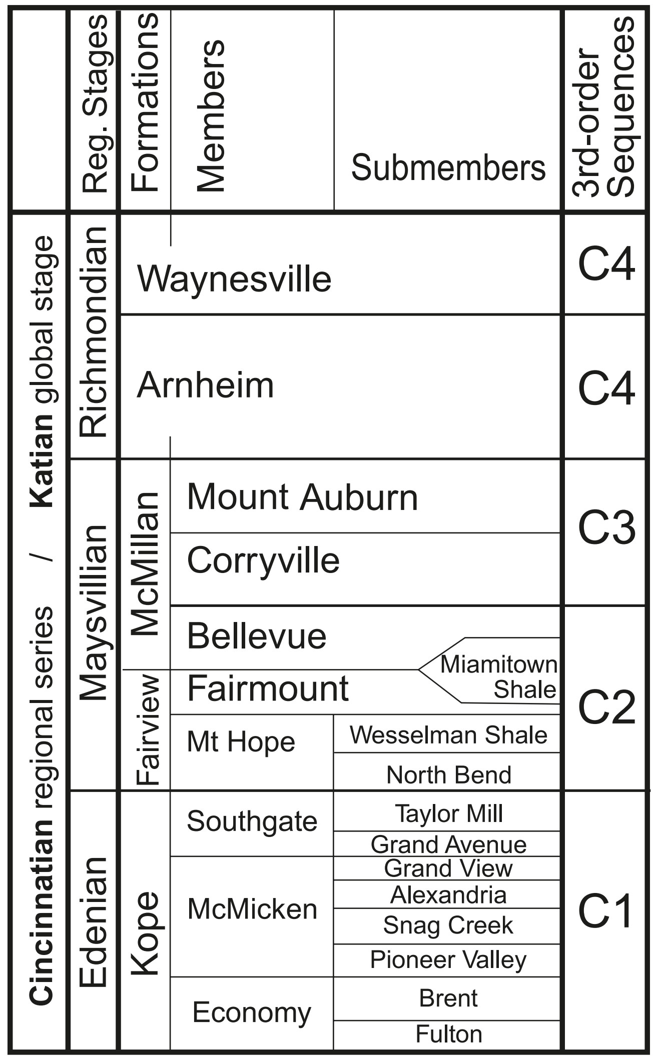
specific mechanism responsible for sediment delivery and modulation remains unclear. Still, there are a number of possibilities that might be considered.

First, the Sebree Trough, a northeast–southwest-trending depression through central Ohio and southern Indiana, could have served as a conduit for the transport of sediment around the forebulge (Mitchell and Bergström 1991; Kolata et al. 2001). This is a reasonable delivery mechanism, but it is unlikely that such a conduit alone would have modulated sediment supply in an episodic or cyclic manner.

Another possible sediment delivery mechanism concerns the development of a strong thermohaline gradient in the water column. A warm, low-salinity surface layer could have derived from fluvial runoff that failed to mix with cooler seawater. In this layer, clay may not have flocculated, thereby remaining suspended as a spreading surface plume or detached flow (see Pierce 1976). If this happened, the thermo–halocline may have been sensitive to changes in climate, sea level, or surface conditions, thus providing a mechanism for cyclic, as well as irregular episodic, sediment delivery. But even so, it is unlikely that this mechanism would have permitted the long-distance transport of silt, and it follows that the relatively high silt content of the Cincinnatian mudrocks herein is inconsistent with this interpretation.

An alternative mechanism is suggested by the fact that the cumulative thickness of siltstone beds in the upper Kope Formation (and equivalent Garrard Siltstone) and the Fairview Formation increases to the southeast. This suggests a source area in portions of the southern foreland basin, which might have been overfilled by Edenian time (Fig. 3).

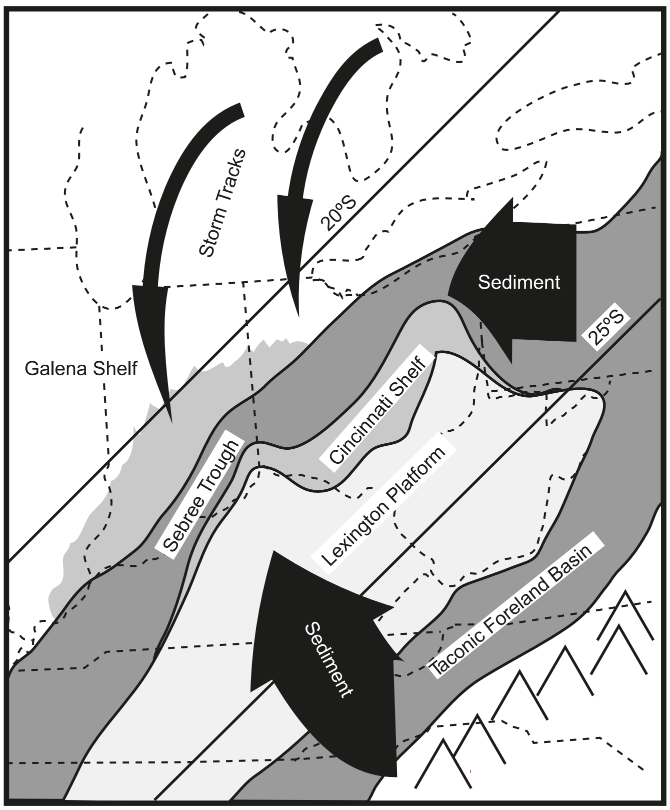
Fig. 2. Section showing stratigraphic names used in this paper. Third-order sequences adapted from Holland and Patzkowski (1996). Principle framework of formations and members adapted from Caster et al. (1955); these units are superior to most later lithostratigraphic units in their regional correlability, high-resolution, and concordance with third- and fourth-order stratigraphic cycles (see Holland 1993; Brett and Algeo 2001*b*). Some later refinements are included: Brett and Algeo's (2001*a*) redefined members and new submembers of the Kope and lower Fairview Formations; Ford's (1967) Miamitown Shale. The entire interval is near the middle of the global Katian Stage (Bergström et al. 2006) and forms the base of the regional Cincinnatian series. Reg., Regional.



Overfilling would have led to the development of a low-gradient, seaward-dipping ramp. This could have affected cyclic siliciclastic sediment delivery to the study region through alternating episodes of retention and release of sediments in coastal environment that accompanied the rise and fall of relative sea level, respectively.

Finally, fluctuations in sediment delivery may simply reflect fluctuations at the source, independent of delivery mechanism. Significantly larger volumes of mud are generated by mountainous areas in tropical wet climates than by similar highlands in dry climates (see Potter et al. 2005). Thus

Fig. 3. Paleogeographic map showing Kope-age lithologies, possible sediment paths, and storm tracks. The Cincinnati region would have been subject to hurricane activity. Episodic starvation is suggested by barriers to sediment transport; the region was separated from the sediment source in the Taconic Mountains by the Taconic Foreland Basin and the Lexington platform. Isopachs suggests a siliciclastic source to the southeast, where the foreland basin might have been overfilled. Alternatively sediments may have been delivered through the Sebree Trough. Additionally, the latitude of the Taconic Mountains, at or near the subtropical highs, might have exposed them to alternating wet and dry climates.



climatic cycles could explain cyclic sediment delivery from the Taconic Mountains, which were near the subtropical highs, as well as they might explain changes in storm frequency in the Cincinnatian (Holland et al. 2001*b*) or wet–dry cycles in the mid-continent Carboniferous (Olszewski and Patzkowsky 2003).

Models of shell-bed genesis applied to Cincinnatian strata

Elements of both the episodic starvation and storm-winnowing models can be traced to studies on Cincinnatian shell beds that were published long before the more modern works of Aigner (1985) and Kidwell (1986*a*). An early version of the episodic starvation model was formulated by Cumings (1908), who proposed that shell-rich limestones accumulated in clear waters, while shales were deposited during episodes of higher sediment influx. Cumings also speculated that storms played an important role in rapidly burying faunal remains in mud (and thus enhancing their preservation potential in some beds) and moulding of skeletal debris into large ripple-like bedforms.

Early versions of the storm-winnowing model are seen in the work of Cincinnati geologists Bucher (1917, 1919) and Rich (1951), who suggested that a mixture of shells and mud deposited over a lengthy period of time in calm water (below the reach of fair-weather waves) would have been prone to the reworking and winnowing action of storm waves. The authors surmised that the removal of several centimetres of mud by such disturbance of the seafloor would have left a lag concentration of skeletal fragments covered later by the mud that settled from suspension upon the abatement of storm activity.

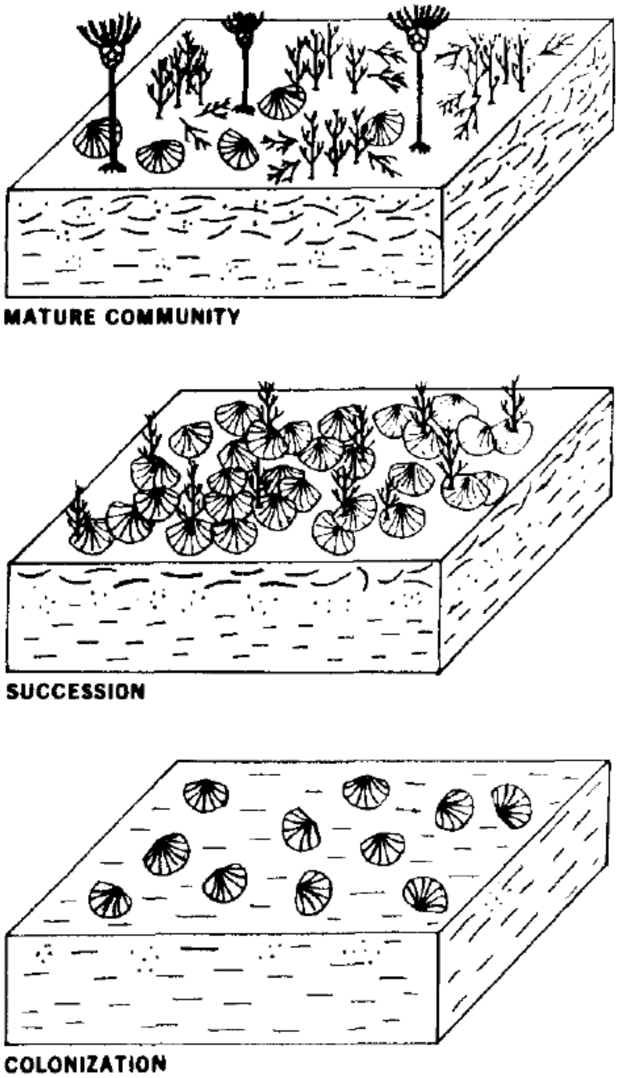
By the early 1960s, a number of workers had begun to examine mixed limestone–mudrock successions from the perspective of paleoenvironmental dynamics and paleoecology. For example, Fox (1962), who supported an episodic starvation model, suggested fluctuations in water temperature as a possible additional factor contributing to the alternating deposition of siliciclastic mud and carbonate. However, with the rising influence of the sedimentary facies concept and corresponding decrease in popularity of "layer cake" stratigraphic models, later workers began to assume that the locally discontinuous limestone beds were strictly local features, and introduced a series of new models to explain spatially patchy shell-bed development. Two main scenarios were generally favoured: one in which biotic community development was modulated by spatial variations in turbidity (Scotford 1965; Weiss et al. 1965; Anstey and Fowler 1969), and another viewing patchy biotic community development as a modulator of local environments (see Fig. 4) (Lorenz 1973; Martin 1975; Harris and Martin 1979; Mahan 1981).

The next major phase in the interpretation of mixed limestone–mudrock successions followed advances in event and sequence stratigraphic research (e.g., Sloss 1963; Einsele and Seilacher 1982; Aigner 1985; Clifton 1988; see also Miall 2004) coupled with an increased understanding of the dynamics and products of storm sedimentation (e.g., Aigner 1985). Aigner's (1985) tempestite proximality model, originally developed from the observation that storms spread sand offshore into mud-dominated environments, was especially influential to the interpretation of ancient marine successions containing evidence of storm deposition.

Application of Aigner's (1985) model to successions like the Cincinnatian revealed that the model required some modification. Cases of shell beds consisting of transported shell debris have indeed been documented elsewhere (see Elmore et al. 1979), but paleoecological work (Fox 1962; Scotford 1965 Weiss et al. 1965; Lorenz 1973; MacDaniel 1976; Harris and Martin 1979; and Mahan 1981; see also Miller 1997; Webber 2005) has clearly revealed that community patchiness is too well preserved in the Cincinnatian shell beds to suggest the transport of shelly remains over any significant distance as might otherwise be expected for sand on a storm-dominated shelf. Thus, it is not surprising that the notion of shell beds having been formed by sea-floor winnowing during storms, as previously favoured by authors such as Bucher (1917, 1919) and Rich (1951), regained popularity.

With the increasing popularity of sequence stratigraphy, limestone–mudrock cycles began to be seen as the result of differential storm winnowing controlled by fluctuations in relative sea level. It was envisaged that mud-rich hemicycles with only thin, sparse beds of packstone were formed

Fig. 4. Ecological succession in Cincinnatian shell beds, as illustrated by Harris and Martin (1979). In the 1960s and 1970s, models of shell-bed genesis emphasized biological factors and sought to explain the perceived lack of regional extent in individual shell beds. Two models arose to explain the successional development of benthic community patches: (*i*) that patchy turbidity controlled community development (e.g., Anstey and Fowler 1969) or (*ii*) that patchy community development controlled sedimentation. The existence of Cincinnatian community patches is well established (Miller 1997; Webber 2005), and the episodic starvation model allows for patchy ecological succession during periods of basin-wide starvation. Reproduced by permission of SEPM (Society for Sedimentary Geology).



during deep-water phases when the seafloor was infrequently affected by storm-generated winnowing. Conversely, grainstone-rich hemicycles were interpreted to record shallow-water phases when storms repeatedly winnowed the seafloor. That sedimentary structures observed in such limestone–mudrock cycles could be explained in this context appealed to many authors, leading to widespread acceptance of the model (Kreisa 1981; Kreisa and Bambach 1982; Brett 1983; Aigner 1985; Tobin and Pryor 1992; Jennette and Pryor 1993). Metre-scale cycles were soon documented (Tobin 1982; Tobin and Pryor 1992), and a subset of these cycles was correlated regionally (Jennette 1986; Jennette and Pryor 1993). This encouraged further recognition and correlation of thin units and ultimately led to the general abandonment of strictly authogenic models of shell-bed genesis (e.g., those of Scotford 1965; Harris and Martin 1979).

Ironically, further work on cycles and correlation revealed a weakness in the modified storm-winnowing model. The idea that metre-scale cycles were caused by water-depth fluctuations implied a corresponding paleoecological cyclicity. Dattilo (1996) used this concept to correlate a few metre-scale cycles in the Miamitown Shale using paleoecological ordination. Building on this pilot study, Holland et al. (2001*b*) applied the same method to approximately 50 m scale cycles spanning most of the Kope Formation and part of the Fairview Formation. Contrary to expectations, when the ordination scores were plotted against stratigraphic position, Holland et al. (2001*b*) found no evidence for metre-scale cyclicity in inferred water depth, despite clear evidence of such changes at larger scales. As confirmed by Webber (2002) the depositional environments inferred for intervals of thick grainstone beds were, on average, not detectably shallower than those inferred for mud-dominated intervals. To explain this, Holland et al. (2001*b*) proposed a revision of the storm-winnowing model for generating sedimentary cycles, suggesting that storm intensity and frequency varied as the result of climatic cycles—as opposed to variations in water depth.

Meanwhile, the correlation efforts on the Kope–Fairview succession were successful (Miller et al. 2001) and seeded further study in the Kope Formation (see Brett and Algeo 2001*a*, 2001*b*), but this again brought surprises. A growing body of evidence had begun to indicate that very thin Cincinnatian units, even at bedding scale, despite being locally discontinuous, were traceable over tens or even hundreds of kilometres (Brett and Algeo 2001*b*; Brett et al. 2003); this could not be accounted for by localized storm winnowing. Careful studies of Cincinnatian mudstone units (Hughes and Cooper 1999; Hunda et al. 2006; Kohrs et al. 2008) also revealed their identity as bundles of successive event deposits, not background deposits as was previously assumed.

In light of emerging data that was apparently at odds with the storm-winnowing model, a few authors (e.g., Brett and Algeo 2001*b*; Brett et al. 2003; Dattilo 2004*b*; Kirchner and Brett 2008) reconsidered the role of episodic starvation in the development of shell beds. As in previous incarnations (Cumings 1908; Fox 1962), the episodic starvation model is based on the premise that shell- and mud-rich lithologies in ancient offshore marine deposits primarily reflect times of low and high rates of siliciclastic mud influx, respectively. In the model as it presently stands, however, more emphasis is made on the importance of storm-generated disturbance in the formation of both mud- and shell-rich intervals. It is becoming increasingly apparent that shell gravels simply show more obvious evidence of storm disruption (e.g., sharp erosive bases, grading, and ripples) than do most siliciclastic mudrocks; even though the latter may well too have been deposited under high-energy conditions, they tend to lack the contrasts in grain size, texture and mineralogy normally essential for rendering sedimentary structures readily observable by conventional means (see Tsujita et al. 2006).

The models and their predictions

If the storm-winnowing and the episodic starvation models are to be assessed, a detailed comparison of their similarities and differences is essential. In the following text, we explore each model and its implications for local processes and, in turn, formulate a series of tests to distinguish between the two modes of sedimentation.

Storm-winnowing proximality model

The first requirement for the storm-winnowing model is a pre-existing fair-weather deposit of intermixed siliciclastic mud and skeletal debris. A shell bed is envisaged to form from this raw material via suspension and re-sedimentation of its constituents throughout the initial increase and subsequent decrease of hydraulic energy during a passing storm; in the latter phase, sedimentary particles are deposited in order of decreasing settling velocity—shells first, followed by silt and increasingly finer grained mud particles. The model, therefore, predicts deposits of three main types: (*i*) fossiliferous "background" or "fair-weather" mud, (*ii*) concentrations of skeletal debris (shell beds), and (*iii*) beds of unfossiliferous, storm-deposited silts and muds (Fig. 5; Tobin and Pryor 1992; Jennette and Pryor 1993). An important expected difference between shell-rich background muds and storm-deposited shell beds is the mud-supported fabric of the former (versus a grain-supported fabric in the latter).

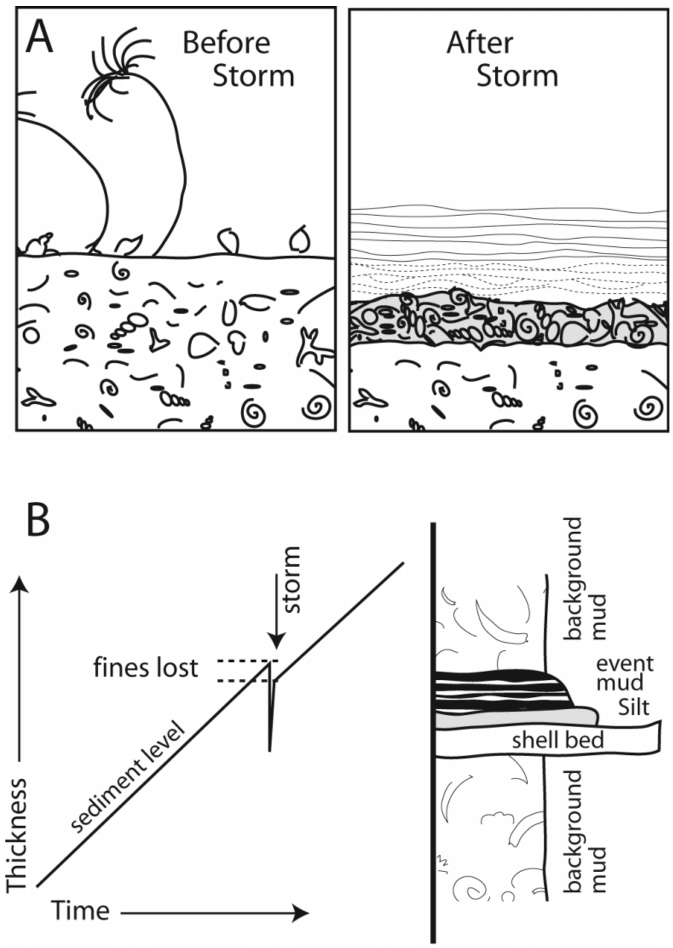
The textural features observed in storm-produced shell beds should reflect the nature of storm disturbance that formed them. A single storm should produce a mud-rich but grain-supported (packstone) shell bed, its thickness reflecting depth of sea-floor winnowing, and, in turn, storm intensity and (or) water depth. Such beds should also contain evidence that the shells were actively excavated from the seafloor, including occurrences of mud-filled shells that had obviously been buried prior to reworking.

The finer grained sedimentary particles derived from the fair-weather mud would be transported basinward by progressively weakening waning-phase currents, leading to the development of an exposed shell pavement in proximal areas of winnowing and in a graded deposit of silt and clay in more distal areas, where the fine-grained materials were allowed to settle from suspension. Repeated episodes of winnowing and basinward transport of mud by multiple storms would be manifested in the development of thicker, cleaner, amalgamated shell beds.

Episodic starvation model

This model attempts to explain the intercalation of mud and shell beds as a product of intermittent siliciclastic sediment influx (Fig. 6). If other factors are favourable, prolonged periods of relative sediment starvation allow for in situ growth of shell beds that are occasionally interrupted by events of mud blanketing. Conversely, periods in which the influx of siliciclastic mud was high would be characterized by the aggradation of thicker mud event deposits punctuated by short diastems allowing for minor shelly pavements and lenses. Even with sediment starvation, shell beds might fail to develop if conditions inhibit biological processes or enhance shell destruction. Individually, these shell beds are similar to Kidwell's (1991*a*, 1991*b*) hiatal or condensed deposits, but they represent less time under conditions of less severe sediment starvation.

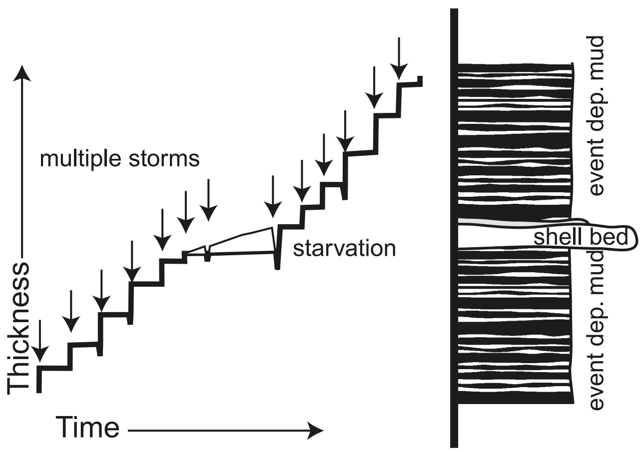
Fig. 5. Storm-winnowing model of shell-bed generation; how shell beds are winnowed from undifferentiated sediments. (A) sea-bottom conditions before and after a storm showing the three basic storm sediments; fair-weather mud is a shell rich deposit that is separated by winnowing into shell beds and winnowed silts and muds. (B) sediment accumulation through time. Fair-weather muds accumulate at a more or less constant rate until geologically instantaneous storms rework a depth of this sediment and redeposit it to form a shell bed (limestone) overlain by silt and mud. Note that, under this model, fair-weather muds are time-rich deposits and shell beds are time-averaged through reworking.



Assumed here is that mud accumulation occurs via discrete events, each of which can potentially deposit a single layer. If multiple depositional events occur in rapid succession, individual mud and silt layers can form thicker bundles via sequential aggradation; features such as micrograding and "lam-scram"(laminated base bioturbated top; see Bromley 1990) texture and occurrences of unusually well-preserved macrofauna can facilitate the identification of individual beds in such bundles (see Tsujita et al. 2006).

As proposed by Harris and Martin (1979) and by Mahan (1981), shell beds should develop, at least initially, partly as a consequence of community succession. Shells would be produced by successive generations of macrofauna that established themselves as larvae on the seafloor. As these would be affected to some degree by destructive mechanical

Fig. 6. Sediment–time diagram showing bed development under episodic starvation model. Here storm winnowing and storm deposition is not considered geologically rare but is assumed to affect all sediments. Mud is deposited when it is introduced episodically to the basin or region through storms or other mechanisms. Shell beds accumulate slowly during long periods of sediment starvation, but are modified by storms episodically. Note that mud is a time-poor deposit, while shell beds represent much longer periods of accumulation. dep., deposit.



and biological processes, shell concentrations representing longer periods of accumulation (decades to centuries) would be expected to contain faunal remains showing a mixture of taphonomic states (Tomašových et al. 2006*b*) and larger proportions of lime mud (Anstey and Fowler 1969). Shell beds representing even longer periods of accumulation (centuries to millennia), where destruction of long accumulated shells proceeds apace with addition of new shells, could be distinguished by the abundance of resistant diagenites, such as phosphatic steinkerns and nodules or carbonate concretions.

Storms, being ubiquitous and having local recurrence intervals on the order of decades to centuries, could potentially rework a shell bed at any point in its development. However, shell beds formed during shorter lived diastems would be more likely to escape the effects of storm winnowing than those recording longer term periods of sediment starvation. Accordingly, we expect that a shell bed whose growth was terminated fairly soon after its initiation would tend to show a lower degree of winnowing than one that developed over a longer period of time. Storm disturbances would mix shelly remains, remove some fine matrix, and contribute to mechanical abrasion and shell breakage. It follows that, over a protracted period of sediment starvation, skeletal components of a shell bed would be reworked several times by multiple storms with multiple "rest" periods between reworking events. Unless subjected to early cementation, the longer a shell bed accumulates before being buried, the more likely it will be disrupted during exceptionally severe storm activity. Repeated reworking, and consequent basinward transport of minor amounts of finer sediment fractions, would result in a cleaner and more mature shell deposit. But it should be emphasized that extreme siliciclastic starvation would produce units of clean grainstones in downramp positions even in cases where winnowing was minimal.

Testable predictions of the models

Superficially, both the storm-winnowing and episodic starvation models of shell-bed formation would seem to explain bedding in the Cincinnatian succession equally well. But as discussed in the following text, there are several points of disagreement by which their respective validity can be evaluated. Specifically, both models can be tested based on (*i*) the existence of fossiliferous fair-weather mud, (*ii*) the scoured depth of sediment winnowing, (*iii*) the inferred energy level and water depth of grainstone deposition, (*iv*) the degree to which shell beds were exposed, (*v*) the existence of unwinnowed shell beds, and (*vi*) the calcareous mud content of the original shell beds.

Here, we review the model predictions and argue that characteristics of the Cincinnatian rocks are more consistent with the episodic starvation model than the storm-winnowing model.

Assessment of model predictions against observed characteristics of the Kope–Bellevue interval

These model predictions can be tested with a range of petrologic, taphonomic, and paleontologic criteria. We include observations from both older and more recent studies that have focused on shells of the Kope Formation (see Brett et al. 2008), as well as new, unpublished data. Our arguments are centered on metre-scale cycles of the Kope–Bellevue succession of the Cincinnatian (Fig. 7). These cycles are typically defined as couplets, each consisting of a siliciclastic mud-rich package and a carbonate-rich package. We address points of contrast between the two models in the context of both siliciclastic-rich and carbonate-rich packages.

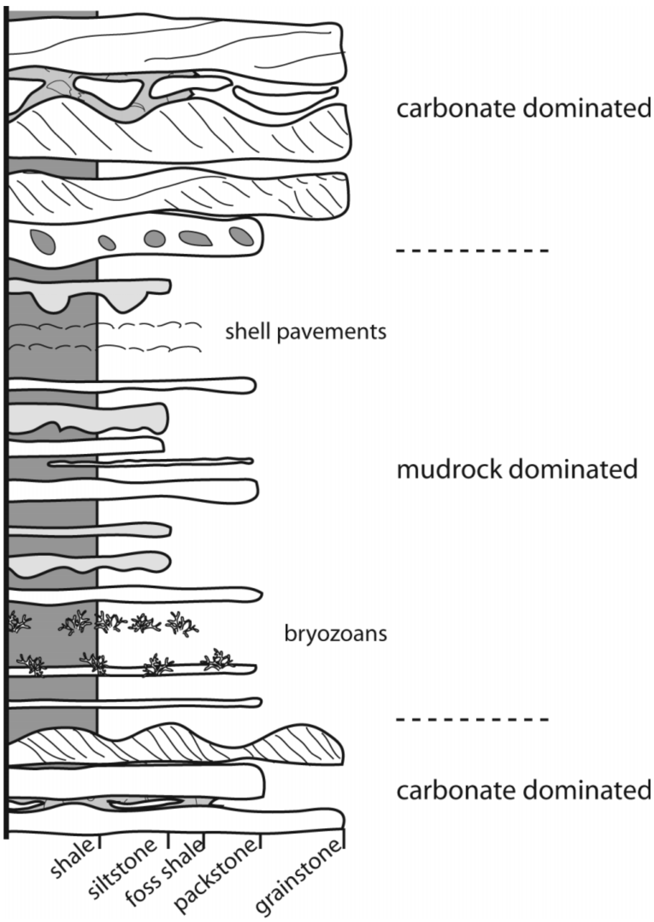
Mudstone microfacies

The storm-winnowing model predicts the existence of two varieties of mud unit—one type deposited under fair-weather and the other under stormy conditions. To test this prediction, it must be determined whether or not both actually exist in the section by assessing the essential characteristics of each. We proceed with a discussion of the predicted characteristics of the two types of mud deposits, the observed characteristics of Cincinnatian mudrocks, and the quality of fit between these two.

Expected characteristics of fair-weather versus storm-deposited mud

At a bare minimum, the precursor deposit had to contain a enough skeletal material to be reworked into a shell bed without *excessive* excavation. However, it could not contain so much shell material that it was bioclast-supported and could itself be considered an unwinnowed shell bed. The idea that "background" mud records continuous mixed deposition under fair-weather conditions is not essential and may be unreasonable. Perhaps storm winnowing generated a series of thinner units. These would be represented by layers of barren mud, some with a concentration of shell debris and (or) silt at their base. Larger storms would rework these into thicker shell beds overlain by or distally traceable to thicker barren muds.

Fig. 7. Diagram of an idealized Kope cycle showing the carbonate and mudrock-dominated phases. Under the storm-winnowing model the mudrock-dominated phases are interpreted as distal tempestites, while the carbonate-dominated phases are considered proximal amalgamated tempestites. Under the episodic starvation model, the mudrock-dominated facies is interpreted as a series of mud-depositional events separated by short periods of starvation, during which shell pavements, bryozoan muds, or thin packstone shell beds could develop. On the other hand, the carbonate-dominated phase developed during long periods of starvation punctuated by brief sedimentation events.



Observed characteristics of mudrocks

Can these hypothetical deposits be identified among the actual sediments of the Cincinnatian? The Cincinnatian mudrocks examined herein are primarily composed of illitic clays (Scotford 1965; Bassarab and Huff 1969) with variable proportions of quartz silt, both allogenic. The other constituents are either authigenic minerals or parautochthonous bioclastic particles.

While general mineralogy has long been known, systematic petrographic studies of Cincinnatian mudrocks have only begun (Hunda et al. 2006; Kohrs et al. 2008). Even so, characteristics such as colour, which exhibits a continuous spectrum of tones between siltstone (light grey) and claystone (dark grey to dark brown) end members, can yield important information on the internal structure of mudrock units. Indeed, in both drill core and outcrop sections, slight variations in the silt and clay content and relative degrees of bioturbation of mudrocks can be detected from heterogeneities in colour and texture. Skeletal remains of macrofauna are conspicuous in these and can be readily studied in terms of abundance, diversity, and taphonomy. These parameters are central to determining the relative importance of fair-weather and storm conditions in the development of mud-dominated intervals of the succession.

Any given horizon can be classified as being either barren (lacking skeletal remains) or fossiliferous ("saturated" with shell fragments). Barren mudrocks vary in silt content and bed thickness. They have been divided by McLaughlin and Brett (2007) into distinctly bedded gray types and less distinctly bedded dark brown types. Fossiliferous mudrocks display more recognizable differences in bed thickness and taxonomic and taphonomic characteristics of the fossils that allow identification of at least four subcategories: (*i*) horizons of well-preserved articulated fossils (obtrution horizons), (*ii*) bedding plane concentrations of shell debris, (*iii*) horizons of intact bryozoan colonies, and (*iv*) fossil-rich mud intervals.

Barren mudrocks

Barren mudrocks, lacking the high concentrations of shelly material that characterize their fossiliferous counterparts can look remarkably homogeneous. On closer examination in fresh outcrops and drill cores, they exhibit thinner, discrete, sharp-based beds of mud (Fig. 8). In some cases, a subtle decrease in the proportion of silt and clay can be distinguished within each bed. Subtle lithological variations (e.g., between siltstone and silty mudstone) are apparent in some outcrops because beds of siltstone tend to resist erosion better than the more clay-rich mudrocks.

Barren mudstones and siltstones can be related to taphonomic attributes of fossil-bearing horizons with which they are sometimes associated. For example, a bed of barren mudstone immediately overlying a horizon of articulated crinoids is likely the deposit that smothered the crinoids and enhanced their preservation. The same probably holds for the mudstone observed to overlie well-preserved bryozoan colonies or shell pavements.

While barren mudrocks can be ruled out as precursor deposits of shell beds, their lack of fossils and inferred episodic deposition makes them ideal candidates for storm-deposited muds.

Horizons of well-preserved articulated fossils: obrution horizons

The horizons of well-preserved articulated fossils commonly found in association with beds of barren mudrocks are here identified as obrution layers (Brett and Seilacher 1991) because this kind of preservation would have necessitated the rapid burial and smothering (obrution) of living organisms (Fig. 9). Obrution horizons are observed to occur both singly and in groups within thicker intervals of barren mudstone; the *Flexicalymene* layers ("butter shales") found throughout the Cincinnatian strata are the most famous of these (Hughes and Cooper 1999; Hunda et al. 2006). They can also be found on the upper surface of limestone shell beds, as exemplified by the crinoid- or edrioasteroid-bearing horizons described by Meyer (1990) or Sumrall et al. (2001). The association of obrution horizons with rapid depositional events is undisputed, so the barren mudrocks with

Fig. 8. Barren mudrock illustrating banding indicative of event deposition. (A) Marion County core 706–713 ft. (parts; 215–217 m) thick mud-dominated interval of Miamitown Shale equivalent. (B) Newpoint Stone Quarry core 460–480 ft. (parts; 140–146 m) interbedded carbonates and shale of the Wesselman Shale submember equivalent. (C) Marion County core close view 721 ft. (220 m) upper Fairmount Member equivalent showing thin laminations. (D, E) Newpoint Stone Quarry core views 461 ft. (140 m) Mt Hope Member. All core 2 inch (5 cm) diameter, mechanically split.

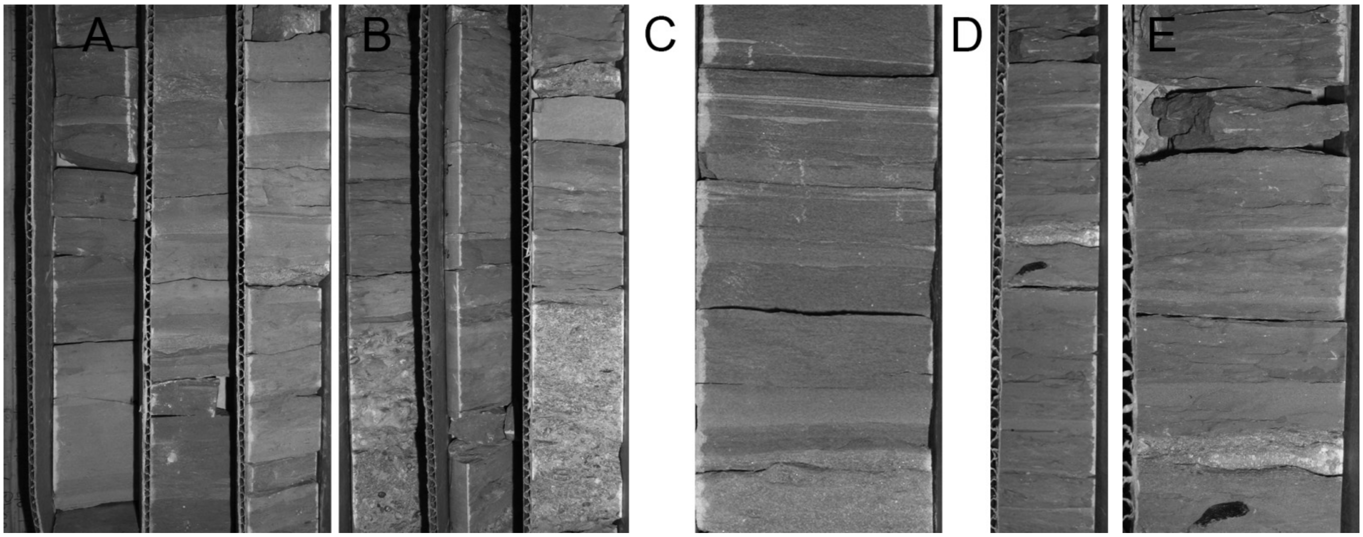
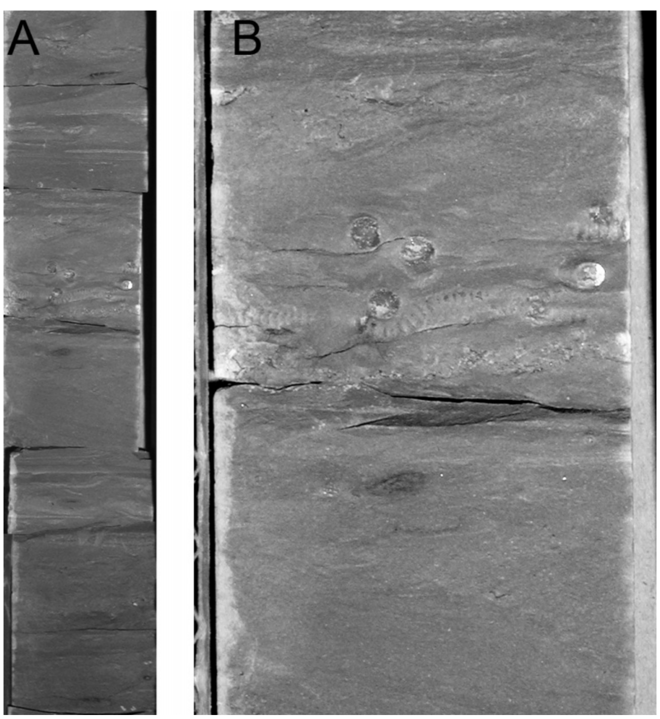


Fig. 9. Obrution deposit in Marion County core. Note the articulated crinoid column entwined in the branches of a ramose bryozoan. Such well-preserved articulated fossils occur sparsely along distinct horizons within otherwise barren mudrock; they indicate sudden burial. Although not rare in outcrop, the sparseness of these deposits makes them difficult to detect in cores. Occurrence at 801 ft. (244 m) in the upper part of the Taylor Mill submember. (A) reduced for context; (B) enlarged for detail.



which they are commonly associated could very well represent storms. Where obrution horizons are associated with shell beds, the mixtures of skeletal remains within the latter, both articulated and disarticulated, and both whole and fragmented (e.g., Dattilo 2004*a*) suggests that the events that brought the smothering muds were also responsible for reworking and winnowing shell material in the earlier, higher energy phase of storm disturbance.

Obrution horizons are often sparsely fossiliferous and patchy in distribution with fossil densities as low as one fossil specimen per square metre. The only reason they can be readily recognized is that their contained fossils are so taphonomically distinctive and well preserved; indeed many obrution beds probably go unrecognized due to their sparse fossil content. Even in cases where several obrution layers form dense bundles, few stratigraphic intervals, if condensed by reworking to a metre depth, contain adequate shell materials to form a continuous pavement of shells.

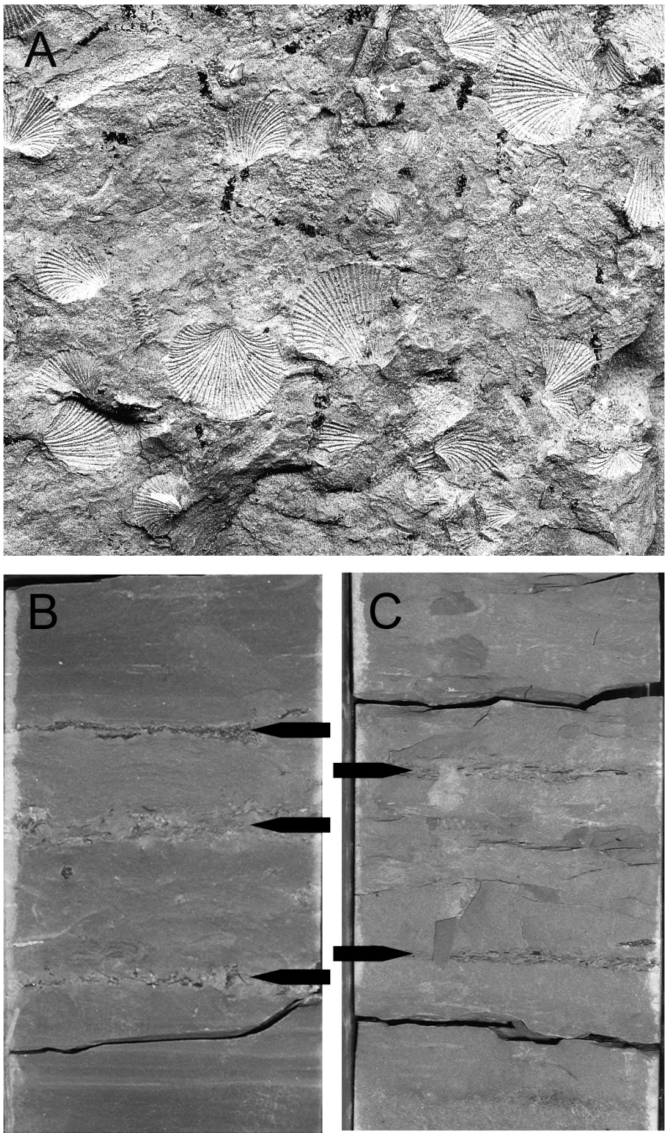
Single bedding plane shell concentrations

Like obrution horizons, single-layer shell concentrations are found within units of otherwise barren mudstones (Fig. 10). Such horizons are common throughout the Cincinnatian succession and are particularly conspicuous in the Kope Formation. They are typically dominated by flat-shelled brachiopods, such as *Rafinesquina*, *Dalmanella*, or *Sowerbyella*, but commonly contain remains of other taxa as well. These horizons could be considered the thinnest of the observed shell beds, too thin to be cemented. It is not difficult to imagine the mudstone immediately overlying them to have been storm deposited, and the entire couplet having been winnowed from precursor “fair-weather mud”. A cluster of these thin shell beds could have been winnowed to form a thicker shell bed.

Horizons of bryozoan colonies

Bryozoan colonies up to tens of centimetres in diameter are frequently found in discrete horizons encased by mudrock (Fig. 11). Although generally flattened and (or) fractured by compaction, they are remarkably complete and fragments can

Fig. 10. Single-layer shell pavements. Like obrution deposits, pavements tend to occur between event deposits in otherwise barren mudrock successions, suggesting sudden burial. (A) bedding plane view of hand sample from Hume at 29.76 m (see Miller et al. 2001), Brent submember. (B) Marion County core 815 ft. (248 m), approximately Grand View submember equivalent. (C) Newpoint Stone Quarry core 375 ft. (114 m) Bellevue member equivalent. Arrows indicate pavements.



be fitted back together to reconstruct colonies (Erickson and Waugh 2002).

The form of bryozoan colonies varies. Some are delicate ramose forms with branches just millimetres in diameter, whereas others are robust frondose forms whose branches exceed a centimetre in thickness and several centimetres in breadth and height. The colonies frequently occur in patches <1 m across and mutually spaced several metres apart in outcrop. The density of skeletal material in these patches depends on colony form; some colonies are open, while others are compact, approaching the skeletal density of shell beds. As with the obrution layers discussed earlier in the text, the bryozoan colonies are observed both within units of barren mudstone, and directly overlying limestone shell beds.

Many bryozoan-rich horizons appear to be obrution layers, manifesting single events of burial. However, it is possible that some colonies survived such events and continued to grow upward over longer periods of time, or grew more gradually under fair-weather conditions, keeping just ahead of sediment accumulation on the seafloor. Further study is required before this can be determined.

In any case, it is unlikely that the large, but delicately constructed, bryozoan colonies could have survived fragmentation if once buried, then later exhumed during a storm. Even robust colonies would not have survived intact. More likely is that these colonies grew in place, and, as such, represent components of unwinnowed mud deposits.

We emphasize that reworking and consequently fragmentation of a colony should generate a lens of bryozoan fragments and lenticular bryozoan-fragmental limestone. Such features are indeed common in the studied succession, and we have encountered at least one large fragment of bryozoan colony, still enclosed in a rip-up clast of mudstone, incorporated into a shell-rich limestone bed in the Kope Formation.

Intervals of fossil-rich mudrock

Some fossil-rich mudrock lithologies occupy stratigraphic intervals rather than single horizons. These intervals contain shells that are packed sufficiently tight to support the overall sediment fabric (Fig. 12). What distinguishes these intervals from limestones is the incoherent nature of its muddy matrix, which appears somewhat coarser grained than typical of other mudrocks in the Cincinnatian succession. The mineralogical composition of this coarse material has not yet been determined, but we suspect that it is at least partly diagenetic. There is also a tendency for this sort of fossiliferous mudrock to be associated with shallower nearshore facies and to contain large and (or) robust shells exhibiting degrees of breakage and abrasion.

The only distinct signs of event deposition in these mudrocks are the thin irregularly bedded and commonly lenticular packstones that occur intermittently throughout these intervals. In view of their high fossil content, these intervals could have supplied adequate shell debris to generate shell beds through storm winnowing. However, since these lithologies are already bioclast supported, they themselves can be classified as shell beds. Furthermore, taphonomic evidence from the Bellevue suggests that these units were subjected to strong currents, and may have already undergone winnowing, under fair-weather conditions, prior to their final deposition and burial.

Winnowing the precursor mud

From the preceding discussion, it is apparent that obrution beds, single-layer shell-pavements, and bryozoan-rich horizons were all episodically emplaced and do not fit the expected characteristics of fair-weather mud deposits. Perhaps even more serious is the recognition that fossil-rich mudrock intervals were *themselves* probably winnowed (on par with limestone beds) and, as such, would not have provided the raw material for the formation of *new* shell beds via winnowing. Since it seems unlikely that fair-weather mud would have been everywhere entirely consumed, we are forced to

Fig. 11. Bryozoan-rich intervals. Generally bryozoan-rich intervals consist of entire, though broken colonies which appear to have been buried suddenly. (A) Newpoint Stone Quarry core 462 ft. (141 m), Wesselman Shale equivalent. (B) Newpoint Stone Quarry core 477 ft. (145 m), North Bend Member equivalent. (C) Clark County core 555 ft. (169 m), Southgate Member equivalent. (D) Newpoint Stone Quarry core 430 ft. (131 m), Fairmount Member equivalent.

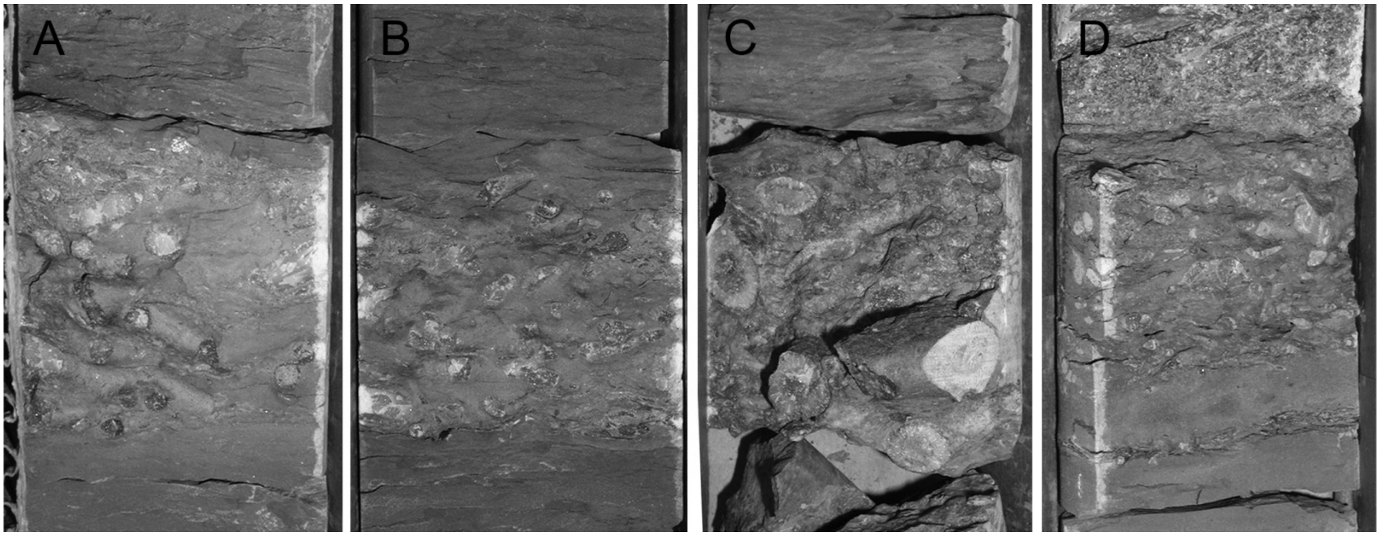
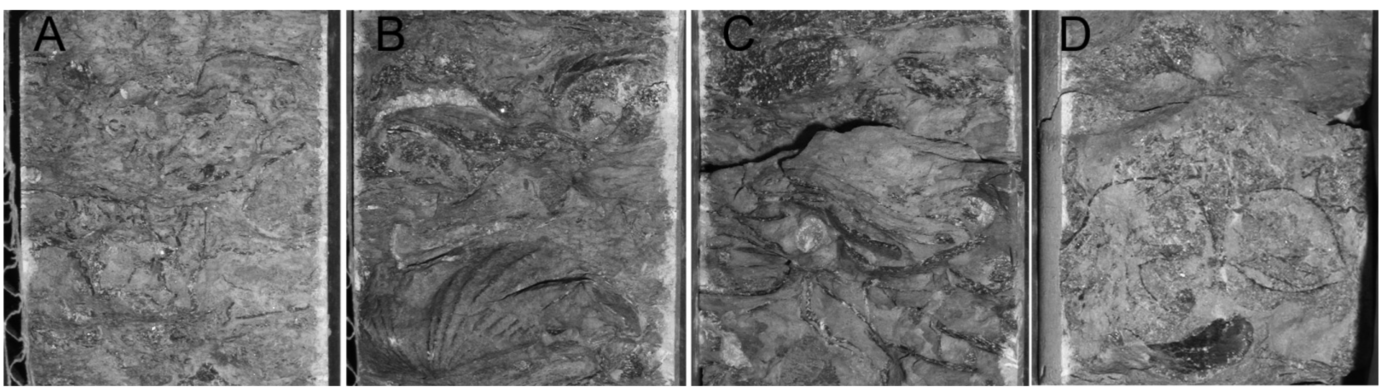


Fig. 12. Fossil-rich mudrock, all from the McMillan formation, probably Mt Auburn member equivalents. Note the large robust brachiopods *Platystrophia ponderosa* that dominate this microfacies, and the bioclast-supported structure; these are winnowed, high-energy shell beds, differing from packstones in having a soluble mudrock matrix. (**A–C**) Clark County core: (A) 403 ft. (123 m); (B) 406 ft. (124 m); (C) 435 ft. (133 m). (**D**) Newpoint Stone Quarry core 312 ft. (95 m).



conclude that it did not typically take the form of undifferentiated precursor sediment: fossils floating in a matrix of mud. Much fair-weather mud may be incorporated into shell beds or, as proposed by McLaughlin and Brett (2007), it may be represented in the organic-rich brown shale that becomes prominent in more distal facies

To salvage the storm-winnowing model, one must consider the possibility that storms served to condense interbedded barren muds and a variety of fossiliferous horizons, themselves deposited in an episodic manner. Having established this as a candidate for precursor sediment, the next step is to determine if this sediment could have, at a *plausible* depth of excavation, supplied sufficient shelly material to make a shell bed. Within an order of magnitude, depth of actual erosion is not difficult to determine; unevenness and channelization of scours reduce the problem to measuring local relief on the bottoms of shell beds. Gutter casts are characteristic of certain horizons (see Jennette and Pryor 1993) and range from a few centimetres to decimetres in depth. Larger scours, up to ten metres wide, are observed at some horizons in the Kope Formation and show a maximum relief of up to a metre (Brett et al. 2008). Therefore, it is reasonable to surmise that the excavation of seafloor mud reworked typically to a depth of a few decimetres, and perhaps rarely up to a few metres. However, the lack of major channels and scours renders deeper reworking *implausible*.

The fact that fossil-rich mudrock intervals are grain supported leads to a quantitative measure of how deeply storms would have to winnow barren seafloor muds to generate a given thickness of shell bed. Assuming that grain-supported fossiliferous mudrocks contain approximately the same concentration of shells as shell-bed limestones, we collected closely spaced samples of mudrock through the fossiliferous upper “shingled *Rafinesquina* zone”, the barren shale intervals of the upper Fairview and Miamitown Shale, and part of the fossiliferous lower Bellevue member (see Dattilo 1996, 1998) at the Rice and Gage streets locality CHS of

(Dattilo 1996) in Cincinnati. These were weighed, disaggregated in water, and washed through a 1 mm sieve. The filtrate, mostly fossil shells, was then re-weighed, and the results tabulated (Table 1).

The barren and fossiliferous mudrocks were ultimately determined to be compositionally and stratigraphically distinct (Fig. 13). Fossiliferous and barren mudrocks were found to contain 20%–50% and <4% fossils, respectively, with the latter figure possibly accounted for by the inadvertent collection of single-layer shell pavements.

Individual fossiliferous mudrock samples contain from 6 to >24 000 times (the approximate limit of detection for 1 kg samples) more fossils than individual barren mudrock samples, with an average ratio of approximately 1:60 for the shell content of the respective lithologies. Not accounting for compression, a maximum depth of 2 m of mud would yield a mere 3.3 cm shell bed by winnowing. This may be a low estimate, but even a threefold error in measurements would only yield a 10 cm shell bed. The generation of a shell bed thicker than this would have required an unreasonable depth of winnowing. Given the figures, one must also seriously consider the possibility that fossil-rich mudrocks might not have been grain-supported shell beds in their original uncompacted form.

There is still another point to consider—in the storm-winnowing model shell beds and storm-deposited muds are generated at the expense of precursor sediment. Predicted in this context is that a stratigraphic interval containing more limestone (mostly cemented shell beds) should, on average, contain less fossil-bearing mudrock (putative precursor deposits; Fig. 14A). But an analysis of the Fairview through Bellevue equivalents in the Newpoint Stone Quarry core shows that this is not the case. Figure 14B is a 1 m running average of the percentage of solid limestone, fossiliferous mudrock, and barren mudrock through the core. In this figure, "fossiliferous mudrock" includes all recognized shell pavements and bryozoan-rich horizons and thicker intervals of fossil-rich mudrock. The pattern clearly indicates that fossiliferous mudrocks are more abundant in the limestone-rich intervals, not less.

Table 1. Measurement of fossil percent by weight in shale samples collected through nearly 4 m of section at the Rice and Gage streets locality, upper Fairmount member through Miamitown shale interval, graphed in Fig. 13 (see Dattilo 1996 for stratigraphic details).

Horizon (metres)	total weight (g)	fossil weight (g)	fossil content (%)
111.80	1646.10	47.18	2.8662
110.50	909.90	297.58	32.7047
109.00	2653.20	1011.28	38.1155
108.90	531.00	123.78	23.3107
107.50	980.70	309.68	31.5774
107.10	1482.00	532.38	35.9231
105.80	1694.20	19.28	1.1380
104.90	823.80	382.28	46.4045
103.60	743.80	28.98	3.8962
102.90	965.70	17.88	1.8515
102.20	1022.70	9.58	0.9367
100.80	239.90	0.24	0.1000
100.00	939.80	0.14	0.0149
98.50	129.10	0.00	0.0000
97.50	1070.80	0.04	0.0037
97.00	955.70	0.14	0.0146
96.00	1800.70	0.04	0.0022
92.50	3093.50	0.64	0.0207
92.00	2680.90	5.38	0.2007
91.00	3211.90	0.64	0.0199
90.50	2299.10	0.74	0.0322
90.20	2391.70	13.78	0.5762
88.70	178.00	61.28	34.4270
88.50	989.40	527.58	53.3232
87.40	1998.90	968.78	48.4657
86.50	1603.50	598.98	37.3545
84.90	1544.40	649.88	42.0798
84.40	1606.40	693.78	43.1885
83.60	865.80	10.94	1.2636
83.10	791.10	4.84	0.6118
82.80	1045.10	387.88	37.1142
81.40	1055.40	0.64	0.0606
81.10	888.00	0.00	0.0000
80.50	764.40	12.94	1.6928
80.00	804.90	0.74	0.0919
77.30	981.30	0.44	0.0448
72.00	906.40	0.00	0.0000

Note: Total weight is the dry weight of the original sample minus the weight of limestone and undissolved shale clumps larger than 4 mm; fossil weight is the weight of all fossils larger than 1 mm; fossil content is the quotient of fossil weight and total weight.

Carbonate microfacies

While the idea of storm-influenced mud deposition has received little discussion, storms have long been implicated in the formation of limestones rich in skeletal debris (Aigner 1985; Jennette and Pryor 1993; etc), because the sedimentary structures associated with storms are easier to study in limestones. Some of the signs of storm influence cited for shell-bed limestones are identical to those noted above for mud deposits (e.g., sharp erosive bases with scour marks and gutter casts).

Grainstones

The typical thick grainstones found in the shell-bed-dominated hemicycles, especially in the Kope Formation, display sedimentary structures such as symmetrical wave ripples, cross-beds, and mudstone rip-up clasts that indicate high-energy depositional conditions. The common obvious occurrence of such features contrasts with the general lack of easily observable sedimentary structures in mudstones.

In the Kope Formation, thick grainstone beds contain the ossicles of small delicate crinoids, and shells of the small, thin brachiopods *Sowerbyella* and *Dalmanella*, all associated with quiet, deeper water environments, and statistically indistinguishable from the fauna of the mudstones (see Holland et al. 2001*b*; Webber 2002). While the fossils are typically fragmentary, there is no evidence of significant transport. The faunal compositions of the Fairview and Bellevue formations have not been so exhaustively studied.

Quiet water origin for grainstones

If thick grainstones reflect deposition under higher energy conditions than mudrocks, the increased energy obviously didn't impose any major ecological effect on the seafloor bi-

Fig. 13. Weight percent fossil content of mudrocks through two metre-scale cycles in the upper Fairmount–Miamitown shale interval at the Rice and Gage streets locality (see data, Table 1) showing the differences between fossil-rich mudrock intervals and barren mudrocks. (A) frequency of samples containing different weight percentages of fossils; bins 0 (non detected), <10%, <20%, etc. Note the strong bimodal distribution. (B) Samples organized by increasing fossil content showing the distinct break between barren and fossiliferous shales. (C) fossil content plotted against stratigraphic position; contrary to the expectations of the storm-winnowing model, note that fossiliferous shales are associated with the carbonate-rich phases of these two cycles. These data suggest that fossil-rich mudrock contains, on average, 40 times more fossils than barren mudrock.

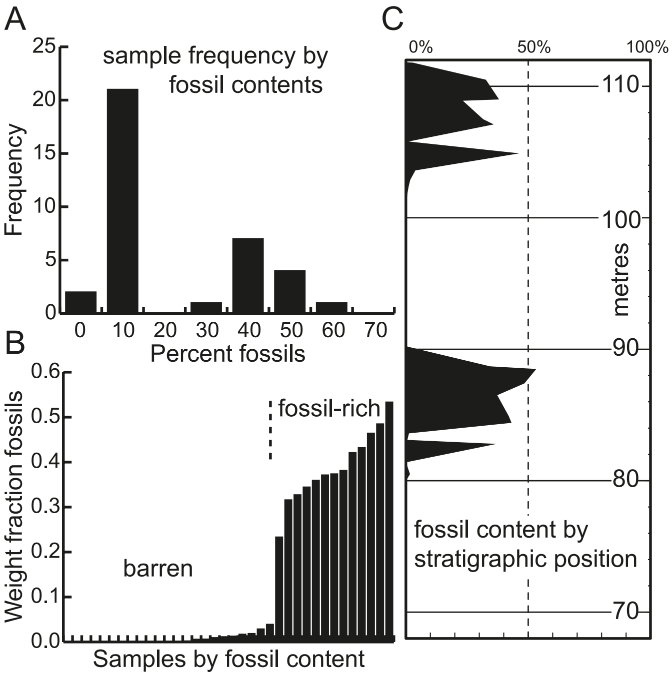
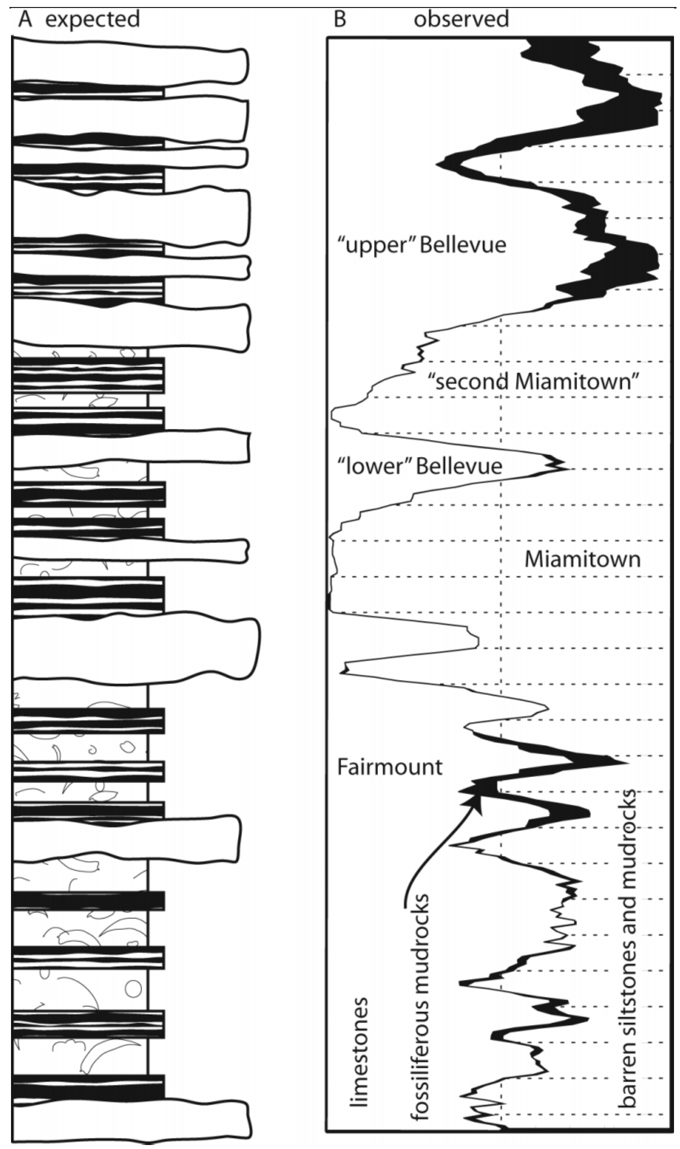


Fig. 14. Expected (A) versus observed (B) stratigraphic distribution of fossiliferous mudrocks. The storm-winnowing model stipulates that shell beds are generated in place at the expense of previously deposited fossil-bearing fair-weather muds. (A) diagrammatic representation of the expected relationship between fossiliferous mudrocks and carbonates; fossiliferous mudrocks should account for a greater average stratigraphic thickness in carbonate poor sections than in carbonate rich sections. (B) plot showing 1 m running average of relative stratigraphic thickness of three lithologies: limestones, mixed bioclastic mudrocks, and siliciclastic siltstones and mudrocks. Note that, contrary to expectation, fossiliferous mudrocks are more commonly associated with limestone-rich intervals.



ota. It is possible that the bulk of the shells contained in the grainstones were derived from the underlying quiet-water muds via winnowing. Reworking and winnowing of shells derived from a muddy substrate would account for the mud-filled cavities, crevices, and pores commonly observed in bioclasts hosted by a relatively mud-deficient limestone. However, deep reworking is unnecessary. The fragmentation and other high-energy textural characteristics of these grainstones could be taphonomic imprints of brief high-energy events, storms, separated by long periods of calm. If such events rarely affected the seafloor (perhaps in deep water), the in situ shell-producing fauna would have required no particular adaptations to high-energy conditions; their life strategy would have only been to survive and repopulate the seabed. In other words, it is conceivable that the grainstone beds might actually represent quiet-water deposits that formed by the long-term accumulation of bioclasts in the relative absence of mud.

Packstones

By definition the difference between packstones and grainstones is the presence of a mud matrix in the former and its absence in the latter. The mud matrix of packstones provides even more direct evidence of shell reworking than the mud fillings observed in bioclastic constituents of grainstones. In fact most packstones, found in limestone- and mudstone-dominated hemicycles, show evidence of reworking and winnowing and, although rare, fossils remains associated with escape structures provide striking evidence of sudden burial by reworking (e.g., Dattilo 2004*a*).

Infiltration structures are also frequently observed in packstones. These include umbrella structures and shelter porosity, both of which record the downward migration of fine material through the shell bed before or during final burial. While such structures would be expected in a shell bed that was first winnowed then redeposited, the infiltrating mud might also have been deposited on the shell bed *without* winnowing.

While the presence of infiltrated mud in some packstone beds provides signs of winnowing not detectable in grainstones, packstones generally contain better preserved fossils and only rarely display sedimentary structures indicative of extremely high-energy events. Before the remarkable faunal similarity of Kope Formation grainstones and packstones was fully appreciated (Holland et al. 2001*b*; Webber 2002), these difference were attributed to differences in water depth and associated differences in strength of waves and currents along with higher frequency and power of storms (Tobin and Pryor 1992; Jennette and Pryor 1993). The lack of muds, higher shell fragmentation, and more dramatic sedimentary structures observed in grainstone beds, were accordingly explained as products of the higher frequency and magnitude of seafloor disturbance experienced in shallower water during storms.

There is an alternative explanation for these characteristics, however. If the frequency and intensity distribution of storms were stable over time, then the textural differences between packstones and grainstones could be explained by differences in the temporal scale of shell-bed formation rather than differences in water depth; shelly benthic communities exposed for longer periods on the seafloor would be subject to disturbance by a larger number of storms as well as events of greater magnitude than those buried earlier in their development. This is the heart of the episodic starvation model. However, it takes a careful analysis to distinguish the effects of more frequent and powerful storms from the effects of longer exposure.

Exposure and temporal scale of shell-bed formation

Taphonomic attributes of the faunal remains can provide information on shell-bed exposure time independent of degree of winnowing (Tomašových et al. 2006*b*). One of the more easily observed differences between grainstone beds and packstone beds is the tendency of shells in the former to exhibit a mixture of taphonomic states. Most Cincinnatian limestones contain a mixture of relatively pristine and damaged shells, and in packstone beds, articulated spar-filled brachiopods that were presumably buried alive (Brett and Baird 1986, 1993; Holland 1988) are mixed with disarticulated and fragmented shells. The high density of well-preserved organisms in some of these packstones (Dattilo 2004*a*) suggests either short exposure times on the seafloor or longer exposure time with insignificant shell destruction.

Shell destruction was clearly severe in the formation of grainstones, which typically contain a high proportion of comminuted shell material with few whole unabraded shells and an even lower number of articulated spar-filled specimens. Such a mixed taphonomic signature has been attributed to the high-energy conditions that led to grainstone development.

Presumably, under the storm-winnowing model, remains of deeper water fauna would be exhumed and winnowed by storms to form an initial shell bed. Further winnowing by subsequent storms would progressively grind down the exhumed shell material to a comminuted state. In the mean time, living organisms would continue to produce shells in this higher energy environment, some surviving destruction. This idea is difficult to reconcile with the fact that the more recognizable shells and shell fragments in grainstone beds are deep-water forms. The hypothesis that grainstones formed through protracted periods of sediment starvation explains the mixed taphonomy of the grainstone beds at least as well as a decrease in water depth or an increase in storm intensity and frequency, and it also explains the deep-water character of the fossil remains.

Edrioasteroid pavements and encrusted hardgrounds

Discontinuities, including encrusted shell pavements and hardgrounds, are also common in Cincinnatian shell beds. Edrioasteroid-encrusted shell pavements from the Corryville Formation, just above the Bellevue Limestone are well known and studied (Meyer 1990). Similar pavements are found in the Kope Formation, Fairview Formation, Miamitown Shale, and Bellevue Member (Dattilo 1996; McLaughlin and Brett 2007). Edrioasteroids had multielement skeletons and were prone to disarticulation, so rapid burial of living organisms was essential for their preservation. The edrioasteroids also needed hard substrates and are accordingly found on the upper surfaces of shell beds; in the studied succession, they are typically associated with layers of the large flat-lying strophomenid *Rafinesquina alternata*. Typically these pavements contain multiple cohorts of well-preserved edrioasteroids, suggesting that the shell pavements lay exposed on the seafloor for at least several years, before finally being buried by a sudden influx of mud.

The fact that edrioasteroids are attached to articulated spar-filled brachiopod shells that had presumably been buried alive, as well as to the abraded interior surfaces of disarticulated shells in the same beds confirms the earlier inference that living and dead shells were mixed together on the seafloor. It is possible that this "mixed" taphonomic signature manifests a protracted period of exposure for brachiopod shells on the seafloor that far exceeded the generational span of the preserved edrioasteroid cohort.

Two revealing examples of edrioasteroid pavements have been documented from the Miamitown Shale to Bellevue Limestone interval (Dattilo 1996). One is developed on the top of a partially winnowed mollusk-rich packstone bed that is traceable throughout the outcrop area in Cincinnati. According to the Aigner (1985) proximality model, such a bed would have formed via a single event of storm-winnowing. If this were the case, it would be remarkable if such partial winnowing of the bed would result in a surface swept clean of debris long enough to be colonized by edrioasteroids. The other Miamitown edrioasteroid pavement is developed on a single-layer pavement of the brachiopod *Rafinesquina* in otherwise barren mudstone. This pavement is known as the "thumbnail *Rafinesquina* horizon" because the brachiopods are unusually small, measuring scarcely 2 cm in diameter. Again, the presence of edrioasteroids on these brachiopods indicates a period of exposure on the seafloor immediately before burial. Furthermore, many of the encrusted brachiopods are articulated and spar-filled. If the brachiopods were alive when they were encrusted, then it would be difficult to argue that they had been winnowed out of mud before being encrusted, and, given the delicacy of edrioasteroids, it would have been impossible to winnow encrusted specimens out of mud after they had been encrusted and buried. This suggests that the shell pavement formed as brachiopods grew and were encrusted during a period, albeit brief, of sediment starvation, ended by a sudden influx of obrutionary mud. This provides an intriguing link between shell pavements and obrution layers.

Evidence of a depositional discontinuity is also seen as sharp upper boundaries in the top surfaces of Kope Formation grainstone beds. Some of these surfaces are encrusted with bryozoans and crinoid holdfasts. More evidence of discontinuity is seen in the Bellevue Limestone, where some beds were clearly cemented before being bored and bryozoan masses may be composed of multiple generations of encrustation and borings. Clusters of the small brachiopod *Zygospira modesta* occur with all specimens oriented beak-downward suggesting that the brachiopods were buried intact, attached by a pedicle to these Bellevue surfaces (see also Richards 1972). Such surfaces suggest some periods of low sedimentation just before shell beds were finally buried, in at least some cases suddenly, by terrigenous sediments. If these discontinuities, edrioasteroid pavements, and encrusted hardground surfaces, were not so commonly found capping Cincinnatian shell beds, then unusual circumstances might be invoked to explain them. However, they are stratigraphically pervasive and often regionally traceable; any model that purports to explain shell-bed formation should integrate an explanation for the discontinuities associated with these shell beds. Special circumstances are required to explain how a storm might so thoroughly winnow mud out of a shell bed as to leave its surface clean. On the other hand, this type of exposure is implied by the starvation model.

Carbonate concretions

Carbonate concretions are a final indicator of long exposure. Small, ellipsoidal concretions are commonly found within the mudstone intervals of Kope Formation, but their almost exclusive occurrence in the uppermost centimetres below grainstone beds suggests that their genesis pertains more to grainstone beds than the mudrocks within which they are encased.

The carbonate-cemented nodules are almost invariably nucleated on pyritic burrows indicating formation in the zone of sulfate reduction. Concretions form horizons to semi-continuous layers 5 to 15 cm below the base of the overlying limestone sometimes in mudstone and in muddy siltstones (Brett et al. 2003). This is not an isolated occurrence. Two thirds of the Kope cycles in the Cincinnati area were found to have concretions immediately below the major limestones.

At least six limestone beds in the Cincinnati area show reworked concretions that are encrusted with bryozoans and crinoid holdfasts. These are identical to in situ concretions. Such concretions evidently formed by early diagenesis in the zone of sulfate reduction and were lithified prior to the final deposition of the limestone layers as evidenced by the occurrence of reworked concretions. Mass balance calculations of Raiswell (1987) suggest that concretionary horizons reflect periods of prolonged stability of the zone of sulfate reduction. The fact that concretions are reworked into some shell-rich beds indicates not only that the concretionary cementation occurred in very early diagenesis, but also that these concretions were associated with periods of low sedimentation that even bordered on erosion. We suggest that the Kope concretion beds formed in older, in some cases rapidly, deposited sediments during hiatuses in sedimentation. These same pauses in sedimentation initiated development of shell beds.

Unwinnowed shell beds?

If shell beds were actually formed from undifferentiated shelly muds by storm winnowing, then unwinnowed shell beds should not exist. On the other hand, shell beds formed through the process of skeletal growth and accumulation might occasionally escape winnowing provided that they grew and were buried before being reworked by powerful storm waves and currents or developed in water below storm wave base.

Certain grainstones, some lacking a fine-grained matrix entirely, do not show evidence of winnowing. This lack of evidence might indicate growth of skeletal grains in the complete absence of terrigenous mud or micrite, so it is possible that these grainstones are unwinnowed. However, one might just as easily postulate that any mud once present in these shell beds had all been winnowed away.

On the other hand, the lack of evidence for winnowing in the fine matrix of fossiliferous mudstones or packstones can reasonably be taken as evidence for a lack of winnowing altogether. Thus there are two potential forms that an unwinnowed shell bed might take. One form might be a fossiliferous mudstone where a body of grain-supported shells is surrounded by terrigenous mud as discussed earlier. Another form might be a packstone where bioclasts are surrounded and filled by the same micrite matrix without cement-filled voids or washed matrix.

Certainly obrution horizons are not winnowed, but it would be difficult to call them shell beds; the fossils are generally too scattered in distribution. On the other hand, single-layer shell pavements are as thin as a shell bed could get, but the shell density is often high. While such layers might have formed by winnowing, the preservation of edrioasteroids encrusting presumably live brachiopods in the "thumbnail *Rafinesquina* horizon" discussed earlier in the text suggests that they may well have grown in place. If other shell horizons formed in the same way, then the thinnest shell beds are also unwinnowed. The bryozoan horizons discussed previously could arguably be called shell beds, and they are generally not reworked—and identifiable reworked packstone counterparts also exist.

Unwinnowed packstones are also found, particularly in the Kope Formation and in the Miamitown Shale. Generally these packstones are also dominated by molluscan fossils, particularly gastropods and bivalves (Fig. 15), but there are a few examples of unwinnowed brachiopod packstones. As required, these packstones lack any evidence of winnowing or infiltration in their micritic matrix.

Several unwinnowed packstones occur as beds or horizons of lenticular shell buildups within muds. These include the characteristic gastropod and bivalve beds of the Kope Formation and Miamitown Shale, as well as small 2 to

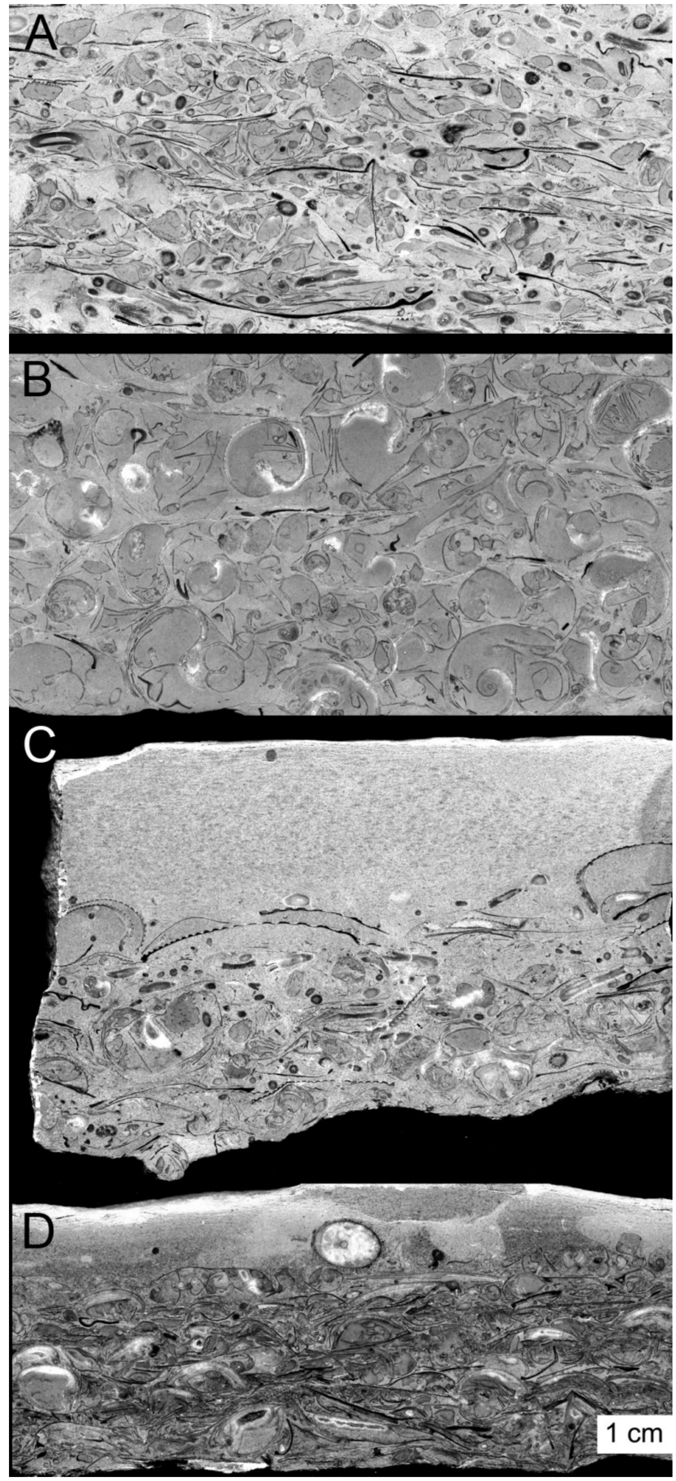


Fig. 15. Unwinnowed packstones. The matrix and pore fillings of these packstones are nearly saturated with mud and do not display the sedimentary structures indicating partial washing or infiltration that would be expected if they were formed by deep storm winnowing. It is more likely that these shell beds formed in place by accumulation on the seafloor , were buried without significant winnowing, and, as such, represent a few examples of shell beds that were not formed by storm winnowing. Handsamples from outcrop, cut and polished surfaces normal to bedding. (A) *Zygospira*-molluscan packstone, Rice and Gage streets locality, 7.35 m, upper Fairmount member. (B) Molluscan packstone, Rice and Gage streets locality, 7.43 m, upper Fairmount member. (C) Cemented, *Ambonychia*-dominated molluscan–bryozoan siltstone, Sharonville Industrial Park, 4.10 m, upper Fairmount member. (D) molluscan packstone, Sharonville Industrial Park, 8.52 m, Miamitown Shale. See Dattilo (1996) for stratigraphic details.

10 cm lumps containing hundreds of *Zygospira* brachiopods that are preserved attached in life position to sections of crinoid columns, bits of bryozoan or shell, and each other from the Bellevue Limestone. Similar occurrences of *Zygospira* attached to crinoid columns have been reported from the younger Richmondian strata of the Waynesville Formation (Richards 1972; Sandy 1996). Other Waynesville age clusters of *Zygospira*, apparently mutually attached, might well be called reef mounds, reaching 50 cm or more in diameter. As with bryozoan beds, these may be discontinuous and patchy in distribution; they appear to represent local accumulations of shells. Again, it is difficult to escape the conclusion that these were incipient shell beds growing in unwinnowed clusters during periods of relatively slow deposition.

Other examples of unwinnowed packstones are found at the bases of beds that are winnowed on top (Fig. 16). These beds present an upward decrease in mud content from spar-free packstone through washed packstone to grainstone. The washed packstone and grainstone intervals may contain fossils with mud-filled cavities and pores clearly derived from the underlying unwashed packstone. If we assume that shell beds form through a winnowing process of erosion, suspension, settling, and infiltration, then this succession appears decidedly inverted. It illustrates clearly that winnowing acted on a pre-existing shell bed.

Origin of micrite in shell beds

The micrite matrix that differentiates unwinnowed packstones from unwinnowed fossiliferous mudstones poses another problem for the storm-winnowing model. Scotford (1965), assuming that the precursor to micrite was carbonate mud, pointed out that storm winnowing cannot explain why micrite is found almost exclusively in the matrix of shell beds. How could storm reworking and winnowing separate siliciclastic muds found between shell beds from carbonate muds found in the matrix of shell beds? Tobin (1982) proposed that precursor muds might have contained carbonate-rich pelloids that survived burial and reworking to settle back into the shell bed. However, such durable pellets should have also survived in the grain-supported framework of a shell bed, so their scarcity in Cincinnatian micrites argues against this model.

Another way to reconcile the storm-winnowing model with micrite-bearing shell beds is to postulate that micrite is secondary. In fact, there is room for doubt as to whether this mud was originally calcareous. The early-diagenetic carbonate concretions of the Kope Formation, discussed earlier in the text, are composed of a fine-grained carbonate that resembles, though imperfectly, the micrite found in shell beds; the concretionary carbonate is similarly fine grained, but has a different texture and is distinctly darker.

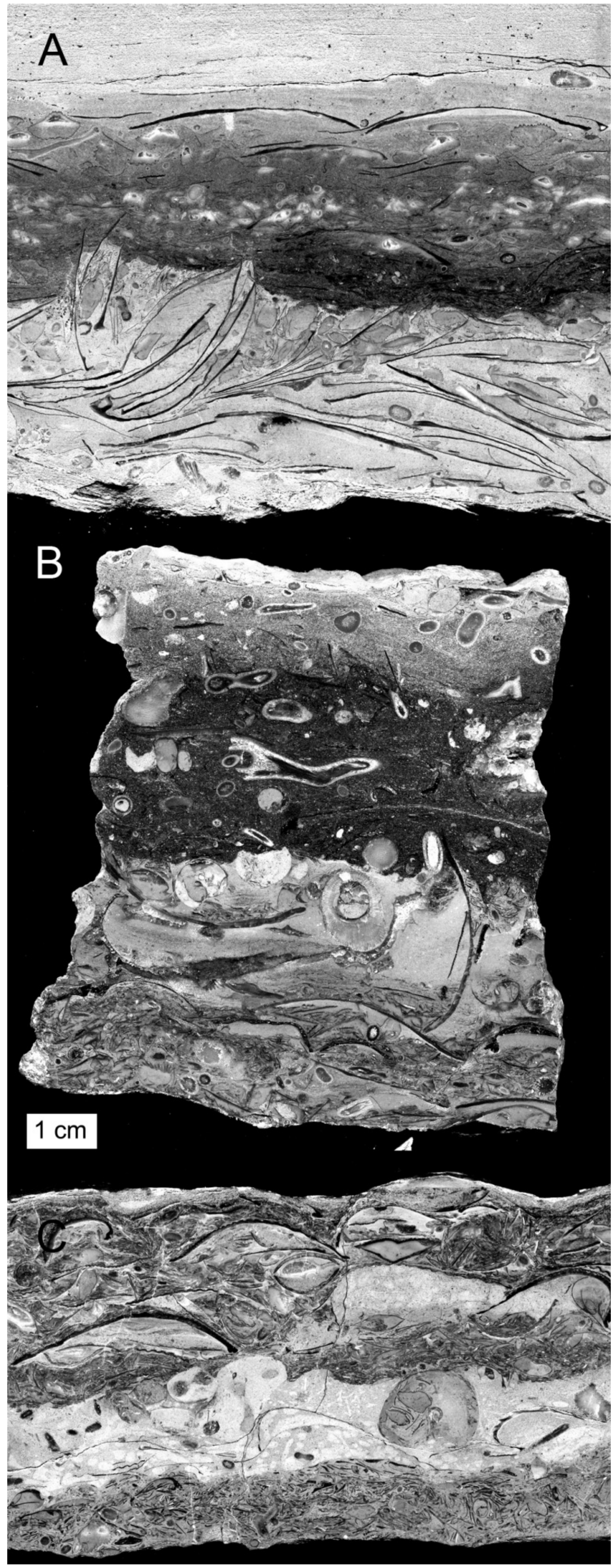


Fig. 16. Partially Winnowed packstones. Like unwinnowed packstones above, the lower part or more than one subunit of these specimens lacks sedimentary structures diagnostic of winnowing. The fact that parts of the same specimens are winnowed is strong evidence that storm winnowing had an effect on shell beds, but might not necessarily have created new shell beds where there had previously been none. (A) Unwinnowed shingled *Rafinesquina* valves with *Zygospira* in the lower portion of the slab protrude upward through an erosional surface into an overlying winnowed fining-upward grainstone to packstone succession; Rice and Gage streets locality, 7.50 m, upper Fairmount member. (B) A more diverse unwinnowed assemblage of bivalves, brachiopods, bryozoans, and gastropods overlain by an erosional surface and winnowed fining-upward grainstone dominated by bryozoans; Sharonville Industrial Park, 9.70 m, upper Miamitown Shale. (C) Unwinnowed molluscan packstone sandwiched between two partially winnowed packstones indicates at least two cycles of shell-bed growth and winnowing; Sharonville Industrial Park, 6.15 m, Miamitown Shale.

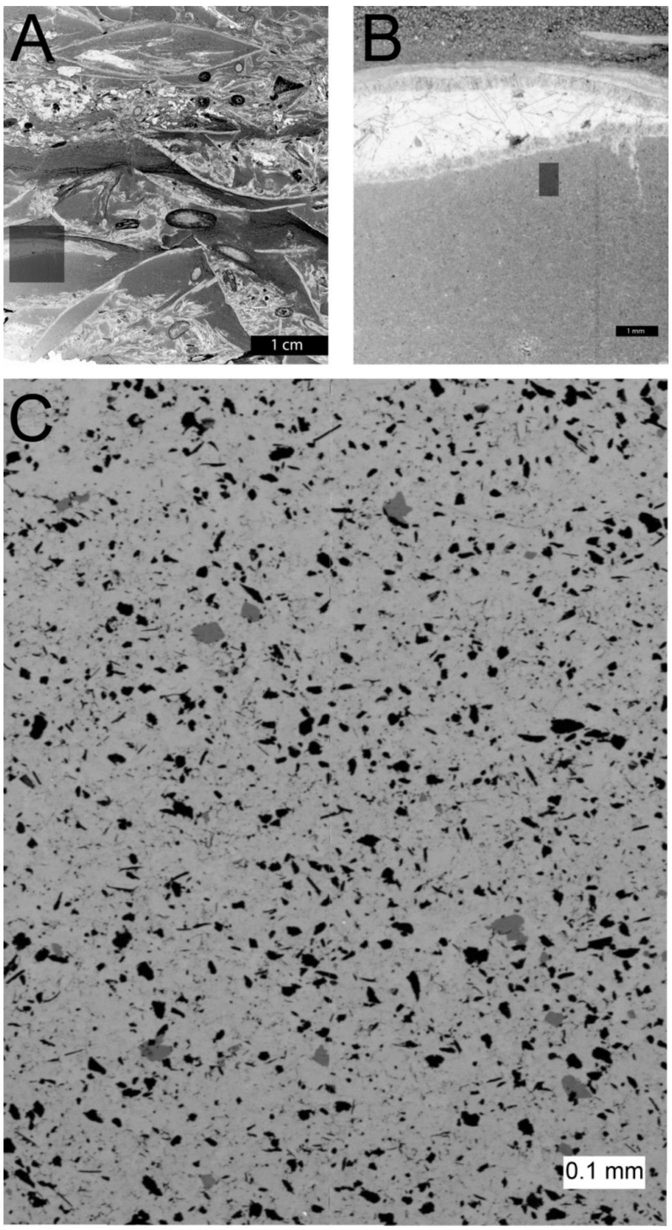
These concretions must have formed through cementation of siliciclastic muds, so it is possible that shell-bed micrite also represents cemented siliciclastic mud. If *all* of the micrite in shell beds fits into this category, then in the context of the storm-winnowing model, the so-called micrite would actually represent siliciclastic mud that remained or reinfiltrated the shell bed after winnowing. Alternatively, in the context of the shell bed generated by in situ growth, this micrite would represent the remnants of the terrigenous material that accumulated over the time of shell-bed growth plus mud that infiltrated the shell bed during final burial.

In both cases, the mud would have *become* a “micrite” by cementation. This *diagenetic* micrite may not be as useful for distinguishing a shell bed generated through storm winnowing from a shell bed generated through a period of starvation. However, like concretionary cementation, it probably would have required long exposure at or near the sediment–water interface, and thus somewhat favors the episodic starvation model.

In contrast, *sedimentary* micrite, which started as *carbonate* mud, can be used to unambiguously distinguish the two depositional mechanisms. Sedimentary micrite is generally thought to have originated as mud-sized particles of calcium carbonate in the sedimentary environment. Storm winnowing cannot explain the concentration of primary lime mud in shell beds. Conversely, the presence of sedimentary micrites is readily explained in the episodic starvation model; the long periods of low sedimentation would allow for the buildup of carbonate mud along with the growth of shelly communities. The main source of this carbonate mud in the Cincinnatian has generally been identified as the mechanical comminution of finely textured skeletal remains (e.g., Anstey and Fowler 1969). Regardless of its mode of origin, if *any* of the non-pelloidal micrite in shell beds fits into the category of sedimentary micrite, then in the context of storm winnowing, such micrite would be difficult to explain. In the context of starvation shell-bed growth, micrite is expected.

Distinguishing the two types of mud depends on recognizing grain support. If silicate grains in the micrite are too widely spaced to have formed a self-supporting structure, then the micrite is likely sedimentary. Otherwise, the micrite

Fig. 17. Silicate–carbonate textural relationships within shell-bed micrite. Evidence of pelloids is lacking, yet spaces between silicate grains are too large to be explained by cementation, making it difficult to explain how micrite could have been generated in a shell bed that was formed solely by storm winnowing. (A) Low-magnification transmitted light view of thin section showing partially winnowed fabric and lamination in some matrix areas. Shaded square indicates position of (B). (B) Enlarged area showing void-filling sediment beneath a *Rafinesquina* valve. Shaded rectangle marks the position of (C). (C) Calcium map showing distribution of calcite (light gray), dolomite (medium gray), and silicates (black). The fabric does not appear to be supported by silicate grains, as would be expected if carbonate grew as a cement between silt and clay grains. Calcite grains are faintly visible and are comparable to the dolomite grains in size. Mount Airy Forest, 5.10 m, upper Fairmount member.



could be diagenetic. Figure 17 illustrates an element map produced by monitoring the characteristic X-ray peak for Calcium and scanning below a focused beam at 15 keV and 100 nA. It was made from a micrite-rich area of a single thin section of a sample from the upper Fairview Formation at the Mount Airy Forest locality. The size and spacing of the silicate grains suggests that they did not form the framework of this micrite, but were supported by similar-sized carbonate particles. There is no evidence of pelletization or that carbonate particles were significantly larger than siliciclastic grains. While the problem deserves further study, it appears that some micrite was originally deposited as fine carbonate particles and is not strictly a result of diagenesis.

Discussion

The preceding survey shows that sediment starvation, not storm winnowing, was responsible for shell-bed genesis in the Kope through Bellevue succession. Barren shales, obrution beds, single-layer shell pavements, and bryozoan shales appear to be events. Event deposition is so pervasive that the fossiliferous fair-weather shale precursor predicted by the storm-winnowing model is not found and likely never existed. Scouring depths were typically a few decimetres and rarely reached a metre. Given such shallow excavation, storm winnowing of typical Kope or Fairview mudrock cannot account for the thicknesses of shell beds observed in these formations.

Shallow scour might have released enough shells from intervals of fossil-rich mudstone, but these shelly mudrocks are so densely packed and taphonomically mixed that they *are* time-averaged winnowed shell beds. Furthermore, they are associated with limestone-rich intervals of the nearshore facies in the upper Fairview and lower Bellevue units. This type of mudrock is not typically found in Kope or lower Fairview formations, where it might have served as precursor.

The fossil content of the limestones, even thick grainstones, suggests that shells must have accumulated in relatively quiet water. Additionally, signs of sediment starvation include taphonomically mixed assemblages, widely traceable encrusted pavements, hardgrounds, and carbonate concretion horizons. These common features require exceptional circumstances to fit into the storm-winnowing proximality model, but they are expected if shell beds grew during episodes of starvation. Unwinnowed shell accumulations and packstones demonstrate that winnowing was not always involved in generating shell beds, and non pelloidal micritic shell-bed matrix even precludes winnowing as a mechanism for separating shell-bed components from terrigenous mud.

Thus the interpretation that limestones represent high-energy event deposition and that mudstones represent low-energy background deposition is backwards. In reality, limestones represent background sedimentation, overprinted and reworked by high-energy events, while mudstones represent event deposition, often high-energy, preserved in the calm of an epeiric sea.

Evolution of shell beds

Final burial of shell beds preserved them at various stages of growth. Ecology and taphonomy can be used to reconstruct that growth and to infer the temporal significance of each lithology, beginning with a blanket of mud on the seafloor. The first organisms to inhabit this substrate would have been the infaunal deposit feeders whose burrows are characterized by the lam-scram fabric of Bromley (1990). Later, deposit feeding trilobites (Hughes and Cooper 1999; Hunda et al. 2006), or gastropods and bivalves might have occupied the seafloor, to be preserved in obrution deposits and molluscan packstones, respectively. With longer exposures, the surface would have been occupied by a succession of organisms as suggested by Harris and Martin (1979). The initial colonizers would have been thin-shelled snow-shoe strategist (Thayer 1975) brachiopods, "rooted" crinoids, and small epifauna. This colonizing stage would be preserved as thin shell pavements. Further development would have led to further accumulations of shells and growth of the larger bryozoan colonies that characterize bryozoan shales. Eventually, thicker packstones would form from coalescing benthic community patches, increased diversity through taphonomic feedback (Kidwell and Jablonski 1983), generation of calcareous mud through mechanical breakdown of shell material, and increased incidences of storm winnowing.

Preservation of calcareous mud may have been enhanced in shallower warmer waters where dissolution was minimal, which suggests the possibility that grainstones may have developed in deeper quiet water where calcareous mud was either not generated or dissolved without accumulation. Alternatively, grainstones may have formed through long accumulation in water virtually free of terrigenous input and often winnowed by storm waves and currents.

Further testing of this view of bedding development in the Cincinnatian and elsewhere might incorporate methodologies recently developed by Finnegan and Droser (2008) to distinguish the paleoecological depth signal (see Holland et al. 2001*b*) from the substrate signal that indicates taphonomic feedback.

Cycles, facies, and proximal-distal patterns

The episodic starvation model also better explains the generation of fifth-order metre-scale lithologic cycles without corresponding faunal cycles in the offshore environment (see Holland et al. 2001*b*; Webber 2002). Assuming that these higher order cycles result from rapid sea-level fluctuations, these fluctuations would have low amplitudes as compared with the lower frequency third-order cycles responsible for Cincinnatian sequences (Holland and Patzkowski 1996). This translates to bathymetrically insignificant depth fluctuations—too small to directly affect benthic energy levels, storm winnowing, or the composition of ecological communities in the deeper subtidal environment. However, such fluctuations might be significant in the extensive peritidal flats of an overfilled Taconic foredeep, alternately exposing and remobilizing then submerging and trapping vast areas of terrigenous sediment. Alternatively, cyclic sediment delivery could be explained by climatic fluctuations in the source area.

The mechanics of proximality in the respective models lead to dramatically different expectations when applied across multiple facies. This stems from the fact that storm winnowing is increasingly effective in the proximal direction, while sediment starvation is increasingly effective in the distal direction. Work in progress will extend this study by testing predictions in the context of stratigraphic succession and regional correlation.

Conclusions

We conclude that the storm-winnowing model cannot account for all of the features observed in the Cincinnatian. The episodic sediment starvation model provides a more satisfactory accounting for these problematic features. It explains the simultaneous local discontinuity and regional extent of thin limestones, the pervasiveness of storm winnowing in all lithologies, the lack of an undifferentiated fair-weather mud, deep-water grainstones, mixed taphonomy and hardgrounds, widespread concretionary horizons, unwinnowed shell beds, and the presence of micrite matrix in shell beds.

The episodic starvation model also provides a more elegant model for the generation of fifth-order metre-scale cycles. It accounts for dramatic lithological variation without a corresponding fluctuation in paleoecological depth signal and could be driven by climate or sea-level fluctuations. This contrasts sharply with the original storm-winnowing proximality model (Aigner 1985; Jennette and Pryor 1993) which required dramatic depth fluctuations to generate metre-scale cycles.

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