DEPOSITIONAL DYNAMICS RECORDED IN MIXED SILICICLASTIC–CARBONATE MARINE SUCCESSIONS: INSIGHTS FROM THE UPPER ORDOVICIAN KOPE FORMATION OF OHIO AND KENTUCKY, U.S.A.

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ABSTRACT

Like many Phanerozoic marine successions, the Upper Ordovician (Caradocian/Cincinnatian; Edenian) Kope Formation in southwestern Ohio and northern Kentucky exhibits distinct, correlatable alternations of thick (metre- to decametre-scale) mudrock-dominated intervals and thinner (decimetre- to metre-scale) shell bed-dominated units. The sedimentologic and taphonomic characteristics provide evidence for controls on the sedimentary and ecologic dynamics of the depositional system and differences in the relative amounts of time represented in mudrock- versus shell bed-dominant phases of the succession. Both phases record the episodic interruption of low-energy background sedimentation by high-energy events of storm-related scouring and reworking.

Evidence for event deposition in the Kope Formation is more apparent in strata rich in skeletal remains than those lacking such material. Due to their typically coarser grained nature compared to muds, shell-rich limestone beds commonly preserve features such as cross-bedding, grading, imbrication, rip-up clasts and bedforms. Conversely, evidence for storm activity, although detectable in mudrocks in some instances, is often subtle and less likely to be recognized than in bioclastic units due to their general lack of significant variation in mineralogy, grain size, colour, fabric and structure.

Our results also suggest that the thinner bioclastic units are condensed, relative to the mudrock-dominated intervals. The former represent the long-term accumulation of thin, mud-starved veneers of winnowed/reworked parautochthonous skeletal debris, whereas the latter involved the episodic deposition of mud layers up to several centimetres thick.

Three models have been proposed to explain the origin of the Kope mudrock–shell bed cycles. The first two assume that the mudrock intervals reflect low energy, deep-water conditions and that shell beds are primarily the product of increased storm wave energy and winnowing that, in turn, resulted from either relative sea level fall, during which storm wave-base was lowered closer to the seafloor, or increased

RESUME

Comme beaucoup de successions marines phanérozoïques, la Formation de Kope de l'Ordovicien Supérieur (Caradocien/Cincinnatien; Edenien) au sud-ouest de l'Ohio et au nord du Kentucky montre des alternances distinctes et corrélatives d'intervalles épais (mètre à decamètre) dominés par de la mudrock et d'unités plus minces (décimètre à mètre) dominées par des lits de coquilles. Des traits sédimentologiques et taphonomiques fournissent de l'évidence de contrôles sur la dynamique sédimentaire et écologique du système de dépôt, ainsi que de l'évidence de différences entre les durées de temps relatives représentées dans les phases de la succession dominées par de la mudrock, versus celles dominées par des lits de coquilles.

Toutes les deux phases enregistrent l'interruption épisodique de sédimentation d'arrière-plan par des événements de haute énergie de balayage et de remaniement causés par des tempêtes. Mais l'évidence d'événements de déposition est plus évidente dans des strates riches en restes squelettiques que dans celles qui n'ont pas de tel matériau. Parce qu'elles sont typiquement composées de plus gros granules, les couches de calcaire riches en coquilles conservent généralement des caractéristiques comme l'hétérogénéité, la gradation, l'imbrication, des clastes "rip-up" et des formes du lit. De l'autre part, l'évidence d'activité des tempêtes, quoique discernable parfois dans des mudrocks, est souvent subtile et difficile à reconnaître parce qu'il y a si peu de variations dans la minérologie, la taille de grain, la couleur, le matériau et la structure. Nos résultats suggèrent aussi que les unités bioclastiques plus minces sont condensées en comparaison avec les intervalles dominés par des mudrocks. Celles-là représentent l'accumulation à long terme de revêtements minces et privés de boue, consistant de débris squelettiques para-autochtones, qui sont balayés et remaniés, tandis que ceux-ci étaient exposés à la déposition épisodique de couches de boue d'une épaisseur de plusieurs centimètres.

intensity and/or frequency of storms without significant change in water depth. We envisage a third model in which the shell beds reflect not only storm winnowing, but also the accumulation of time-averaged skeletal debris during prolonged periods of siliciclastic sediment starvation, possibly associated with minor base-level rise.

Evidence presented herein indicates that the decimetre-scale shell beds of the Kope Formation formed during millennial-scale periods of siliciclastic sediment starvation combined with episodes of storm-related reworking and winnowing. This constitutes an alternative interpretation of shell bed genesis in the Kope Formation, as well as in many other mixed siliciclastic–carbonate successions, that is more in accord with taphonomic, sedimentologic and paleontologic evidence.

On a proposé trois modèles pour expliquer l'origine des cycles de couches de mudrock–coquilles dans la Formation de Kope. Les deux premiers modèles supposent que les intervalles de mudrock reflètent des conditions d'eau profonde de basse énergie, et que les lits de coquilles sont primairement le résultat d'une augmentation de l'énergie de vagues de tempêtes et de balayage, qui se sont produits à cause d'une chute du niveau marin, pendant laquelle la base des vagues de tempêtes s'est baissée plus près du fond de la mer, ou d'une augmentation de l'intensité et/ou de la fréquence de tempêtes sans changement significatif dans la profondeur de l'eau. Nous proposons un troisième modèle, qui s'accorde mieux avec l'évidence taphonomique, sédimentologique et paléontologique, où les lits de coquilles reflètent non seulement du remaniement par des tempêtes mais aussi l'accumulation de débris squelettiques pendant des périodes prolongées (durée de millénia) de privation de sédiment siliclastique, associée peut-être avec la montée mineure du niveau de base. Ceci constitue une interprétation alternative de la genèse de lits de coquilles qu'on pourrait peut-être appliquer à d'autres successions siliclastiques-carbonatées mixtes.

INTRODUCTION

Shell-rich limestone units that interrupt thick successions of otherwise poorly fossiliferous mudrocks in marine successions (Fig. 1) have long intrigued sedimentary geologists and a variety of explanations have been presented to explain their origin (see Potter et al., 1980; Aigner, 1985; Kidwell and Bosence, 1991; Kidwell, 1991a). Recent interpretations have generally regarded constituent beds of these units as being composed of either allochthonous skeletal debris or parautochthonous, storm-winnowed skeletal concentrations. The latter has been favoured by those who have studied Upper Ordovician strata of the Cincinnati area (Jennette and Pryor, 1993; Holland et al., 1997). Documentation of storm-related processes in the formation of shell beds (Seilacher, 1982, 1985, 1991; Aigner, 1985; Kidwell, 1991a,b) has formed the basis of many previous studies. For example, these concepts have been applied in a number of case studies of middle Paleozoic successions of eastern North America, including the Upper Ordovician Cincinnati Group and equivalent Martinsburg Formation (Kreisa, 1981; Tobin and Pryor, 1981; Jennette and Pryor, 1993; Holland et al., 1997, 1999; Brett et al., 2003), the Silurian Rochester Shale (Brett, 1983; Taylor and Brett, 1996) and the Middle Devonian Hamilton Group (Brett et al., 1986; Miller et al., 1988; Parsons et al., 1988).

Most genetic interpretations of mixed mudrock–limestone successions are founded on two fundamental assumptions, both of which are questioned in this paper. The first assumption is that the individual beds of coarse bioclastic debris (variously referred to as skeletal limestones, coquinites, shell beds and packstones and/or grainstones) within the limestone units each record a pulse of storm activity that involved the deposition of either allochthonous shell debris or the in situ concentration of parautochthonous, skeletal material by reworking. The second assumption is that mudrock intervals represent sediment that accumulated under low-energy background conditions, over long periods of minimal seafloor disturbance, excepting occasional pulses of sedimentation in deeper water. At first glance, these assumptions would seem well supported by obvious sedimentologic and taphonomic evidence. Indeed, units of skeletal limestone within many mudrock successions preserve obvious storm-related features, such as scours, ripples, and graded bedding, whereas visible heterogeneities within the mudstones themselves are often limited to subtle colour variations, scattered occurrences of skeletal remains, and silt laminae. Also, based on their relatively uniform, fine-grained character, mudrocks might intuitively be assumed to reflect low-energy background conditions, whereas the coarse texture of skeletal limestones might be assumed to reflect a high-energy depositional regime. Re-examination of evidence cited in previous work, together with new evidence described in this paper, suggest that this view of the sedimentation dynamics for some fossiliferous limestone–mudrock units is neither entirely correct nor complete.

In this paper, we present a detailed account of a well-studied mixed mudrock-skeletal limestone succession — the Upper Ordovician (Caradocian/Cincinnatian; Edenian) Kope Formation — in the Cincinnati Arch region of Ohio, northern Kentucky and Indiana (Figs. 1, 2). We suggest that mudrock

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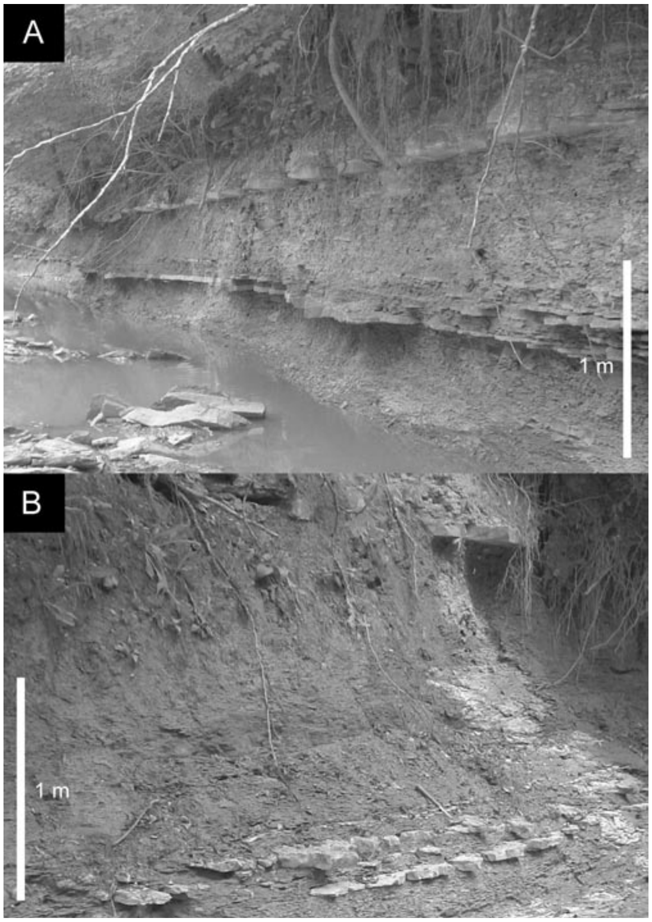


Figure 1. Limestone–mudrock cycles in Kope Formation (Fowler Creek, near Independence, Kentucky). (A) Alexandria submember, cycle 28, showing interval containing thin beds of mudrock bracketed between bundles of limestone beds. (B) Base of shale overlying limestone bundles 25 and 26; limestones of bed 26 thin upward into base of 1.5 m thick mudstone interval.

intervals contain a subtle record of numerous high-energy events, whereas the supposedly 'high-energy' skeletal limestone units preserve evidence suggesting accumulation under predominantly low-energy conditions. Furthermore, we consider that the traditionally accepted view on the relative time spans represented in the mudrocks versus the skeletal limestones be inverted: mudrock intervals previously thought to represent 'time-rich' background deposits are here reinterpreted as 'time-poor' deposits consisting of abruptly and episodically emplaced event beds up to several centimetres thick (including obrution deposits of Brett and Seilacher, 1991). Conversely, skeletal limestones (shell beds) that were formerly considered to be time-poor amalgamated units of shelly storm deposits are reinterpreted below as time-rich deposits fundamentally reflecting repeated storm-related winnowing and reworking of shell debris under conditions of low siliciclastic sediment input.

We review evidence for the nature of the depositional processes represented in intervals of alternating mudstones and skeletal limestones and consider the relative time-richness of the two types of accumulations. Conceptual elements of previous explanations are reexamined in light of new observations, providing the basis for an alternative depositional model. Because characteristics of the Kope Formation are similar to other mixed mudrock–limestone successions, the proposed model may be applicable to the depositional dynamics recorded in many Phanerozoic successions of this type.

GEOLOGIC SETTING

The Kope Formation (Figs. 1, 2), assigned to the Cincinnatian series and spanning the Edenian stage, is a mixed siliciclastic-carbonate marine succession, composed of approximately 70–85% illitic mudstone (Bassarab and Huff, 1969), 15–25% packstone/grainstone and minor amounts of siltstone. Deposition of these sediments took place on a storm-dominated ramp in a shallow epeiric sea setting (Fig. 1).

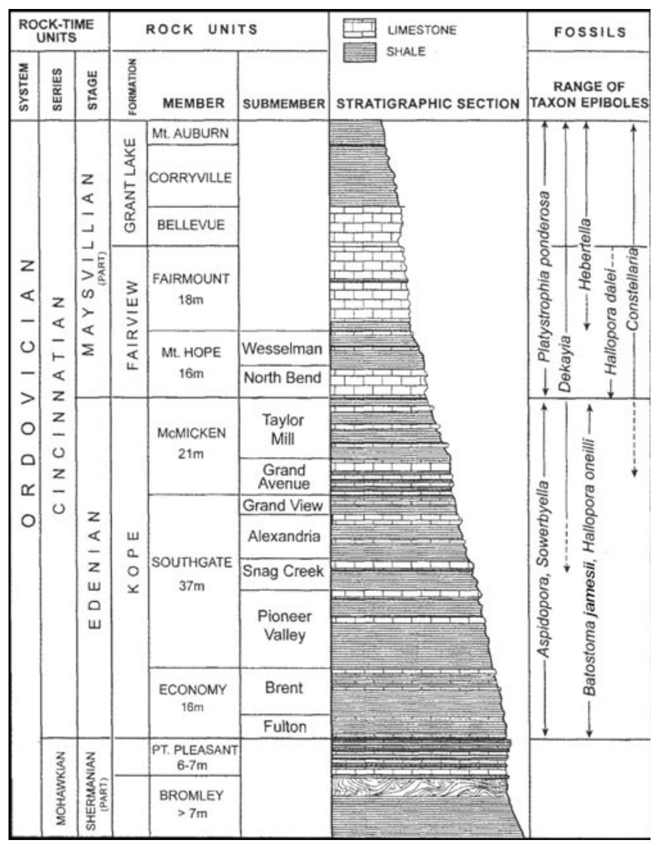


Figure. 2. General stratigraphy of the Upper Ordovician Cincinnatian Series in the Cincinnati, Ohio area. Modified from Caster et al. (1955).

Terrigenous clay and lesser quantities of silt were shed from the Taconic orogenic belt and deposited in the Kope depositional setting which was in and around the periphery of an elongate structural basin, the Sebree Trough (Caster et al., 1955; Mitchell and Bergström, 1991; Ettensohn, 1992; Ettensohn et al., 2002; Fig. 3). These deposits are continuous with the Ordovician Utica Shale in the foreland basin. If ancient storm tracks were similar to recent ones (Ettensohn, 1992; Ettensohn et al., 2002), the study region was located in a major hurricane belt (Fig. 3). Much of Kope deposition probably took place at or above storm wave-base and below fair-weather wave base.

The lithology, fauna and depositional history of the Kope Formation have been studied for nearly a century (Ulrich and Bassler, 1914; Bassarab and Huff, 1969; Hay, 1981; Tobin, 1982; Jennette, 1986; Jennette and Pryor, 1993; Holland, 1993; Holland et al., 1997; Brett and Algeo, 1999). Over the past two decades, studies on the Kope Formation have emphasized the utilization of fauna in high-resolution correlations. One approach has been to use ordination techniques to document faunal bathymetric gradients and, in turn, to generate vertical profiles of relative changes in water depth

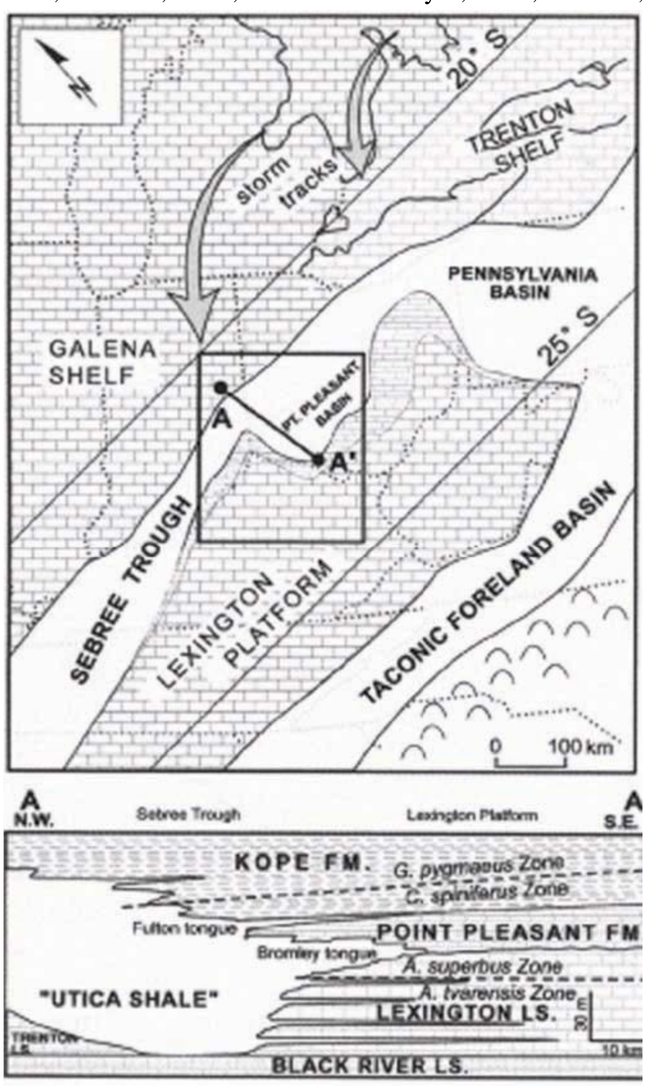


Figure 3. Paleogeography of the Late Ordovician Edenian Age in eastern Laurentia. showing the Sebree Trough, Lexington Platform, Taconic Basin and Taconic Highlands, and generalized stratigraphy across Pt. Pleasant Basin. From Brett et al. (2003).

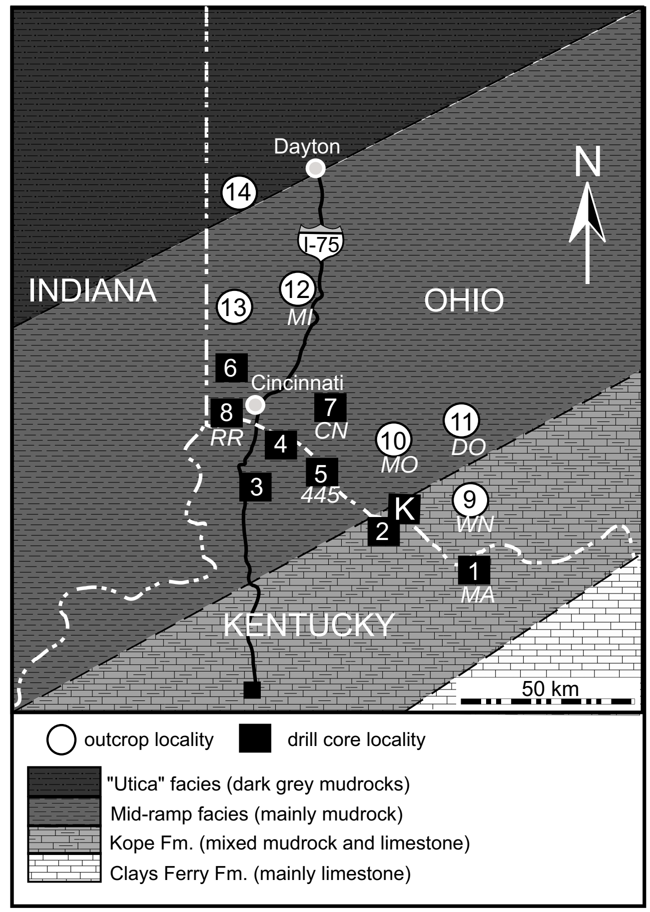


Figure 4. Location map of study area showing approximate facies belts and study sites marked. Sites 1–8 are outcrops and 9–14 are drill cores. Specific locations and abbreviations of important localities are as follows: 1=Maysville, Kentucky (MA); 2=Hilton Lane, AA Highway, near Foster, Kentucky; 3=Fowler Creek, along Rte. 1486, north of Independence, Kentucky; 4=Banklick Creek industrial park, west-facing hillslope and valley east of Rte. 17, Covington, Kentucky; 5=I-275 at Ohio River and Waterworks Road, Ft. Thomas, Kentucky; 6=Sycamore Creek, Loveland–Madeira Road, Indian Hill, Ohio; 7=Cincinnati Nature Center, Perintown, Ohio (CN); 8=Rapid Run, Delhi, Ohio (RR). 9=Winchester, Ohio (WN); 10=Mt. Orab, Ohio (MO); 11=Dodsonville, Ohio (DO); 12=I-75 road cut, Middletown, Ohio (MI); 13=Oxford, Ohio; 14=New Paris, Ohio. IS-Rte. 40, near Kellogg Avenue, New Palestine, Ohio. Abbreviations of important additional localities: 445-Rt. 445 composite reference section, Brent, Kentucky; CF=Clays Ferry, Kentucky (type section of Clays Ferry Formation—up-ramp equivalent of Kope Formation); K=Kope Hollow, Levanna, Ohio (type section of Kope Formation).

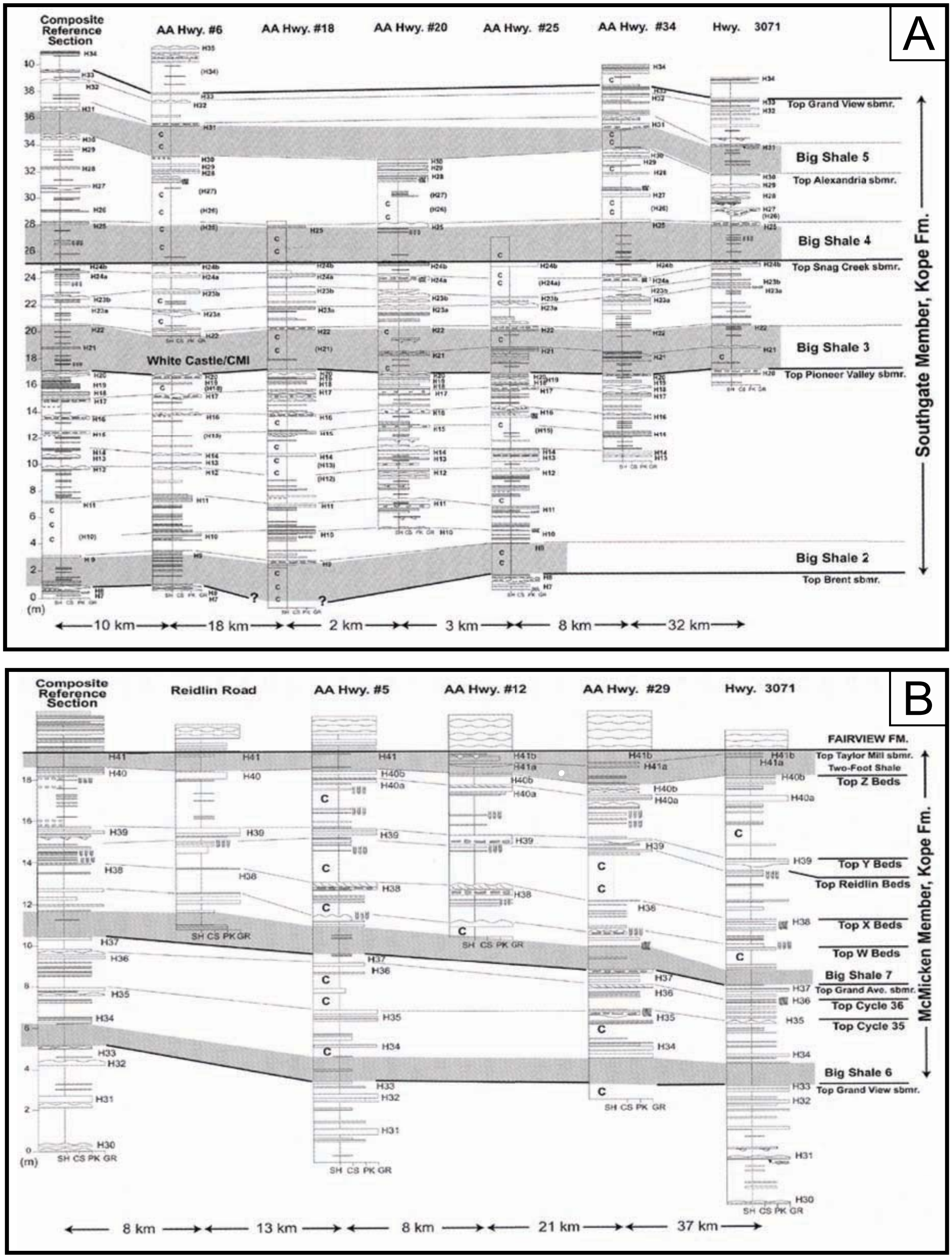


Figure 5. Correlated stratigraphic sections of the middle and upper Kope Formation from the vicinity of Cincinnati, Ohio to near Maysville, Kentucky transect across outcrop locations 8–1, showing persistence of limestone bundles and thicker shales. Limestone bedsets are numbered with H-numbers to reflect their identity with cycle caps identified by Holland et al. (1997); c=covered interval; scales at base of each column show lithology: SH=shale/mudstone, CS=calcareous siltstone/calcisiltite; PK=packstone; GR=grainstone. (A) Southgate Member. (B) McMicken Member. Modified from Brett and Algeo (1999).

Submember	T	CLS	CONC	CS	PK	ripple	clast	GR	ripple	clast
Taylor Mill	9 m	4	2	18	6	0	0	6	3	4
Grand Avenue	5 m	4	0	0	14	0	0	4	2	0
Grand View	5 m	3	1	0	4	0	0	4	3	0
Alexandria	11 m	6	5	8	6	0	0	8	6	1
Snag Creek	8 m	6	1	14	9	0	0	5	0	0
Pioneer Valley (u)	10 m	6	3	20	10	1	2	10	5	3
Pioneer Valley (l)	6 m	3	0	6	3	1	0	0	0	0
Brent	15 m	8	5	23	19	3	1	4	3	1
Fulton	7 m	7	5	7	2	1	0	10	4	1
Totals	76 m	47	23	96	73	8	3	51	26	10

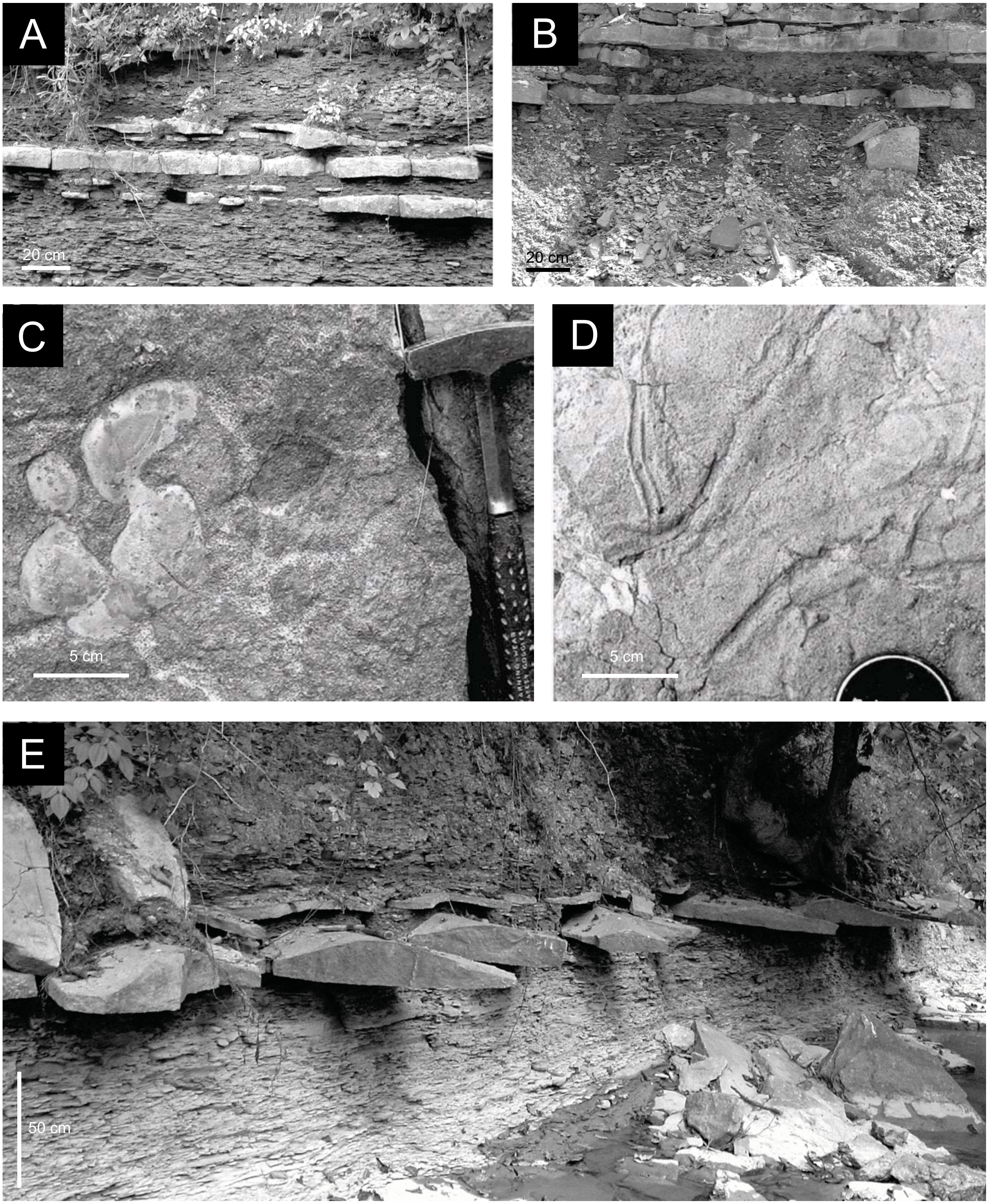
Table 1. Numbers of interbedded lithologies in Kope Formation submembers in the Rte. 445 reference section, at Brent, northern Kentucky. T= approximate thickness of submember; CLS=major cycle capping limestone; CONC=layer of concretions below capping limestones; CS =siltstones/calcisiltites; PK=packstones; GR=grainstones; ripple=ripples on bed tops; clast=rip-up clasts in bed (assessed separately for packstones and grainstones).

that can be correlated between outcrop sections (Miller et al., 2001; Holland et al., 2001b; Webber, 2002).

Brett and Algeo (1999) found that most of the thicker limestone beds and bedsets (15–60 cm thick) and a number of distinctive faunal marker beds could be traced, not only in continuous outcrops up to 1 km long, but also from each outcrop to the next for several tens of kilometres from Cincinnati, Ohio southeastward to Maysville, Kentucky (Figs. 4, 5). Most of these limestone beds were previously recognized as the caps of some 40 metre-scale cycles identified by Holland et al. (1997) at their reference section along Kentucky Rte. 445 and adjacent I-275, near Ft. Thomas, Kentucky (Fig. 4). Thus these beds were numbered in accordance with the numbering of the metre-scale cycles. Kohrs (2003) later traced these limestones and many other markers in greater detail within a distinctive interval, informally named the Alexandia submember in the Cincinnati area, containing six major shale–limestone bundles. Brett et al. (2003) documented a similar persistence of lithologic and faunal marker beds in the Fulton submember of the Kope Formation. Finally, Kirchner and Brett (2003) completed a proximal–distal stratigraphic correlation transect connecting well-known outcrops with previously unstudied Kope sections in drill cores north of the Cincinnati area, and found many of the marker beds and epiboles to be traceable into the subsurface. Thus, proximal and distal portions of mudrock–limestone packages within the Alexandria submember have been correlated in the subsurface based on faunal markers observed in outcrop, as well as additional markers recognized in core (for locations, see Fig. 4).

Evidence of Kope limestones as products of long-term storm winnowing has emerged from studies of Tobin and Pryor (1981), Jennette and Pryor (1993), Holland et al. (1997), and Dattilo (1994, 2004), although some disagreement exists on the major forcing mechanism for winnowing episodes. Whereas Jennette and Pryor (1993) cited sea level oscillations as the principal control on the timing and duration of winnowing episodes, Holland et al. (1997, 1999, 2001) suggested that changes in storm intensity could have produced similar patterns. A recent faunal study of the Kope Formation by Webber (2002, 2005) demonstrated that limestone biotas

Figure 6. Sedimentary structures observed in limestones of the Alexandria submember of the Kope Formation. (A) View of bed 25, showing development of a series of closely stacked lenticular beds; thickest bed is 10 cm thick; Fowler Creek (locality 3). (B) View of same bed 25 bundle interval as in A, with rippled basal grainstone exhibiting sharp and nearly planar base; locality 2, ~55 km southeast of section shown in A. (C) Bed 28 showing sharp, erosive base of a skeletal grainstone (incorporating concretions scoured out from underlying shale and casts of firmground burrow; Fowler Creek, Independence, Kentucky; locality 3. (D) Epichnial trails (*Cruziana*) on upper surface of bed 27; locality 6. (E) Bed 30 showing flat erosive base (locally with reworked concretions) and series of evenly spaced, symmetrical ripples on upper surface; locality 3.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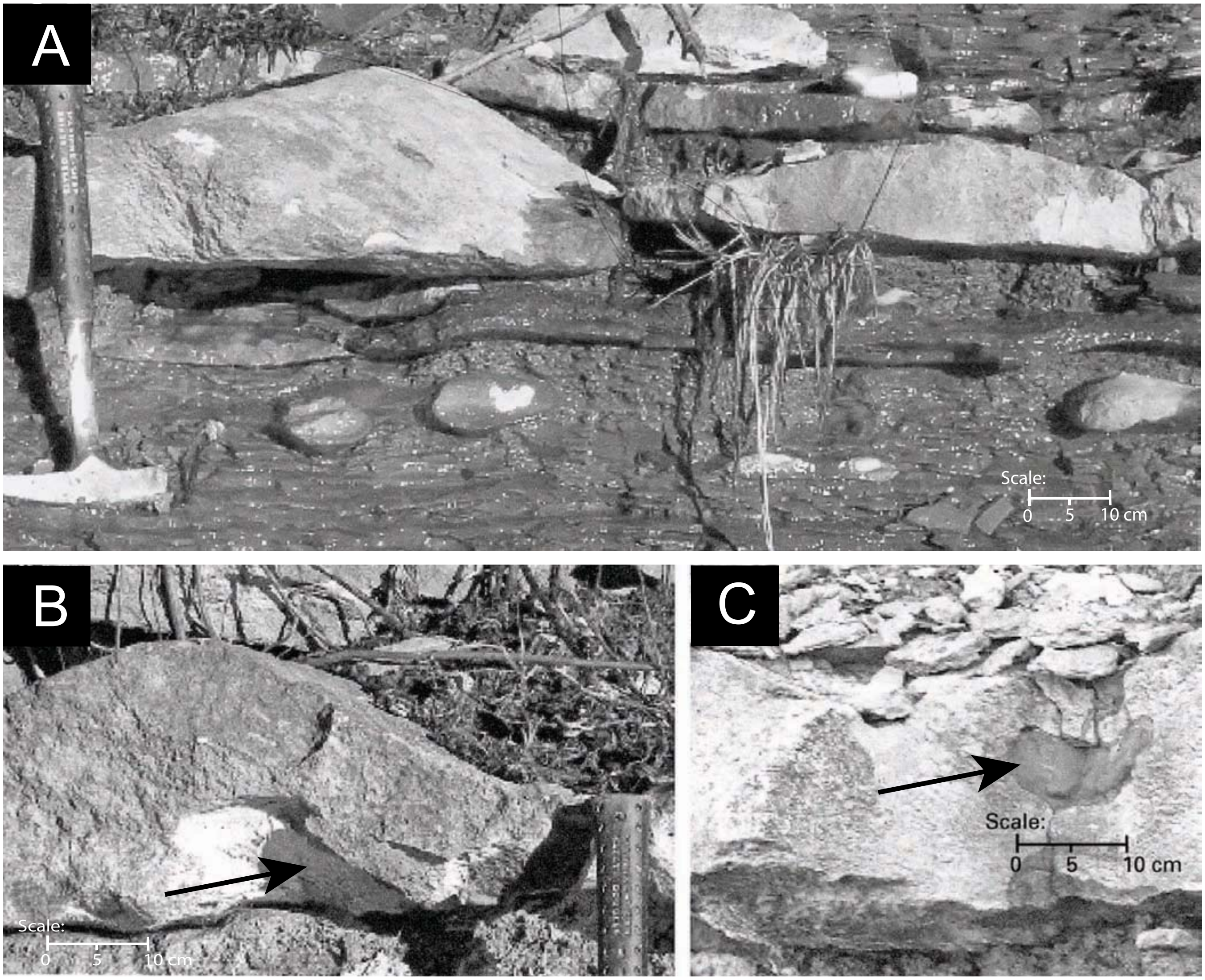


Figure 7. Common features of major ‘capping’ limestone beds; all examples are from Brent submember, locality 4. (A) Sharp, nearly planar base and rippled top of bed 6 with foreset beds in cross-section; subjacent to this bed a row of small mudrock-hosted concretions. (B) Depression left by a large mudstone clast weathered out of the base of bed 6. (C) Rounded, ferruginous mudstone clast (indicated by arrow) embedded bed 6.

differ little from those in the intervening mudrocks, thereby militating against the possibility of major lateral transport, or shallowing/deepening within metre-scale limestone–shale couplets. A storm-winnowing model has therefore been favoured. A modified perspective of Brett and Algeo (1999) holds that lithologic differentiation between mudstone- and limestone-rich intervals resulted from alternating episodes of siliciclastic input and starvation. Dattilo (2004a,b) independently arrived at a similar conclusion. Recent developments reported herein have provided further new insights to Kope deposition that demand a re-assessment of the existing depositional models.

DESCRIPTION OF MUDROCKS AND SKELETAL LIMESTONES

Detailed observation and measurement of all beds thicker than 1 cm were carried out on ten outcrops in the Cincinnati Arch area adjacent to the Ohio River in northern Kentucky and southern Ohio, and ten drill cores from the Ohio subsurface (Fig. 4; Kirchner and Brett, 2003). Data tabulated include the numbers of beds containing each lithology, thicknesses of individual beds, the range of thicknesses among different beds, the sharpness of bed tops and bases, occurrences of sole features, and the presence/absence of rippled tops (Table 1).

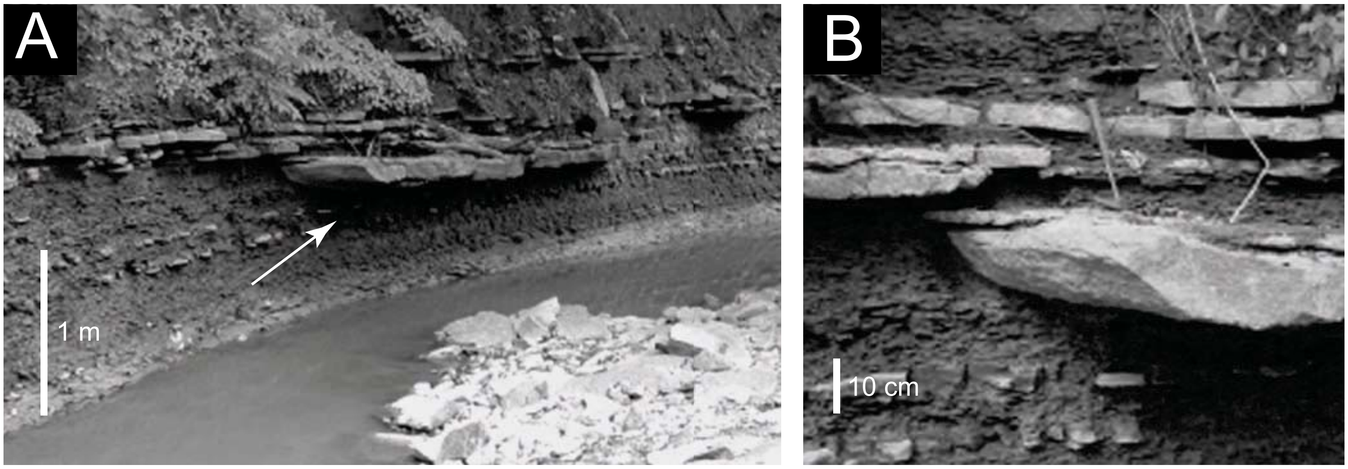


Figure 8. Lenticular, channel-fill limestone encased in mudstone. Channel underlies limestone bed 25 of the Alexandria submember, locality 3. (A) Oblique view of channel ~10 m wide and 40 cm deep filled with bryozoan-rich packstone; bryozoans are largely intact, 15 cm long sections. (B) Close-up view of eastern edge of channel (and overlying beds) indicated by arrow in A.

The ~70 m of the Kope Formation in the Cincinnati composite standard area, yielded a total of about 230 limestone beds thicker than 1 cm, comprising ~20% of the thickness of the formation. Of these, 135 (~58%) were skeletal limestones (primarily crinoid, brachiopod–bryozoan pack- to grainstones) and 96 (~42%) were calcisiltites/siltstones (Table 1).

A survey of the upper cycles (Economy and McMicken members; Figs. 2, 5) in seemingly more proximal sections near Maysville yielded surprisingly similar results (Tables 1–3). The submembers differ slightly in thickness between these areas, some being thicker and some thinner at Maysville than near Cincinnati. Snag Creek and Alexandria submembers are thinner at Maysville than in the Cincinnati area, but the limestone bedsets on average are slightly thicker; thus, the proportion of limestone to mudrock increases to the southeast. The Grand View and Grand Avenue submembers are about the same thickness in both areas, but the Taylor Mill submember is fully 2 m thicker at Maysville and shows a decrease in the proportion of limestone to mudrock.

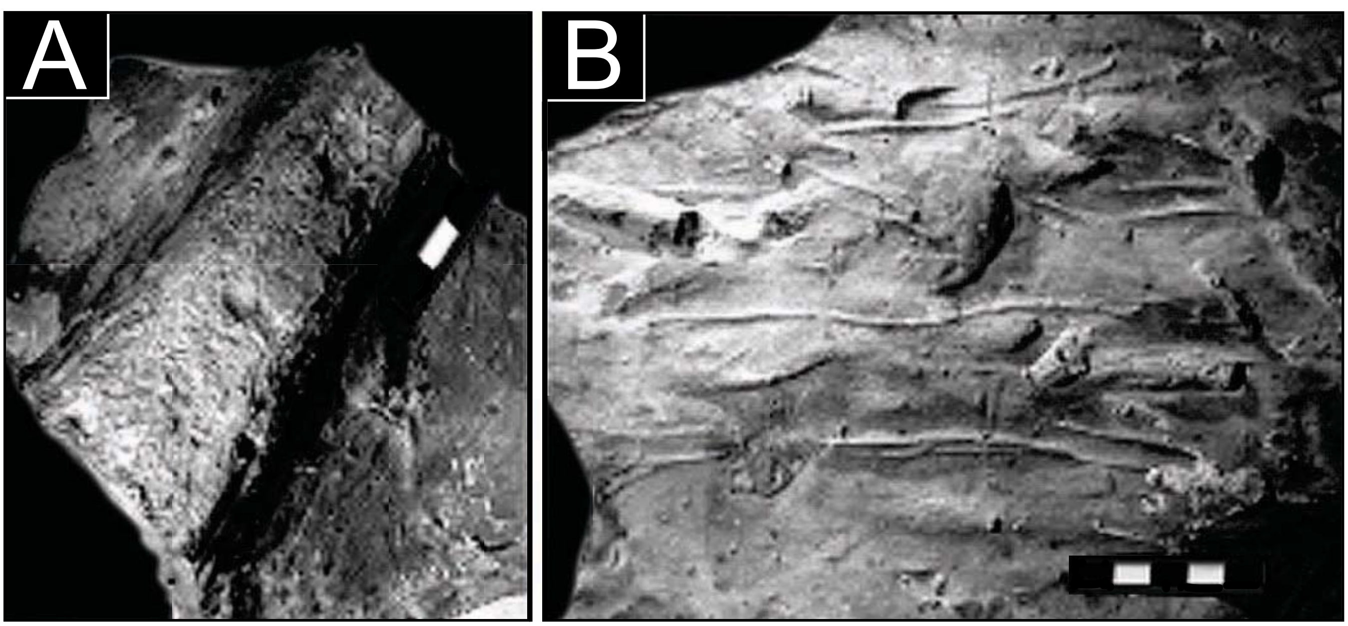


Figure 9. Storm-related structures on soles of siltstone beds, Pioneer Valley submember, locality 445 (scale increments in centimetres. (A) Gutter cast, Kentucky Rte. 445. (B) Sole marks, including groove and prod casts.

Submember	T	CLS	CONC	CS	PK	ripple	clast	GR	ripple	clast
Taylor Mill	11 m	4	0	20	10	0	0	4	0	0
Grand Avenue	5 m	4	0	2	12	0	1	3	0	0
Grand View	5.5 m	3	0	3	0	0	0	5	1	1
Alexandria	7 m	5	0	7	2	1	0	6	3	2
Snag Creek	7 m	6	0	22	7	1	0	4	1	1
Totals	35.5 m	22	0	43	31	1	0	22	5	4

Table 2. Numbers of interbedded lithologies in the mudstone portions of Kope Formation submembers in the Maysville, Kentucky area. T= thickness (approx.); CLS=major cycle capping limestone; CONC=layer of concretions below capping limestones; CS=calcisiltites/siltstones; PK=packstones; GR=grainstones; ripple=ripples on bed tops; clast=rip-up clasts in bed (for either packstones or grainstones).

Interestingly, however, the numbers of siltstone, and packstone/grainstone beds and their relative proportions were found to be nearly the same at Maysville as in the Cincinnati area (Table 2). These strong similarities in the number and proportion of beds within submembers (despite considerable and consistent differences in proportion of the three types of beds among cycles) indicate that the patterns of interbed distribution are region-wide, and indeed, careful examination of the positions of beds suggests that many of these span the distance between Cincinnati and Maysville.

SKELETAL LIMESTONES (PACKSTONES AND GRAINSTONES)

Skeletal limestones make up the greatest proportion by thickness and frequency of interbeds in the Kope Formation.

Submember	Rte. 445	Maysville
	CS:PK:GR	CS:PK:GR
Taylor Mill	8:6:6	20:10:4
Grand Avenue	0:14:4	2:12:3
Grand View	0:4:4	3:6:5
Alexandria	8:6:8	7:4:6
Snag Creek	14:9:5	11:7:4

Table 3. Comparison of relative frequency of interbedded lithologies in the Kope Formation between the Rte. 445 reference section (Ft. Thomas, Kentucky, Cincinnati area) versus the Rte. 68 road cut (Maysville, Kentucky). CS=calcisiltites/siltstones, PK=packstones, GR=grainstones.

The overall mean thickness of skeletal limestone beds is ~10 cm (N=600; SD=5.86), with a slightly lower mean for the Cincinnati area than for Maysville. On average, about 16 skeletal beds occur per decametre-scale cycle (Table 1).

The most numerous limestone beds in the Kope Formation are packstones (~36% of all beds >1cm). Most of these beds have sharp bases, but a small number appear gradational. Only a small proportion (8 beds; 10%) has rippled tops (Table 1; Figs. 6, 7). Thin, discontinuous to lenticular packstones of skeletal debris also form the lower part of sharp-based, graded, silt/mud units of the mudrock intervals. The majority of the packstones show little or no evidence of size sorting of skeletal components. Shelly remains are set in a terrigenous muddy to silty matrix with minor amounts of micrite. Skeletal grains in the packstones are biologically standardized in size, including crinoid pluricolumnals 1–10 cm in length and 2–10 mm in diameter; clusters of aligned crinoid columns up to 30 cm long are common. Brachiopod valves are 1–10 cm in maximum width. Ramose bryozoans generally occur in fragments less than 1 cm but, in some cases, are preserved as large, intact colonies exceeding 10 cm in size.

Skeletal packstone beds preserve ample evidence of processing by waves or currents, including: 1) sharp bases with firmground burrows, rip-up clasts (Figs. 6, 7) and gutters/shallow channels (Figs. 8, 9); 2) alignment of fossil debris; 3) convex-up or, rarely, edgewise shells and trilobite sclerites; and 4) starved ripple or stringer geometries.

Beds composed of grainstone and pack- to grainstone comprise only ~22% of all beds, but are typically the thickest beds in each submember, and form most of the bounding limestone bundles of metre-scale cycles. All have sharp, erosive bases, but fewer than 10% possess reworked clasts. Several grainstone beds preserve a cap of laminated siltstone or calcisiltite, and more than half (30 beds; 59%) display rippled tops (Figs. 6, 7). Grainstones show partial to complete winnowing of mud and may exhibit a degree of size sorting of skeletal clasts. Certain beds are composed largely of crinoid columnals just a few millimetres in diameter, but most show large brachiopod valves, segments of bryozoans set in a sand/gravel sized matrix of smaller crinoid ossicles and/or shell fragments. The bioclasts display a variety of preservation states from heavily corroded fragments to complete, intact brachiopod valves or sections of crinoid columns. Brachiopod shells may show a variety of colours from pale pinkish grey to nearly black; in general, more heavily corroded shells show darker colours, suggesting early diagenetic mineralization at or near the seafloor.

Significantly, 23 of the 50 (46%) thick pack- to grainstone beds that cap small-scale cycles are underlain by shales with horizons of small carbonate concretions (within 20 cm below their bases) in at least one outcrop in the Cincinnati area (Fig. 7). Four thicker beds contain reworked concretions (Fig. 6C); in each case, the reworked and encrusted concretions were found in more than one locality. A number of the skeletal limestone beds bear sharply defined positive- or negative-relief epichnial burrows on their upper surfaces, and thus must have been relatively firm prior to final burial, but only a few instances of encrusted hardgrounds are present.

A sample of 41 major skeletal grainstone–packstone bundles capping cycles 7–40 was surveyed at seven major sections between Alexandria and Maysville, Kentucky resulting in 227 bed samples (Table 1). Of the 41 capping beds, all were found to have sharp bases in all localities, and 18 (44%) contained large mudstone intraclasts in at least some outcrops (61 of the 227 samples or ~27% of all samples). Most of the thick basal beds were also found to have sharp upper contacts with thin shale partings. However, most of these limestones are overlain by a series of thin packstones that, in turn, appear to be gradational with overlying mudrocks. 30 of the skeletal limestone bundles (73%) show rippled tops in at least one exposure (~27% of all tallied limestones). In five instances two or more beds within a given bundle or bedset were found to preserve ripples oriented in different directions (but never at right angles to one another).

The dominant constituents of the skeletal limestones are crinoid debris, whole and fragmented brachiopod valves, and ramose bryozoans. A clear distinction exists in the dominant brachiopod constituent. *Sowerbyella rugosa* is common to dominant in 17 of 20 beds of the Brent and Pioneer Valley submembers (Economy Member), *Dalmanella* sp. is common in 13 of the 20 beds, and only three beds were observed to contain *Rafinesquina* sp.. By contrast, the skeletal limestones of the Southgate and McMicken members (Snag Creek, Alexandria, Grand View, Grand Avenue, Taylor Mill submembers) are heavily dominated by *Dalmanella* sp. (17 of 20 beds); *Sowerbyella* is abundant in one bed and to be absent in nearly all the rest. Nine of 20 beds, particularly in the Grand Avenue and lower Taylor Mill submembers, contain common to abundant *Rafinesquina*. The loss of *Sowerbyella* above the Pioneer Valley submember is a key feature of the Kope Formation biotic composition; the cause of this faunal change, however, remains unknown.

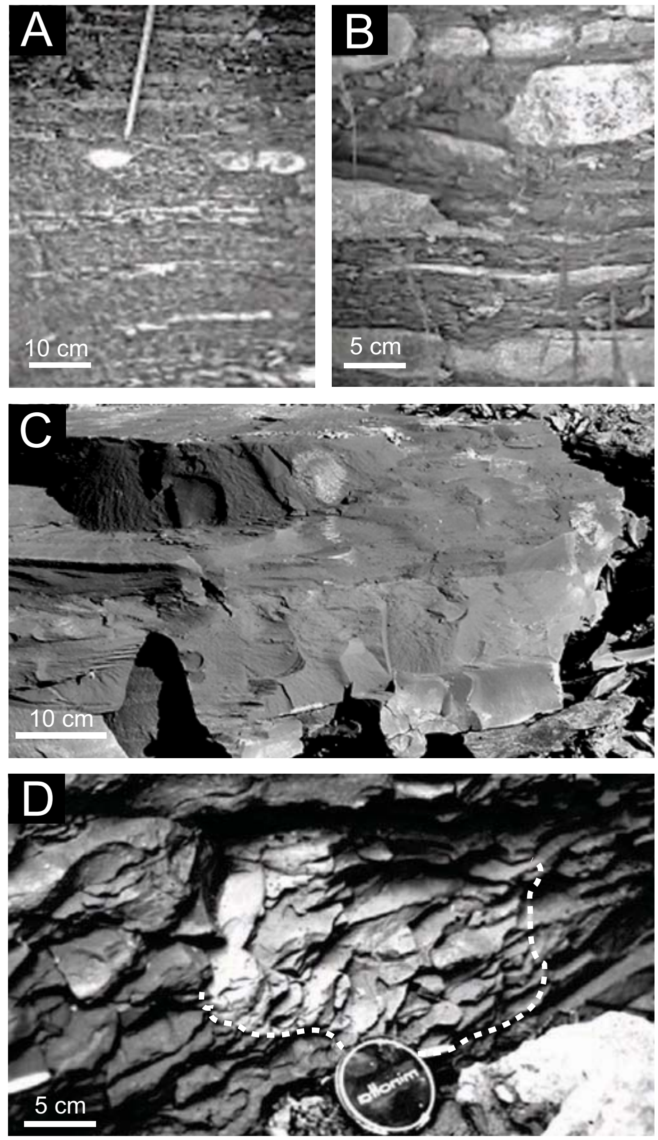


Figure 10. Common features of mudstone-dominated intervals, Kope Formation. (A) Thin lenticular packstone and siltstone beds and a single row of concretions within mudstone/shale; Fulton submember, locality 15. (B) Mudrock-hosted concretionary beds; same submember and locality as A. (C) Sharp contact between light grey and darker brownish-grey mudstone in an unweathered block from the Fulton submember, locality 6; the upper bed contains the Triarthrus trilobite molts shown in Figure 11A. (D) Gutter infilled with grey mudstone and encased in mudstone. Dotted line outlines base of lower surface of the 10 cm deep gutter, lower Fulton submember, locality 5.

LENTICULAR CHANNEL-FILL LIMESTONES

Most of the pack- to grainstone beds or bedsets are roughly tabular and laterally persistent on a regional scale. However, lenticular packstone units up to 50 cm thick are present locally. These appear to occur only in certain metre-scale cycles. Excellent examples occur in the thicker mudrock intervals (“big shales”) near the bases of decametre-scale cycles. Figures 8A and 8B show a lens of bryozoan-rich limestone, up to 27 cm thick, in cycle 25–26, that partially fills a scoured channel about 10 m across up to 40 cm deep at locality 6. The upper portion of the channel fill above the down-cut grainstone lens consists of bryozoan-rich mudstone. Bryozoan zoaria in the channel are largely intact ramose colonies, suggestive of autochthonous remains of organisms that colonized the channel. In some cases a slight degree of alignment of skeletons is evident. The base of the channel is relatively flat, but the east side shows a steep wall (inclined at about 56°)

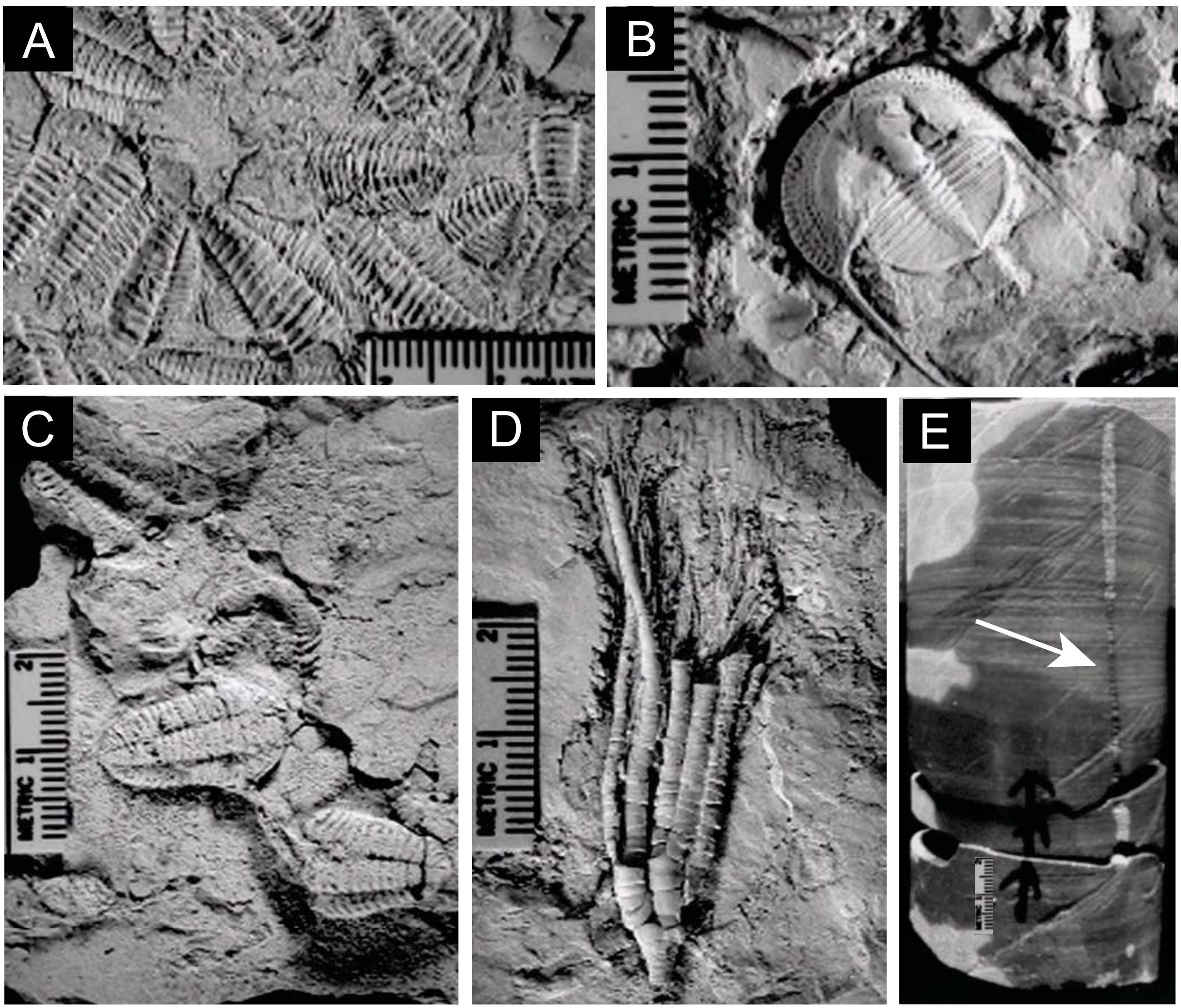


Figure 11. Evidence for rapid burial of multi-element skeletons in the Kope Formation; A, B and D from Alexandria submember, locality 6; C and E from Alexandria submember, locality 12. (A) Underside of bed in cycle 28 showing cluster of articulated molts (thoracopygidia missing cephala) of *Triarthrus becki*, preserved as external molds oriented convex-down. (B) Complete specimen of *Cryptolithus bellulus* from the “upper *Cryptolithus* bed” of cycle 29. (C) Articulated specimens of *Flexicalymene* sp. from mudstone just below bed 28, preserved as internal molds oriented convex-up. (D) *Ectenocrinus simplex* from cycle 29. (E) Drill core segment showing a 15 cm long articulated crinoid stem preserved in vertical life position (indicated by white arrow) in laminated silty mudstone. Scale increments in millimetres. Specimens in A–D deposited in the collections of the Cincinnati Museum Center

with tool marks. The west side is gentler (~30°); where the limestone pinches out on either flank the edge of the channel. It continues as an inclined surface cross-cutting the underlying mudstone and overlain by bryozoan-rich mudstone. The entire channel fill directly underlies a laterally continuous skeletal limestone bed. Another channel, in cycle 26–27, is only recognizable due to the draping of one of its margins by a discordantly inclined bed of bryozoan-rich limestone that dips approximately 35° from the horizontal (Figs. 8A, 8B). The channel contains deformed siltstone masses near its base, and is underlain by somewhat deformed mudstone. Similar, but smaller channels have been observed in the same interval at four other localities; in some cases they are filled entirely with mudstone, rendering their outlines identifiable but extremely subtle.

CALCISILTITES AND SILTSTONES

Beds of calcisiltite and siltstone are less variable in thickness than are the skeletal limestones (N= 94; mean=7 cm; SD=4.33 cm). All preserve planar to slightly hummocky cross-lamination, plus sharp bases with tool marks. About half of the observed beds were noted to bear minor basal lags of skeletal debris composed mainly of trilobite sclerites, crinoid ossicles and current-aligned graptolites. Nearly all of the beds studied (91 beds in seven sections), were noted to have sharp, scoured bases, in many cases preserving prod and/or groove marks (Fig. 9). Most of these beds also have a "lam-scram" fabric (sensu Bromley, 1990), featuring lamination in the lower part and abundant burrows in the upper part that indicate post-event colonization. Whereas Chondrites, *Planolites* and *Teichichnus* are present in most beds, *Diplocraterion* is more or less restricted to beds with gutter casts that, in turn, are present only on certain widespread siltstones. Only five of the 94 beds were observed to have gutter casts on the bases. Five beds were found to preserve crinkly millimetre-scale ripple-like feature in which may be wrinkle marks. *Rusophycus* is occasionally present on the bed bases (Fig. 9), and *Trichophycus* burrows occur in mudstone-filled scours directly overlying some siltstone and fine-grained grainstone beds.

Siltstone beds are not randomly distributed; rather, they tend to be concentrated in certain submembers. The highest frequency of siltstone beds is in the lower 7 m of the Brent submember, where 17 beds thicker than 1 cm are present (an average of 2.4 beds/m). When corrected for thickness, the upper Economy Member (upper Pioneer Valley submember), the overlying Snag Creek submember, and the Taylor Mill submember (uppermost Kope Formation) have the next highest frequency of siltstone, with about two beds per metre each. By contrast, few siltstones occur in the Grand View and Grand Avenue submembers. In the Cincinnati area, mudrock intervals show an average of three calcareous siltstone

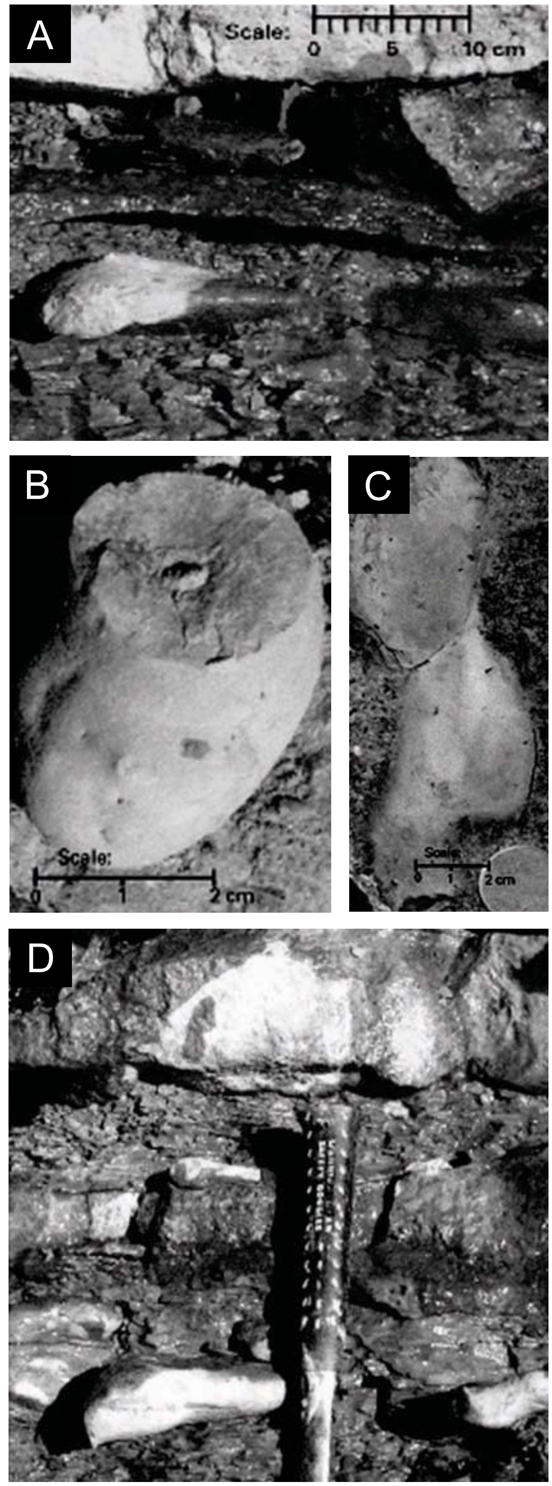


Figure 12. Concretions in the Kope Formation; locality 4. (A) Horizon of small concretions a few centimetres below complex, amalgamated grainstone bed; bed 6, Brent submember. (B) Pyritic burrow encased in concretion; Brent submember. (C) Reworked concretion in base of skeletal grainstone bed; bed 30, Alexandria submember. (D) Layer of concretions (near middle of photograph) showing nearly complete lateral fusion to form a semi-continuous bed; Brent submember.

(or calcisiltite) beds (>1 cm thick) per metre (Table 1), and a much larger number of siltstone laminae.

There is a strong tendency for siltstone beds to occur in the upper portions of mudstone intervals. In a majority of metre-scale cycles (16 of 20; 80%), siltstone beds are more common in the upper than the lower half of the cycle. A notable exception, however, is in the "big shales" that form the bases of decametre-scale cycles, five of eight which show a sub-symmetrical pattern with a few thick siltstone beds near the bottoms and tops of the packages; the remaining three of eight show and upward decrease in the frequency of siltstone beds.

MUDSTONES AND SHALES

Due to their soft and easily weathered character, intervals of mudrock (mudstone and shale) are commonly obscured by colluvium, but good exposures are present along cutbanks of creeks. Data pertaining to structure and fabric were collected primarily from trenched sections and drill cores (Table 4).

Even though mudrock intervals typically appear monotonous, close scrutiny of fresh surfaces reveals subtle heterogeneities. The majority of these intervals can be divided into a series of packages primarily defined by stratal arrangements of massive mudstone beds, siltstone laminae, skeletal debris beds and concretion horizons. The majority of the terrigenous mud contained in the Kope mudrocks, up to 90%, is composed of illite (Bassarab and Huff, 1969). However, lithologic heterogeneities within the massive mudstone beds are also indicated by subtle colour differences in their constituent claystones, varying between brownish grey, medium-grey, pale olive and greenish grey (Fig. 10). Dark brownish-grey mudstones apparently have higher organic matter contents, while light-grey mudstones are more calcareous with up to 20% $CaCO_3$ cement. Differences in silt content and clay fabric (from more ordered in silt-poor to more chaotic in pure claystone) are also observable and have been documented for a portion of the Kope (Kohrs et al., in press). Where visible, contacts between mudstone beds are typically sharp and, in rare instances, scoured with up to 2 cm of relief.

Small, ellipsoidal carbonate nodules, 3–14 cm in length, occur in distinct, laterally traceable horizons (Fig. 12). Many preserve nuclei of slender, cylindrical, pyritic burrow fills (typically weathered to limonite; Fig. 12B). A few horizons of very small nodules occur within thick mudstone intervals, typically associated with thin siltstone beds (Figs. 10A, 10B). The majority of concretions, however, occur slightly below thicker beds of skeletal limestone (Fig. 7A).

Mudock intervals exposed near Cincinnati, on average, contain 10–15 limestone/siltstone beds, thicker than 5 mm per metre, although the true number of all events is undoubtedly underestimated due to the exclusion of sub-centimetre-scale beds from our dataset. Observations of bedding surfaces in cores indicate that compacted layers average <1 cm. Certain beds provide evidence for episodic deposition as obrution events, for they contain well-articulated crinoid columns, trilobites and other multi-element skeletons that imply rapid burial (Fig. 11). Recent, high-resolution stratigraphic studies of the Kope Formation confirm that some of these obrution beds are laterally persistent and extend even into distal facies in the subsurface cores (Brett and Algeo, 1999; Kirchner and Brett, 2003; Kohrs, 2003).

SEDIMENTARY PROCESSES IN MUDROCK INTERVALS VERSUS SKELETAL LIMESTONE UNITS

Observations on a centimetre to sub-centimetre scale in the Kope Formation (Hughes and Cooper, 1999; Brett et al., 2003; Kohrs, 2003), reveal that the traceable skeletal limestones do not necessarily represent single beds but, rather, also preserve minor beds of mudstone, shale and calcisiltites, which we refer to as shell bed-dominated intervals. Similarly, the mudrock-dominated intervals are actually a collage of mudstone layers, thin siltstone layers, concretion horizons and thin lenticular packstones.

MUDROCK-DOMINATED INTERVALS

In the absence of thick shelly accumulations, storm-generated features are difficult to recognize. This has led to a common view that mudstones reflect relatively quiet, if episodic, accumulations of mud in environments below storm wavebase. This view is fundamentally based on the assumption that the preservation of fragile and commonly articulated skeletal remains such as trilobite molt ensembles and the lack of apparent corrosion or abrasion of fossils indicate low-energy, non-turbulent depositional conditions. Contrary to this view, there exists abundant evidence, not only for episodic mud and silt deposition, but also for substantial erosional scour of the muddy seafloor.

The strongest line of evidence for episodic turbulence and sedimentation within mudrock-dominated intervals comes from siltstone beds. The erosive bases, tool marks, hummocky cross-lamination and lam-scram fabric preserved in these beds all point to storm-generated disturbance. Nearly all siltstone beds preserve planar lamination or small-scale hummocky cross-stratification, indicating combined wave-current flow. About half of these beds show minor grading, indicating rapid settling of suspended silt particles, and preserve thin concentrations of shelly debris at their bases, suggesting some degree of scour and/or winnowing.

The significant relief indicated by siltstone-filled gutters and shale-filled scours at a few horizons indicates substantial episodic seafloor erosion (Figs. 9A, 10D). Moreover, the sharp definition of tool marks, even on planar bases of siltstone beds, together with the occurrence of overhangs in

Alexandria Cycle/ Locality	Thickness of mudrock interval	Number basal limestone beds	Thickness of basal limestone	Siltstones	Shell hash	Obrution beds	Concretions (cm below upper limestone)
29–30 a	60–62	2	30–35	1	10	1	x
	b60–64	2	6–20	0		1	x
	c40–45	2	?	1		1	x
28–29	a120	3–4	35	5	10	4	5–8
	b135				11	3?	—
	c		35–40	5	10	4	—
27–28	a120	2	25	3	6	5	5–8
	b106	2	4	5			x
	c135	2	25–30	6	4	5	x
26–27	a205		16	8	16	1	27 cm
	c175	2	17	10	2	1	20–25 cm

x = concretions reworked into base of limestone

Table 4. Thicknesses of metre-scale cycles and capping shell beds, numbers of event beds and concretions (listed as centimetres below major limestone beds) in the shales of cycles of the Alexandria submember in the Cincinnati, Ohio–Covington, Kentucky area. Localities listed: (a) Sycamore Creek, Indian Hills, Hamilton Co., Ohio (locality 6); (b) I-275 1 km south of bridge over Ohio River, Brent, near Ft. Thomas, Campbell Co., Kentucky; (c) Fowler Creek adjacent to Kentucky Rte. 1486 exit from Kentucky Rte. 17, ~3 km north of Independence, Kenton Co., Kentucky.

the near the tops of mudstone-hosted gutters, indicate that in addition to the mud removed during the formation of the gutters, several centimetres of soft, surficial seafloor mud may have been stripped from the surrounding seafloor. It is critical to note that such scoured surfaces are rarely overlain by a thick, persistent layer of shell hash; at most, only a few scattered skeletal fragments typically lie in the bases of gutters, where up to 10 cm of mud have been removed. Thus, it is clear that even where evidence exists for substantial mud removal, persistent skeletal debris layers of any thickness are absent.

In contrast to the thicker skeletal limestones, rip-up clasts have not been observed at the bed bases of siltstone beds, thin shell hash layers, or in shales above scoured mudstone contacts. The absence of rip-up clasts in the mudrock intervals is conspicuous, given the observed abundance of other storm-related features as well as the apparent evidence for scouring downward into stiff muds. This suggests that formation of angular rip-up clasts observed in many of the thicker skeletal limestone beds required processes beyond those involved in formation of sharp guttered contacts in cohesive muds. The seafloor evidently remained soft during mud deposition, probably due to high net rates of clastic sedimentation. But this might not have been the case at times when thicker skeletal limestones were accumulating (see below).

Local lenses (several millimetres to ~1 cm thick) and pockets of skeletal debris (muddy packstones) do occur within mudrock-dominated intervals, but typically they appear to represent remnants of local patches of organisms (sensu Tsujita 1995, 2001), including local monospecific thickets of crinoids (preserved as profuse masses of current-aligned, articulated crinoid columns or 'log jams') and single large bryozoan colonies. These patchy concentrations of broken skeletal material indicate only slight local reworking.

More dramatic evidence of erosion is provided by larger channel structures observed in specific metre-scale cycles at multiple outcrops (Fig. 8). Measuring up to 10 m across and 1 m deep, these are evidently unusually large scours.

The best-studied examples are oriented subparallel to gutter casts in a northwest– direction, and are inferred to represent storm-surge channels by multiple episodes of erosional scour of the muddy ramp by basinward-flowing currents. Pods and larger masses of bryozoan-rich limestone that occur within these channels are interpreted as remains of colonies that, owing to the funneling of food-rich waters along these topographic lows (even during fair-weather periods), preferentially colonized the channel banks and thalwegs. Alternatively, the firm muds of the channel floor may have simply been more suitable substrates for colonization. Either way, such extensive seafloor erosion probably resulted from a lowering of sea level. Thus, these features might represent minor sequence boundaries.

Episodes of erosion and deposition. although difficult to recognize in the intervals of more massive mudstone, are evident in some features, including: (1) sharp planar to scoured surfaces with up to a few centimetres of relief separating

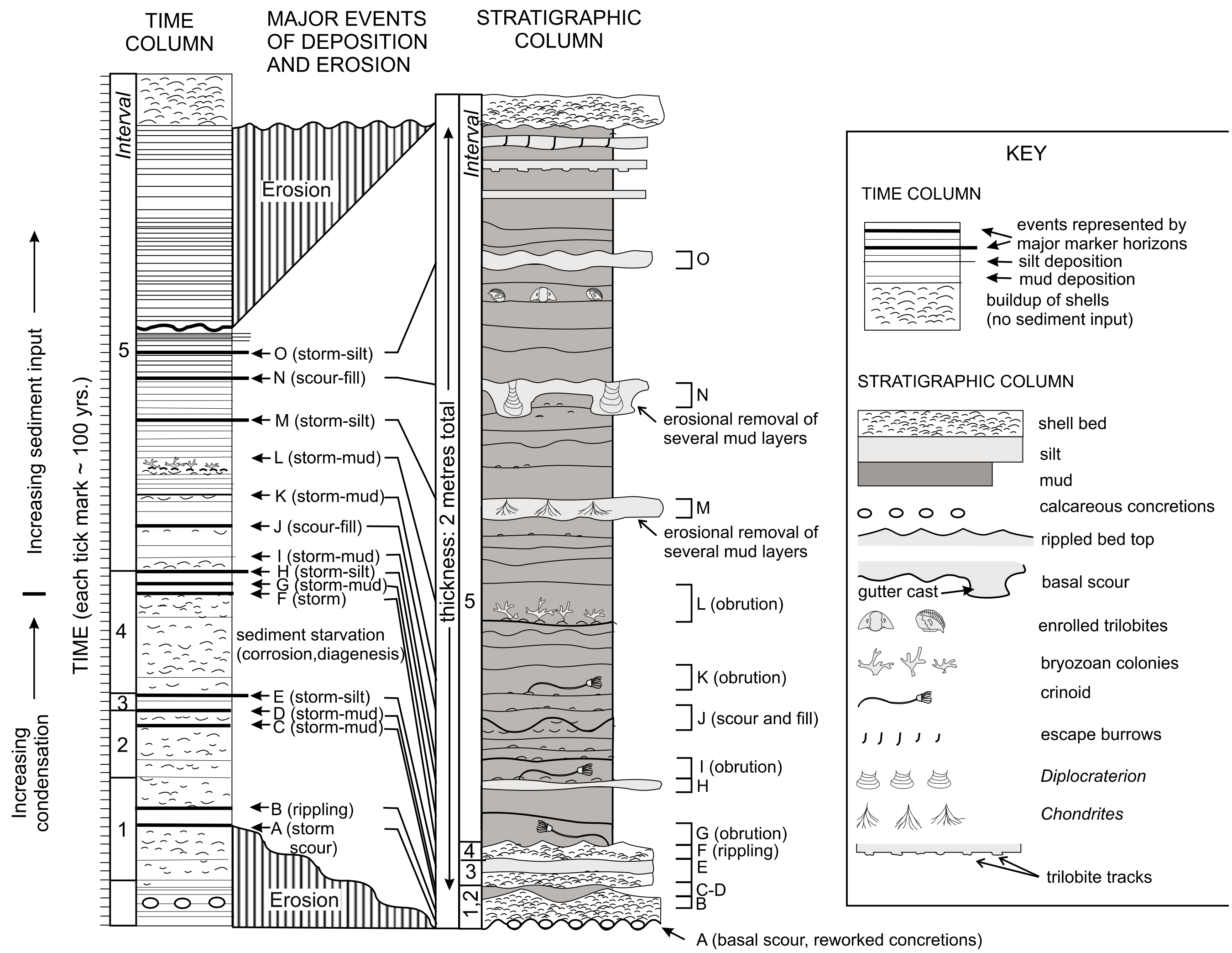


Figure 13. Idealized stratigraphic profile of part of the Kope Formation showing metre-scale cyclicity of alternating shell-bed accumulation and mudrock-dominated depositional phases. Column to the left of the stratigraphic profile is scaled to time rather than thickness with scale in century increments. Horizontal lines indicate depositional events (short lines=mud; long lines=silts or carbonate sands). Each event is essentially instantaneous so that line thickness is constant and exaggerated with respect to time. Specific events and interpreted processes are indicated to the right of the stratigraphic column. Time intervals 1 and 2 represent intervals of generally low sediment input. Intervals 3 and 4 represent more extreme sediment starvation with few mud or silt accumulation events; skeletal debris builds up in 'background' times. Intervals 1 through 4, comprising about a third of the total time, are represented by thin, complex shell beds. Time interval 5 encompasses an episode of more rapid sediment aggradation, recording multiple events of mud and silt deposition (including obrution deposits). Many upper layers are subsequently removed in erosional events, preceding and contemporaneous with the next phase of shell hash accumulation. The preserved mudstone interval, comprising about a third of the total time represented in the cycle, occupies the great majority of thickness of the succession.

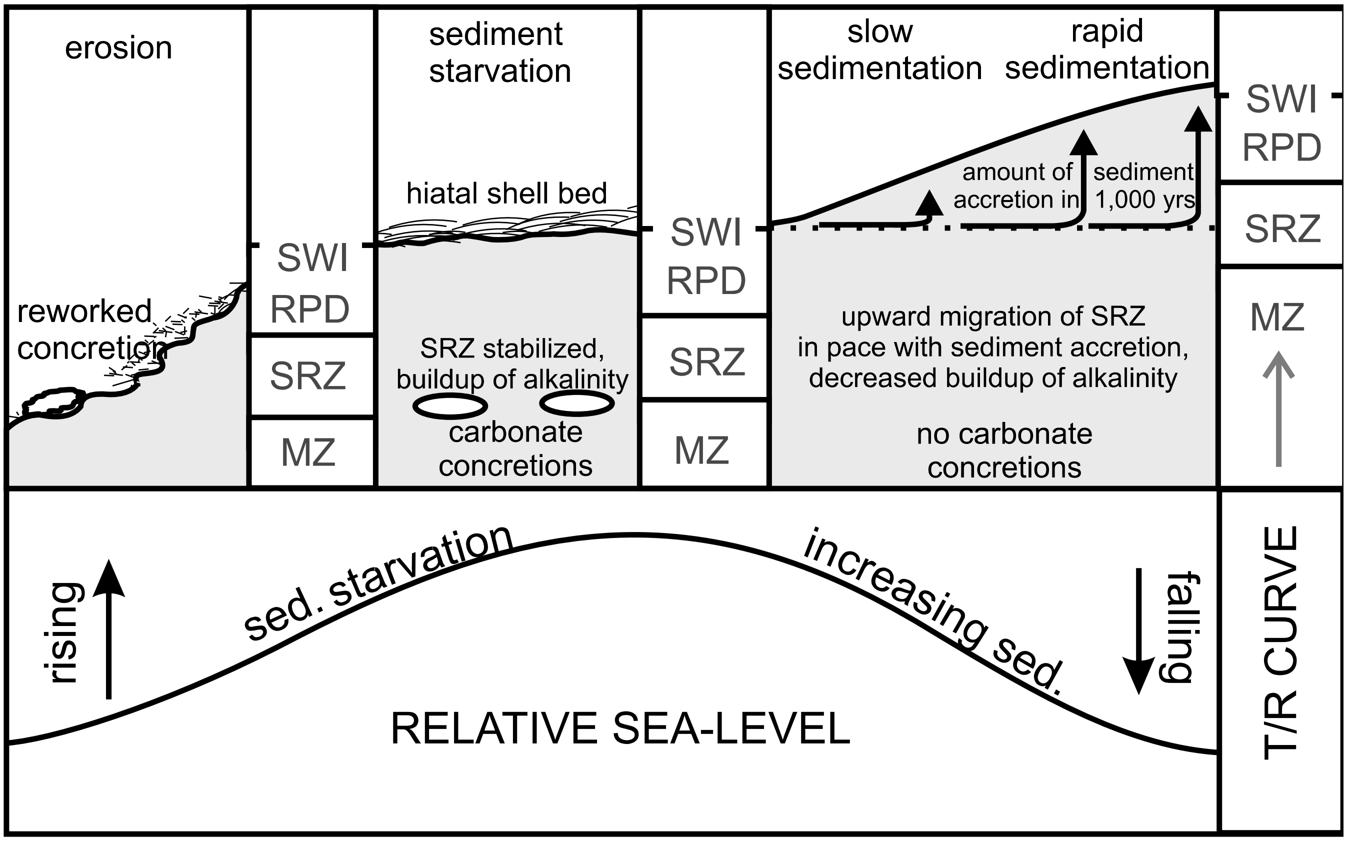


Figure 14. Relationship of sediment accumulation rates to formation/exhumation of concretions and sea level oscillations. Bars show position of SRZ (sulfate-reduction zone), RPD (redox-potential discontinuity) and SWI (sediment–water interface) at different stages of a sea level cycle. These zones remain static during period of sediment starvation but keep pace with sediment accretion during times of higher sediment influx. Carbonate concretions nucleate during conditions of sediment starvation in the stable SRZ. Under conditions of moderate to rapid sediment accretion, these zones migrate upward in the sediment and no concretions will form. However, in sediment-starved periods, extreme storm erosion may erode down to the SRZ and exhume concretions. Starvation/erosion and concretion formation occur during rising base level □

mudstones of slightly different colour or texture; (2) fragmented and reoriented debris; (3) alternations of burrowed and unburrowed mudstone; and (4) obrution ('smothered bottom') deposits (Figs. 10, 11).

The presence of numerous, if subtle, storm-related sedimentary structures and other characteristics throughout mudrock-dominated intervals of the Kope Formation indicate that processes of erosion and deposition associated with storm-generated seafloor disturbance fundamentally controlled the architecture of these intervals. We conclude that the mudrock intervals were not deposited in substantially deeper water environments or during times of greatly reduced storm action relative to the shell bed (skeletal limestone) dominated intervals. Evident in these intervals is that, while the muddy seafloor unquestionably experienced low-energy during much of the time, it was subject to frequent disturbance by storm currents and waves that were at least as intense as those recorded in the skeletal limestone.

SHELL BED-DOMINATED UNITS (SKELETAL LIMESTONES)

Units dominated by skeletal limestone (or more specifically, shell beds) in the Kope Formation are much thinner than their intervening mudrock-dominated intervals. In some cases, such a unit is expressed as a single limestone bed. However, the majority of these so-called "beds" are composite units (bedsets) consisting of a larger number of complexly stacked and amalgamated pack- and grainstone beds (Fig. 6A). Thin mudrock interbeds observed within these units consist of barren, greenish grey shales and shell-rich, brownish grey mudstones that, in some places, grade laterally into muddy packstones.

Several lithologic and taphonomic features of the thicker and more laterally persistent limestone bedsets suggest some degree of storm scouring, winnowing and re-deposition. Some of this evidence has been documented in various previous studies, especially those of Jennette and Pryor (1993), Holland et al. (1997) and Brett and Algeo (1999). Significant features include: (1) sharp, irregular bases of skeletal limestone beds; (2) current alignment of elongate skeletal remains (crinoid stalks and conical cephalopod shells); (3) imbrication and edgewise orientation of planar shells (brachiopods and bivalves); (4) evidence of skeletal reworking, including out-of-place geopetal fills and diagenetically altered shells; (5) symmetrical ripples on upper surfaces of beds (Fig. 7A); (6) scour-and-fill structures;(7) graded bedding; (8) planar lamination, small-scale cross-bedding, and crude hummocky cross-stratification; and (9) angular rip-up clasts of mudstone (Figs. 7B, 7C) and, less commonly, reworked concretions and/or platter-like hardgrounds. Most of these features are typical of grainstones, but not of the muddy packstone interbeds. Of the listed features, the first five items are only recognizeable because shells are present, and the recognition of the sixth and seventh largely depend on grain-size variations, as provided by variations in the sizes of bioclasts. Thus, a strong inherent bias exists toward recognition of storm-related features in skeletal limestones relative to mudrocks.

A notable distinction between the scoured bases of skeletal limestones versus silt- and mud-filled scours is the higher incidence of reworked angular mud clasts at the bases of skeletal limestone units relative to that observed in mudstone. A possible reason for this difference that, whereas stiff, perhaps indurated, mud existed below skeletal accumulations, the mud beneath mud and silt deposits was firm and cohesive, but not indurated. Second, the large bioclasts in shell-rich intervals (e.g., brachiopod valves) may have served as tools that gouged out pieces of cohesive or semi-indurated mud.

The presence of grading, planar to cross-lamination, and ripples on bed tops indicates that skeletal material was shifted by currents and waves; evidently, the last major storms to disturb the seafloor during shell accumulation generated enough water movement on the seafloor to mold shell debris into distinct bedforms, although the distance of shell transport during disturbance was probably slight. The consistency of ripple orientations at particular levels suggests that each of the rippled beds was redeposited by a single, unique event, further indicating that the skeletal debris was reworked during brief, high-turbulence events, probably associated with hurricanes. However, there is evidence that these conditions were the exception rather than the norm during times of skeletal limestone accumulation.

Two lines of reasoning suggest that shell-rich intervals record environmental conditions that were not greatly different from those of the intervening thicker mudstones and that, as in the latter, low-energy conditions dominated the time interval represented by limestone units. First, skeletal limestones contain faunal suites that, although not identical, are strikingly similar to those of the stratigraphically adjacent mudrocks. This is indicated by qualitative observations as well as statistical studies that have generally failed to find consistently distinctive suites of mudrock- versus limestone-specific taxa (Holland et al., 2001; Miller et al., 1988; Webber, 2002). Also, longer term faunal changes in the Kope Formation are recorded in both mudrock and limestone assemblages in tandem; for example, certain taxa occur in consistently high abundances within mudrocks and limestones of some Kope submembers. This is exemplified by *Sowerbyella* sp. and *Cryptolithus* sp. in the upper parts of the Brent and Pioneer Valley submembers, *Zygospira* sp .and *Iocrinus* sp. in the Alexandria submember, and *Rafinesquina* sp. and bryozoans in the Grand View and Grand Avenue submembers. In addition, some of the faunal elements represented in the skeletal limestones are forms that would normally be considered best adapted to quiet-water conditions; these include non-rooted crinoids (that attached by a slender tapering distal column), delicate ramose bryozoans and thin-shelled, 'snowshoe strategist' brachiopods [see Thayer (1975); Dattilo (2004b)]. Furthermore, thinner shell beds that are locally preserved within the limestone bundles are similar in taphonomic attributes and species composition to those comprising the scattered lenses found in the adjacent mudstone-dominated intervals. Thus, it is apparent that background environmental conditions represented in the limestone bundles were probably at least as quiescent as those represented in the mudrocks.

The second line of reasoning concerns evidence of mud deposition preserved within skeletal limestone-dominated units. Thin (centimetre-scale) intervals of barren mudstone, in some cases preserving evidence of obrution (Fig. 6A), are locally preserved within amalgamated limestone units. Also, sharp based grainstones can be seen to cut into, or pass laterally into, muddy packstones lacking evidence of high-turbulence events. These muddy shell beds appear simply to represent in situ, time-averaged accumulations. Mud-filled shells and abundant concavo-convex brachiopods (Sowerbyella) that seem morphologically adapted to nestling in soft, fluid sediment indicate that background deposition took place on a quiescent, muddy seafloor. It follows, then, that the shells preserved in the bioclastic limestone beds also probably accumulated in a normally low-energy regime, but were episodically concentrated during storm-induced turbulence events. Accordingly, although mud was probably deposited during times of quiescence, it is likely that net mud accumulation was insignificant due to the tendency of mud to be stripped from the seafloor during storms.

SUMMARY OF SEDIMENTARY PROCESSES

The Gestalt appearance of skeletal limestone beds in weathered outcrops is so different from that of the intervening mudrocks that it is tempting to assume that either two lithologies developed in markedly different depositional environments, or that the constituent shells of the limestone beds were imported from elsewhere. Indeed, the most obvious lithologic features preserved in the skeletal limestones suggest deposition in a high-energy regime, whereas the fine-grained character of mudrocks (especially massive mudstones) would traditionally be assumed to represent long, more or less uninterrupted, periods of quiescence. However, closer examination of the available evidence reveals a perhaps counterintuitive scenario of deposition, namely, that despite the dissimilarities in the appearance of the two lithologies, both record similar energy regimes. More specifically, evidence in both lithologies point to sedimentation under generally low-energy background conditions and episodic erosive scouring and rapid re-deposition of coarser sediments during storms.

The occurrence of large rippled bedforms, cross-lamination and rip-up clasts in the skeletal limestones, and lack of the same features in mudrocks, are readily explained by grain-size differences in the two lithologies. Simply stated, the physical properties of mud simply precluded the formation of the bedforms and obvious internal sedimentary structures: whereas thick, rippled beds can be formed from coarse-grained siliciclastics and/or skeletal debris, they obviously cannot form in mud, either soft or firm.

It appears that whereas the limestone beds were produced by the net accumulation of episodically and repeatedly reworked and winnowed skeletal debris, the mudstone-dominated intervals formed through the episodic stacking of siliciclastic mud layers, each of which was deposited during a single event of hydraulic disturbance. Further appreciation of the major controls on the formation of these units requires consideration of the significance of their temporal scope of accumulation.

TEMPORAL SCALES OF MUDROCK-DOMINATED INTERVALS VERSUS SKELETAL LIMESTONE UNITS

Determining the temporal scope and therefore the dynamics of sedimentation of ancient stratigraphic units at a sub-formational scale is problematic in the absence of geochronometric dates, particularly where the lithological characteristics of the intervals of interest differ significantly. It is possible to estimate, at the very least, relative differences in sediment accumulation rates and, we refer to the total time interval represented per unit thickness of strata as ‘time-richness’. A number of important features can help to constrain this. It is often possible to infer the scope of time-averaging based on taphonomic features and the taxonomic composition of biotas (Brett and Baird, 1993). We argue that shell beds in the Kope Formation represent substantially more net time per unit thickness on average than do the mudstones, despite the extensive compaction of these mudstones and its absence in the limestones (Fig. 13).

MUDROCK-DOMINATED INTERVALS

Constituent beds of thicker mudrock units are composed of a finite series of beds. For example, detailed dissection of five metre-scale mudstone intervals by Kohrs (2003) revealed between 15 and 20 resolvable individual beds per metre. Of these beds, the majority preserve evidence of incremental mud accumulation in discrete pulses of deposition:

(1) Intervals of barren, structureless to vaguely laminated mudstone and/or siltstone, up to a few centimetres thick, typically rest directly on thin shell hash beds and display burrowed tops. These sharply based calcisiltites commonly show minor grading and/or “lam-scram” fabrics, the latter indicating the maximum thickness of single-event deposits.

(2) Many beds contain, at the very least, rare articulated specimens of fauna with multi-element skeletons, indicating some degree of benthic oxygenation. Considering the large populations of burrowers and scavengers that would have been present on even a dysoxic seafloor, multi-element skeletal remains showing this type of preservation must have occurred within no more than a few days.

Thin fossiliferous beds containing well preserved faunal elements, such as graptolites, articulated trilobite carcasses and exuviae, and complete crinoids have been noted frequently (Fig. 11; e.g., Tobin and Pryor, 1981; Hay, 1981; Holland, 1993; Jennette and Pryor, 1993). Such obrution deposits indicate episodes of rapid mud deposition, the overlying sediments having accumulated in a few hours to days to prevent, or at least inhibit, dissociation of skeletal parts. In a few instances the rate of deposition in single events is demonstrably very high. For example, a 15 cm-long articulated crinoid stem was found preserved in vertical life position in laminated silty mudstone (Fig. 11E); in this case, it is clear that at least 15 cm of sediment was deposited during the single event in which the crinoid was buried. This is an exceptional specimen, but minimum thicknesses of many other single-event deposits can be estimated from incomplete segments of crinoids and trilobite exoskeletons extending through several millimetres of mudstone and siltstone. The wide geographic extent of such thin obrution beds strongly suggests mass mortalities on a regional scale, caused be rapid blanketing by flocculated muds following major storms (Kohrs, 2003).

If the total thickness of individual mudrock-dominated intervals is represented mostly by stacks of mudstone beds that were deposited during single events, then the bulk of their total thickness represents a very short interval of time

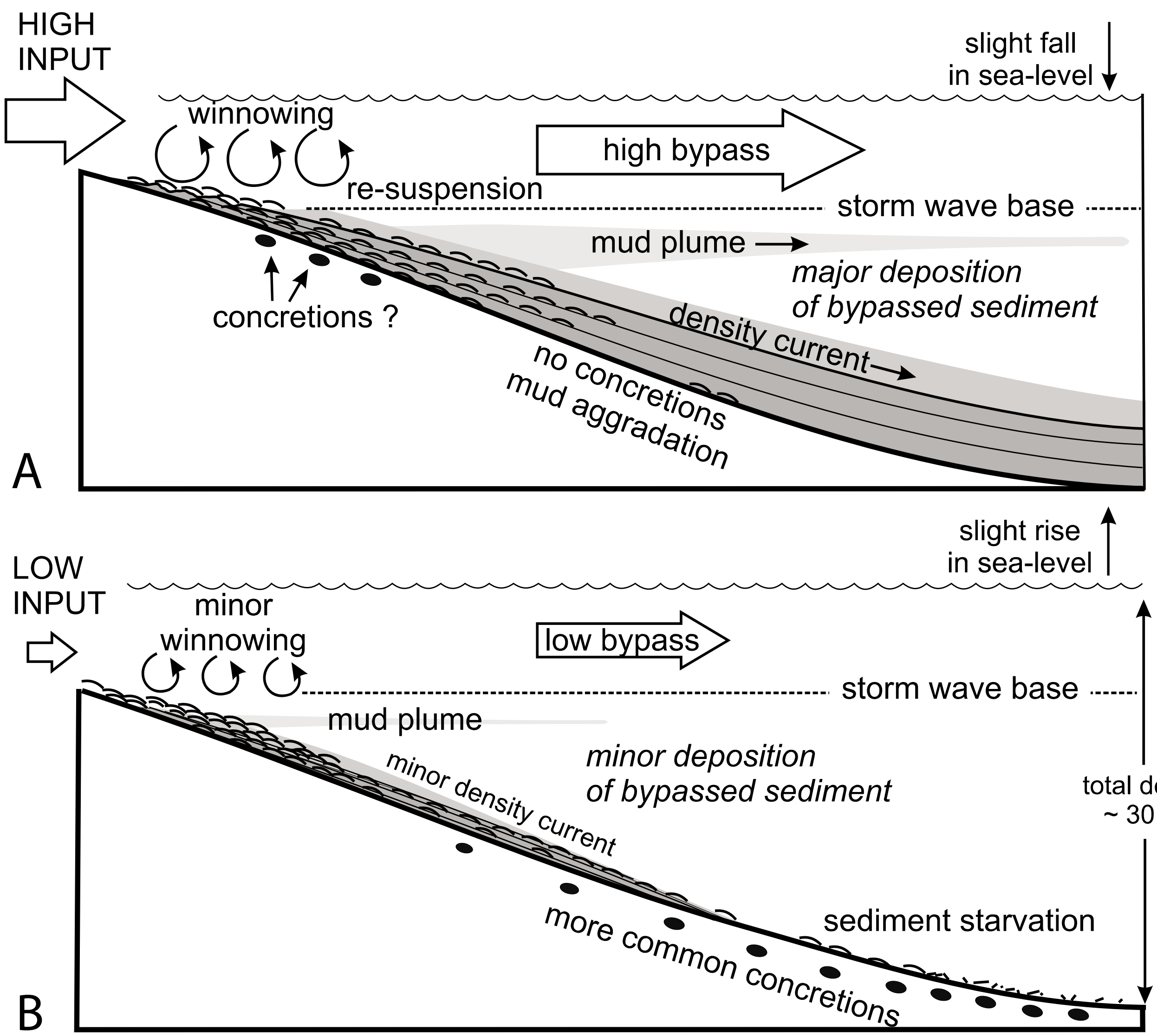


Figure 15. Two models of development of shell-rich limestone beds in mudrocks of Kope Formation. (A) Shell-rich limestones due to intensification of storm-wave winnowing. Constant to increased sediment input implies high rates of sediment bypass as a result of winnowing and fallout of abundant muds in down-ramp positions. Concretion formation is enhanced up-ramp where sediment-starvation stabilizes the base of the sulfate-reduction zone and leads to a shallow subsurface zone of alkalinity. (B) Formation of shell-rich beds as a result of sediment starvation and winnowing. Low input of sediment is matched by reduced sediment bypass, and shells are exposed to repeated storm disturbance. Minimal sediment accumulates down-ramp whereas sediment-starved conditions prevail in the basin. Low rates of sediment aggrad[

(Fig. 13). Most of the total time represented in these intervals must be in lacunae represented by the sharp, commonly erosive bases of these units and in the interspersed thin skeletal hash beds. But even in such accumulations, only local, within-habitat time-averaging is indicated. Skeletal debris occurs in patches, stringers and scattered lenses within mudstone intervals; in many cases these appear to represent local concentrates of fragmented bryozoan remains derived from either single colonies or patches of colonies. Crinoid stem 'log jams' indicate current-related re-orientation and clumping of remains derived locally from uprooted crinoid thickets. The thin skeletal concentrations in the mudrock intervals commonly contain fragmented and re-oriented material but, unlike the cases in the thicker limestone beds, the bioclasts are not highly comminuted or corroded. The preservation of local thickets of crinoids in otherwise barren mudstone suggests time-averaging on scales of a few decades to centuries at most. Thus, the events may represent approximately century-scale severe storm events. Taken collectively, this evidence suggests that metre-thick mudstone intervals probably record hundreds to thousands of years at most.

SHELL BED-DOMINATED INTERVALS

In contrast to mudstones, the skeletal limestone intervals and their constituent beds of shell debris show abundant evidence for prolonged time-averaging under effectively sediment-starved conditions. These intervals are internally complex, preserving evidence of stacking, partial terminal reworking, and amalgamation of two or more distinct beds of skeletal debris (Figs. 13, 14); shelly beds thicker than about 5 cm represent laterally and vertically amalgamated collages of lenses, pods, and wedges of shelly debris and, in some instances, discontinuous lenses of mud.

Evidence for condensation and time-averaging within these shelly limestones has been emphasized by Holland et al. (1997) and Brett and Algeo (1999) and is summarized here (Figs. 13, 16). Most importantly, the limestones show mixtures of skeletal material of varied taphonomic grade, a significant proportion of this material being fragmented and abraded shells. Brachiopods in the limestones are polychromatic: ranging in colour from pinkish in fresh, unaltered shell material to blackened, especially in broken, corroded shells. These beds also contain mixtures of ecologically disparate organisms, including burrowing bivalves, soft-substrate nestling, quasi-infaunal brachiopods, and hard substrate-encrusting bryozoans, providing evidence for ecological scales of time-averaging (Kidwell, 1986, 1991a,b).

Mud clasts are more or less confined to the bases of the limestone beds. Many of these mud clasts are angular in outline and typically lighter in colour than subjacent mudstones, indicating that their source mud was sufficiently hard to allow brittle fracture, and probably indurated by early-diagenetic calcite cement. Encrusted, bored and/or mineralized hardgrounds occur on some bed tops, including those preserving rippled surfaces. Concentrations of phosphatic, pyritic and/or chamositic debris, as well as occurrences of rare, in situ, reworked concretions, indicates that the sediment deposition on the seafloor was inhibited for a sufficient period of time to allow the upper sediment column to be indurated by cementation as well as reworked.

The regionally traceable layers of in situ carbonate concretions or nodules subjacent to many of the thicker limestones in the Cincinnati-area (Figs. 12A–D), in contrast to their relative rarity in the more proximal deposits of the Maysville section, suggest a greater tendency of concretions to form in dysoxic, deeper-water environments. Only a small proportion (3 of 23; <10 %) of concretionary beds are not associated with overlying thick, skeletal limestone beds, indicating that there was a causal connection between the accumulation of thicker amalgamated limestones and the development of concretions (Brett and Algeo, 1999). In the Alexandria submember, for example, subjacent concretions occur in association with five of the seven major limestone bedsets. The remaining skeletal limestone beds preserve reworked concretions (Fig. 12C). Moreover, the frequency of 'underbed' concretions appears to increase toward more distal outcrops. These concretions are likely formed within a limited depth below the sediment–water interface where they required significant periods of non-deposition and/or repeated removal of accumulated sediment in order to attain diameters of ≥10 cm (Fig. 14).

Concretions appear to have preferentially nucleated on pyritized burrow-fills, in some cases accentuating burrow morphologies (Fig. 12B). Less commonly, they formed around clusters of faunal remains, including masses of current aligned graptolites; in these cases, $CaCO_3$ precipitation may have been favoured due to either the 'seeding effect' of hard parts or to the local generation of highly alkaline pore-water conditions that resulted from the microbially mediated decay of soft tissue (Berner, 1980; Brett and Baird, 1986; Raiswell, 1987; Mozley, 1995; Raiswell and Fisher, 2000). On the basis of Raiswell's (1987) mass balance calculations, it is probable that concretions formed very slowly, and that conditions required for their formation were probably met when a thin zone of microbially generated alkalinity at the base of the sulfate-reduction zone (associated with anaerobic methane oxidation) in the upper few centimetres of sediment. Stabilization of such a biogeochemical interface may have encouraged pervasive cementation to ultimately form concretionary bodies. Vertical stabilization of this alkaline pore-water zone would have, in turn, required dramatic and prolonged reduction in sedimentation rate (e.g., Brett and Baird, 1986; Raiswell, 1987). Concretions are less likely to have formed when sediment accretion was rapid and uniform (Fig. 14); because the constant, upward migration of the thin alkaline zone associated with a high rate of seafloor aggradation would have prevented pore-water HCO_3^- from reaching sufficient concentrations to trigger the precipitation of calcium carbonate cement at specific stratigraphic levels (e.g., Raiswell, 1987; Raiswell and Fisher, 2004).

In some cases the concretions form nearly interlocking layers, suggesting that the geochemical zone responsible for concretion formation remained stable for very long periods of time, perhaps up to several thousands of years. If so, the causal connection with overlying skeletal hash beds may be indirect, both reflecting stabilization of the sediment profile and sediment–water interface for extended periods of time and, in turn, the persistence of sediment starved conditions for several millennia.

The concretions undoubtedly formed penecontemporaneously with the skeletal hash accumulations. The presence of reworked concretions within the skeletal limestone beds clearly indicates an interval of time that included the formation and growth of the concretions, the exhumation of concretions from underlying sediment, and incorporation of the concretions into the nascent bed of skeletal debris. In addition, some concretions in these limestones are encrusted with bryozoans and crinoid holdfasts, evidence of yet more time involved in the generation of shell beds.

These temporal considerations suggest that the minimum time bracket for these shell hash beds can be estimated at 3–5 ky. This suggests that the complex shell beds are condensed or time-rich relative to the much thicker mudstones.

MODELS OF ACCUMULATION FOR SKELETAL DEBRIS–MUDSTONE INTERVALS

Existing models for the genesis of skeletal limestone units have viewed beds of concentrated shell debris as representing either of two types of deposits: allochthonous shell-rich deposits or parautochthonous shell accumulations. We evaluate but reject these alternatives and propose a hybrid model.

ALLOCHTHONOUS SHELL-BED MODELS

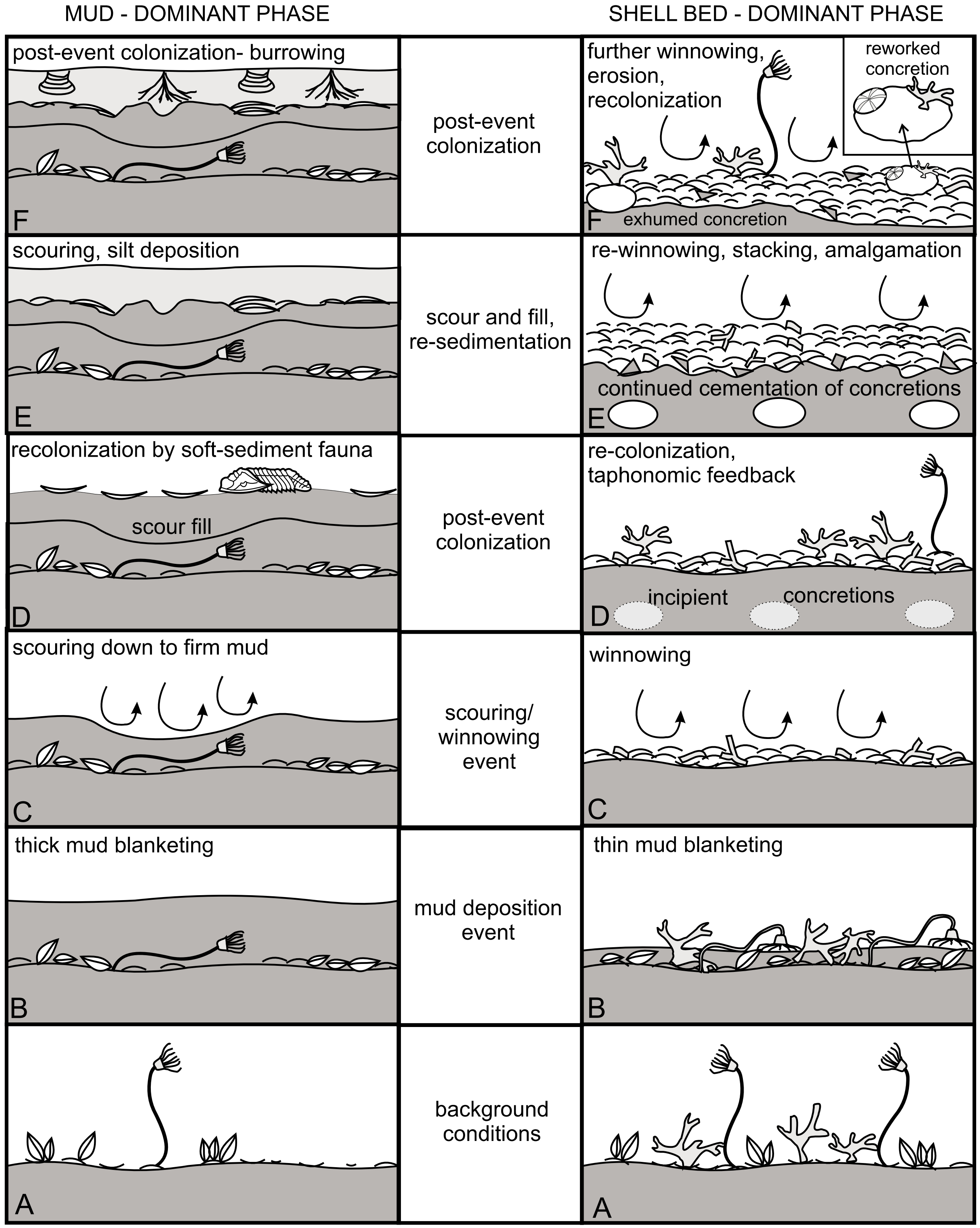
A few widespread shell beds composed of allochthonous skeletal debris, most notably the "black shell turbidite", have indeed been documented (Elmore et al., 1979; Prince et al., 1987). However, in shallow offshore environments, where most modern examples of skeletal accumulations have been documented, lateral transport of skeletal remains is rare and limited (e.g., Kidwell and Bosence, 1991; Kidwell, 2001a,b). Lithologic, taphonomic and faunal characteristics of shell beds in the Kope Formation argue against an allochthonous mode of shell accumulation. This includes: (1) similarities in the faunal composition of shell hash beds and adjacent mudrocks (Webber, 2002); (2) preservation of local, in situ faunal patchiness (especially in the overlying Fairview Formation; Miller, 1997; Barbour Wood, 1999); (3) preservation of regional faunal gradients within regionally traceable limestone beds; (4) preservation of articulated multi-element skeletal remains in limestones; and (5) incorporation of obviously locally derived clasts, such as reworked concretions, in basal lags of limestone beds that occur a short vertical distance above in situ, mudrock-hosted concretions of identical size and shape. The inferred volume and areal distribution of individual beds also mitigates against an interpretation as deposits of allochthonous shell debris because the shelly fauna within the source area would have had to generate enormous volumes of skeletal material. Using an average bed thickness of 5 cm, an area of 32,000 km^2 (a minimum value derived from mapping of beds), and an average siliciclastic content of 15% [derived from Ford's (1967) insoluble residue studies of the Kope and Fairview formations], a rough calculation suggests that a volume of approximately 1.6 x 10^8 m^3 of carbonate material would have been necessary to produce one limestone bed.

Relative to the study area, the nearest shallow-water region that could conceivably have supplied calcareous skeletal debris to form the limestones would have been the Lexington Platform located some 120 km to the southeast (Ettensohn et al., 2002). Here, the equivalent strata of Clays Ferry Formation comprise a mixture of mudstone and shell beds. Even if the platform could have been somehow swept clear of all carbonate material, this region could not have produced enough carbonate material to create even a single bed of skeletal debris in the Kope Formation. Moreover, there is no known transport mechanism for distributing shell debris rather uniformly over such a vast, low-gradient region. We can therefore confidently rule out the possibility of allochthony for the bioclastic constituents of the limestone beds.

PARAUTOCHTHONOUS SHELL-BED MODELS

Given that most, or all, of the skeletal limestone beds of the Kope Formation must represent parautochthonous deposits, there remain a few ways in which shell debris could have accumulated without significant lateral transport, namely: (1) concentration and long-term aggradation of shell debris on the seafloor by storm-related winnowing; (2) accumulation during long periods of sediment starvation (Kidwell, 1991a; Kidwell and Bosence, 1991); and (3) a combination of these two mechanisms.

Figure 16. Analogous seafloor processes during the mudstone dominant phase (MDP) and shell-bed dominant phase (SDP) of deposition; sediment accumulation and erosion occurs in both phases but with different effects. (A) Background conditions at the outset of interval in which skeletal debris accumulates during a pause in sedimentation. (B) A mud-blanketing event in which a thick layer is deposited in MDP (note obrution deposit with buried intact crinoid) and a thin mud layer is deposited in SDP. (C) Seafloor erosion during a storm. Scouring is effective in cutting down to firm muds in MDP but cannot erode through the relatively thick mud blanket or concentrate a significant amount of shell debris, whereas in SDP winnowing removes thin mud blankets and aggregates shelly debris buried by several previous events. (D) Post-event redeposition and colonization. In MDP relatively thick silt/mud layer buries scoured surface and muds are colonized by 'snowshoe strategist' brachiopods and vagrant trilobites. In SDP, minimal mud accumulation occurs and recolonization involves strong taphonomic feedback with exposed shells. (E) Scour and resedimentation. In MDP, storm erosion produces irregular scoured surface with gutters buried by silt layer. In SDP, scouring creates irregular erosion surface and firm mud clasts may be torn up. Soft muds are removed, shell debris is further stacked and concentrated, and a thin silt layer may accumulate on top of shell hash. (F) Recolonization. In MDP, opportunistic burrowers colonize storm silts producing Diplocraterion, Chondrites and other traces. In SDP, shell hash and exhumed concretions are colonized by hard-substrate adapted taxa (e.g., bryozoans, crinoids and boring organisms).


MUD - DOMINANT PHASE
SHELL BED - DOMINANT PHASE
post-event colonization- burrowing
F
post-event colonization
further winnowing, erosion, recolonization
reworked concretion
exhumed concretion
F
scouring, silt deposition
E
scour and fill, re-sedimentation
re-winnowing, stacking, amalgamation
continued cementation of concretions
E
recolonization by soft-sediment fauna
scour fill
D
post-event colonization
re-colonization, taphonomic feedback
incipient
concretions
D
scouring down to firm mud
C
scouring/ winnowing event
winnowing
C
thick mud blanketing
B
mud deposition event
thin mud blanketing
B
A
background conditions
A

Two critical aspects of the depositional dynamics recorded in Kope strata are that the deposition of both mudrock and skeletal limestone beds (>5 cm) involved storm processes, and that the laterally persistent units of skeletal limestone units are significantly more condensed or time-rich than mudstone intervals. In view of these considerations, the simple accumulation of skeletal debris as swell lags or winnowed products of single major storms (see Brenner and Davies, 1973) can be ruled out as a significant factor.

At least two plausible explanations remain for how these shell-rich limestones might have formed as autochthonous deposits. First, it is possible that the limestones represent long intervals of time characterized by increased winnowing and nearly complete sediment bypass. If so, the limestones could reflect either: (1) increased storm-wave influence on the seafloor as a consequence of a drop in sea level or aggradation of the seafloor into a shallower water zone (Jennette and Pryor, 1993); or (2) periods of increased storm intensity (Holland et al., 1999; Webber, 2002). As suggested by Brett and Algeo (1999), a second possible explanation is that the genesis of skeletal limestones in the Kope Formation might have involved siliciclastic sediment starvation as per the r-sediment model of Kidwell (1986). Evidence presented herein suggests that, at least in limited portions of the Kope Formation ("metre-scale cycles"; Jennette and Pryor, 1993; Holland et al., 1997), seafloor conditions recorded by mudrock and limestone units were not strongly differentiated in terms of water depth. Indeed, quantitative studies of fossil assemblages in synjacent mudstone and limestone intervals (Webber, 2002) indicate that both phases of deposition occurred at similar water depths. Although the proportion of mudstone to skeletal limestone is inferred to be lower in shallower-water facies, both mudrocks and skeletal limestones occur in deep-water and shallow-water facies alike. Hence, the processes that generated alternating shelly limestone and mudrock cycles must have operated somewhat independently of depth. The notion of each metre-scale cycle represents periods of shallowing, in which the seafloor was more severely and frequently affected by storm waves, can therefore be effectively ruled out.

We cannot completely discount the interpretation of Holland et al. (1997, 1999) that increased storm intensity was the primary formative mechanism for limestone units. However, the idea that increased frequency and intensity of storm activity greatly favoured the accumulation of shell debris over mud fails to explain some important features, such as the numerous observations demonstrating that events of storm-generated seafloor disturbance recorded in the mudrock-dominated intervals might have been as frequent and intense as those represented in the skeletal limestone units (Fig. 15). It follows that apparent lack of evidence for storm disturbance in the mudrocks does not necessarily mean that their environment of deposition was rarely affected by storm processes as is commonly assumed. Rather, it may well merely be a consequence of the low degrees of contrast in colour, texture and mineralogy, which obscures key features. If skeletal remains, commonly the only material coarser than clay or silt that could have been reworked and/or concentrated on mud-dominated seafloors, were scarce, it is unlikely that the mud-on-mud contacts between storm-deposited mud layers would be recognized in the resulting mudrock (see Tsujita et al., 2006). Thus, we infer that storm processing of sediments was ongoing during deposition of both mud-rich and shell-rich sediments, and that shell beds simply display the evidence more prominently merely because of their ability to preserve evidence of storm disturbance by their more heterogeneous sedimentary fabric (Fig. 15).

We argue further that the seemingly intuitive notion that shelly limestones represent high-energy conditions whereas mudstones represent low-energy conditions, is not entirely correct. Our observations indicate that quiescent depositional conditions prevailed for most of the time represented in the shell-rich limestones and that episodes of storm reworking simply overprinted the 'background' fabric. Conversely, mudstone depositional intervals were not purely low energy either, but were episodically affected by strong current and wave activity generated during storms.

Thirdly, generation of shell beds simply by winnowing alone (i.e., without a concomitant reduction in sediment supply) requires the bypass of enormous volumes of fine-grained sediment (Fig. 15). Increased storm frequency and intensity would be expected to increase, not decrease, sediment influx to the depositional basin. Bypass of even larger amounts of sediment would have been required to create thick shell beds. Hence, winnowing itself cannot account for the formation of thick beds of skeletal limestone.

Shell abundances in the mudrock intervals indicate skeletal material must have been very scarce in the original seafloor mud, certainly less than 5% of the volume of the sediment. One might speculate that once-abundant shells were preferentially dissolved in shales relative to the limestones due to differences in pore-water chemistry, and were effectively erased from the sedimentary record. However, the evidence at hand does not support this notion: the mudrocks are calcareous, their contained fossils are pristine, and the calcitic faunal remains are typically better preserved than in the limestones. Furthermore, even though remains of aragonite-shelled fauna (bivalves) are preserved as molds, their details are sharply defined, indicating that the shells must have dissolved long after burial. Thus, densities of shells in the mudrocks appear to provide reasonable estimates of their original densities. Taking into account a 50–80 % decrease in bed thickness that would have resulted from mud compaction, it is likely that shell densities of mudstones are now higher than those of the original seafloor muds. Thus, it is improbable that skeletal debris beds could have been created by winnowing alone, because to produce the observed widespread shell beds several centimetres thick would have required the removal of tens of metres of uncompacted to slightly compacted muds, and it is inconceivable that these beds could represent single, intense, events of erosion coupled with winnowing.

Even if winnowing were an ongoing process during constant mud influx (as opposed to an erosion-based scenario), the same volume of sediment would have passed through the environment, ultimately accumulating in deeper water settings. In other words, a comparable volume of sediment, including both mud and silt-sized carbonate particles would have been deposited down-ramp from the amalgamated beds (Fig. 15). The tracing of individual amalgamated shell beds in outcrops along a proximal–distal gradient [based on faunal analyses of Miller et al. (2001) and Holland et al. (1997)] from Maysville to the Cincinnati area has revealed only a slight splaying of individual limestone bedsets and very minor increase in the thickness and frequency of internal mud layers. The lateral differences in sediment volume indicated in these correlations are so slight that they fail to even approach those predicted by the bypass model. Moreover, insoluble residues from capping packstone beds indicate that there was no significant increase in siliciclastic mud concentration across the outcrop belt (Kirchner, unpublished data). In the deep-ramp settings observed in core, the limestone intervals are, in fact, more condensed than those studied in the outcrop belt and are associated with abundant carbonate concretions.

The formation of these layers, of course, did involve some degree of winnowing. Direct evidence does exist for removal of several centimetres of mud at the bases of some shell beds, as exemplified by occurrences of reworked concretions. Gutters underlying calcisiltite beds that lack shelly fills and contain only thin veneers of reworked skeletal debris, but, this is clearly not enough sediment removal to account for the thicknesses of shell beds.

HYBRID MODEL FOR THE FORMATION OF SKELETAL LIMESTONE–MUDROCK CYCLES

The great lateral extent of the thicker, more complex, skeletal limestone bedsets of the Kope Formation suggests a forcing function that was more pervasive than storms. Moreover, diagenetic evidence, including mineralization of bioclasts, local hardgrounds and the presence of concretionary beds in close proximity to many of the thicker shell beds indicates a regime of reduced sedimentation during shell bed accumulation.

We suggest that the formation of a thicker shell bed required either or both, a significant increase in shell production, or a drastic decrease in siliciclastic accumulation. The following model combines aspects of previously proposed scenarios and, in particular, builds upon the insightful Jeram hypothesis of Seilacher (1985). Seilacher observed that shell beds on the south Indo-Pacific Island of Jeram accumulate in a stepwise fashion, each involving a period of minor mud deposition and soft-substrate colonization, and a later episode of winnowing and recolonization of shell gravels. In the latter phase, debris is stacked down onto an older shell pavement that armours the seafloor, forming a "reference horizon" and inhibiting further erosion.

Faunal evidence from the Kope Formation indicates that oxygen levels were sufficient, at least episodically, to render the seafloor suitable for colonization by benthic organisms. Even so, a considerable richness of benthic organisms could have developed only when oxygenation was particularly high and when the problems of sediment mobility and turbidity were mitigated. Storm winnowing probably increased substrate stability temporarily, but was itself insufficient to significantly reduce long-term accumulation of soupy mud. Evidently, erosion and scouring did occur within times of mud aggradation, as well as during shell-bed accumulation, but served mainly to re-suspend and re-deposit mud (Figs. 15, 16).

The formation of shell beds, although initiated by physical processes, was later significantly influenced by ecological factors. Reduced rates of sediment accumulation, associated with either winnowing or sediment starvation, promoted the stabilization of the seafloor surface, enhancing the potential for seafloor colonization by shelly benthic fauna requiring firm substrata for their establishment. Accumulation of skeletal remains from the first colonizers would have helped to pave and further stabilize the seafloor which, in turn, would have allowed still more organisms, particularly stenotopic, sessile, hard-substrate-dependent taxa such as cemented bryozoans and pedically attached brachiopods, to colonize the seafloor. Thus, taphonomic feedback (Kidwell and Jablonski 1983; Finnegan and Droser, 2004), combined with relatively low sedimentation rates, would have allowed a significant net accumulation of shell debris (Fig. 16).

In shallower areas of the Kope seafloor, few organisms, other than infaunal forms such as soft-bodied burrowers and some bivalves, could have occupied major tracts of seafloor during times of rapid mud aggradation. The exception to this was where 'islands' of storm-concentrated shell debris, patches of storm-deposited silt/sand or firm surfaces exposed by storm scour, facilitated colonization by epifaunal organisms. Conversely, during times of reduced siliciclastic deposition, rich communities of benthic organisms would have been capable of widely populating the seafloor. In any case, the establishment of shelly communities and the consequent accumulation of shell debris beds probably necessitated some degree of initial substrate-priming (sensu Tsujita, 2001) followed by a period of time characterized by low turbidity and/or improved oxygenation.

Once a layer of skeletal material had built up, sediment reworking during subsequent events of storm-generated seafloor disturbance would have further concentrated this material. Also, the bioclasts themselves could have enhanced seafloor erosion during events of turbulence by serving as 'tools' that abraded and helped dislodge pieces of underlying, more cohesive muds (see also Tsujita, 2001). However, as per Seilacher's (1985) Jeram model, buildup of a critical thickness of shelly debris would have eventually served to armour the seafloor against further erosion, allowing shell debris to stack downward onto the developing shell pavement during subsequent winnowing events. Elements of the shell pavement would have enhanced skeletal accumulation even further by providing desirable settlement sites for sessile epifauna that were otherwise unable to colonize the seafloor during episodes of mud deposition. Thus, the slight faunal differences between shell pavements and the intervening mudrock units probably record, at least in part, changes in community structure that accompanied increased substrate stability that, in part, resulted from taphonomic feedback (Fig. 16).

Occasional, very intense episodes of storm-generated disturbance were capable of reworking and laterally shifting significant volumes of skeletal debris in the upper levels of shell debris blankets, as indicated by such storm-related features as cross-bedding, grading and rippled bed tops (Fig. 16). Presumably these were the last large storms to affect the seafloor during a given interval of shell bed accumulation. Stabilization of a rippled bed top would have allowed the preservation of epichnial traces, in some cases enhancing the induration of seafloor sediments and ultimately producing a hardground. Many ripple-topped shell beds are draped by a thick layer of barren mudstone, signalling the onset of increased mud aggradation; hardground horizons are commonly phosphatized, recording severe sediment starvation that accompanied the development of a flooding surface. As indicated by the well-preserved hardground biotas on the tops of shell hash beds (Meyer, 1990), the accumulation of shell debris was probably terminated by rapid deposition of a mud layer that was too thick to allow complete removal by subsequent erosional events.

Even in the unlikely circumstance that sediment supply was drastically reduced, thicker shell accumulations produced by intensified storm winnowing should have recorded complementary relationship between deposits of proximal and distal portions of the depositional gradient. Reduced net mud accumulation in shallow water areas affected by bypass presumably would have accompanied increased rates of sediment aggradation in down-ramp sections via sub-storm wave-base fallout of winnowed/bypassed sediment. This does not appear to have been the case with Kope deposition. Rather, individual shell beds show little variation in thickness over the entire region, and a minimal degree of stratigraphic splaying is evident for mudrock units in basinward-thickening packages. Moreover, evidence from cores indicates that the shell beds in outcrop not only persist in distal ramp sections, but actually become thinner and grade into more compact nodular packstones in a basinward direction (Kohrs, 2003; Kirchner and Brett, 2003). The laterally extensive nature of shell-rich limestones across a proximal-to-distal gradient suggests that shell bed formation was favoured by a reduction in overall sediment supply that affected the entire area (Figs. 11, 16), possibly associated with minor rises in relative base level and sediment sequestering. A further test of this idea will require a more thorough understanding of the overall geometry of limestone and mudstone units across the ramp-to-basin profile. Study of subsurface relationships is in progress in order to develop that framework.

CONCLUSIONS

Most studies of mudrock deposition have dealt with foreland basin deposits proximal to source areas; as such, the depositional processes of distal mud deposits in epeiric sedimentary basins remain poorly understood. Intuitively, one might anticipate that the sedimentary dynamics in such regions would have been be characterized by periods of gradual and minimal mud accumulation and strong time-averaging of skeletal material, punctuated by rare winnowing events that produced shell lags from the time-averaged debris. Our observations, however, indicate that this did not characterize the Upper Ordovician Kope Formation of eastern U.S.A.

Our results strongly support the notion that the skeletal limestones of this unit are relatively condensed, or 'time-rich', whereas mudrocks, even in this distal area, accumulated as a series of abruptly and episodically emplaced deposits, and thus are 'time-poor'. This interpretation adds to the model of Brett and Algeo (1999) by interpreting the mudrock intervals in a context of storm activity. Evidently, both mudrocks and skeletal limestones in the Kope Formation were significantly affected by storm processing. Evidence of storm-related seafloor disturbance is indeed much easier to recognize in shell-rich limestone beds, because these can preserve large-scale bed forms, grading, cross-bedding and rip-up clasts but, it is not possible to preserve obvious storm-related sedimentary features when the sediment is almost entirely mud. Also, the occurrence of a larger number of storm beds per thickness in limestone-dominated intervals would, of course, be a predicted consequence, if, as we argue, the limestones record condensed intervals, while episodic beds would be spaced out in mudstones. In fact, given the bias against recognition of storm-generated sedimentary features in mudrocks, the abundant, if subtle, evidence for storm processing we observe suggests that storm episodes may have been as frequent during their accumulation as during the development of skeletal debris beds.

The genesis of skeletal limestone units in the Kope Formation appears to have required periods of siliciclastic sediment starvation combined with the episodes storm-related disturbance that affected more or less the entire depositional setting. This constitutes an alternative to models of shell bed genesis that invoke storm-related winnowing in this and other Cincinnatian units in the same region. Periods of normal to high net rates of siliciclastic sedimentation appear to be recorded in mudrock intervals, along with comparable frequencies of storm disturbance relative to limestone intervals. Mudrock intervals represent periods when siliciclastic dilution rates were too high to allow the significant accumulation of skeletal debris.

Further research will determine how fully this model explains the origin of limestone–mudrock cycles throughout the Kope Formation. We suspect that our conclusions may also apply to many other mixed carbonate–siliciclastic units, for example the Silurian Rochester Shale (Brett 1983), the Devonian Hamilton Group of New York (Parsons et al., 1988) and the Triassic Muschelkalk of Germany (Aigner, 1985). In this paper, we have deliberately avoided discussion of cyclicity and ultimate mechanisms that might produce alternating intervals of sediment starvation and aggradation, in order to focus upon processes that generated shell beds and mudstones. However, it is clear that these processes could record some degree of cyclicity.

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