EVENT BEDS AND SMALL-SCALE CYCLES IN EDENIAN TO LOWER MAYSVILLIAN STRATA (UPPER ORDOVICIAN) OF NORTHERN KENTUCKY: IDENTIFICATION, ORIGIN, AND TEMPORAL CONSTRAINTS

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INTRODUCTION

In recent years sedimentary geology has seen a resurgence of interest in detailed examination of outcrop-scale phenomena as a result of several important developments in the way geologists view the stratigraphic record. Notions of event sedimentation, cyclicity, and sequence stratigraphy have provided heuristic models for interpretation of individual beds, as well as stratigraphic successions and architecture.

A key development is the increased recognition of the highly episodic nature of sedimentary accumulation. Geologists have come to identify the probable signatures of ancient storms, turbidity currents, slumps, ashfalls, earthquake shocks, and other catastrophic phenomena (Seilacher, 1982; 1991; Clifton, 1988). Such unique, single events provide key time planes in local sections and, rarely, broader areas. Proximality of events (i.e., sedimentological features of event beds reflecting intensity of environmental disturbance) may also permit identification of onshore-offshore or shallow-deep water gradients in marine sediments (Fig. 1).

A second major advance in sedimentary geology is the recognition, or more correctly, the resurgence of interest in cyclicity of many scales within the sedimentary record. In particular, geologists have begun to recognize that a number of recurring, possibly periodic, processes may be recorded in certain sedimentary facies. The renewal of interest in the Milankovitch-band perturbations in the Earth's orbit and their effects upon climates has triggered a re-examination of many sedimentary sections for the possible presence of periodic cycles (DeBoer and Wonders, 1984; Gale and House, 1995). If small- and intermediate-scale Milankovitch-driven cycles can be recognized consistently in sedimentary rocks, it will have a revolutionary impact on stratigraphic correlation as well as the ability to determine the relative amounts of geologic time recorded in particular sedimentary packages. However, the Milankovitch cycles studies have had their cogent critics (e.g., Wilkinson et al., 1996, 1997).

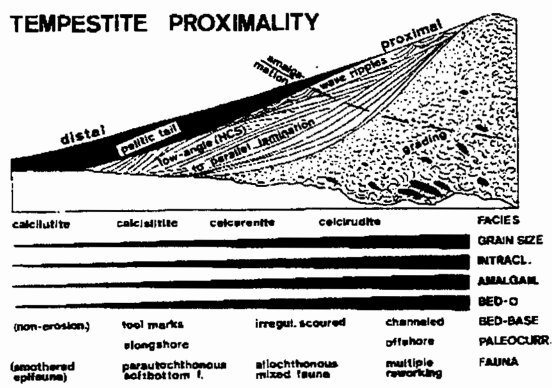

Figure 1. Proximal to distal spectrum of storm-generated deposits (tempestites). From Aigner (1985).

The Edenian-Maysvillian strata in the area of Cincinnati contain many limestone beds exhibiting features inferred to reflect rapid (i.e., event) sedimentation, and the ubiquitous rhythmicity of shale-limestone couplets has been interpreted to represent some type of cyclic sedimentation process. A number of authors have investigated event beds and small-scale cycles within the Kope and lower Fairview formations and associated units (e.g., Tobin 1982; Jennette and Pryor 1993; Holland et al., 1997; Miller et al., 1998). In this contribution, we will review the conclusions of these workers regarding the nature and significance of event beds and cycles in the Kope and lower Fairview formations and add observations and interpretations based on our own field studies. Our work along the AA Highway between Alexandria and Maysville has also permitted us to correlate many of these event beds and small-scale cycles over distances of ca. 80 km, and, hence, we are able to report on their lateral continuity and proximality characteristics for the first time.

EVENT BEDS

Event beds are extremely useful in correlating between sections of the Kope Formation. Recognition of specific marker horizons is facilitated by features such as unusual or distinctive faunal elements, trace fossil horizons, or taphonomic features. Sedimentary structures such as megaripples, gutter casts, rip-up clast layers, or beds of reworked concretions also provide distinctive marker horizons. Such distinctive marker horizons allow regional correlation of most of the thicker limestone beds within the Kope Formation and some portions of the Fairview Formation (Figs. 7-8, pp. 56-57, this volume). It should be noted that these limestones are the very beds which have been used in the past to recognize the caps or boundaries of small-scale cycles (e.g., Jennette and Pryor, 1993; Holland et al, 1997; their fig. 5, p. 100, this volume). Results of our correlations (2nd Brett and Algeo paper, this volume) provide strong evidence for the persistence of certain distinctive dm- to meter-scale limestone beds and bed bundles throughout the Cincinnati-Maysville region. In some cases, even single event beds such as distinctive calcisiltite with gutter casts or with other types of sedimentologic features can be traced over this distance.

Event beds that exhibit distinctive characteristics are highly useful in correlating strata within the Cincinnatian Series. This utility derives from the fact that event beds represent single, unique episodes of sediment deposition and/or deformation and, hence, are timelines. In the Kope Formation, these range from small episodes of deposition of silt and mud to large-scale, possibly catastrophic, seismic deformation horizons. In the following paragraphs, we describe some of the various types of event beds and their importance for correlation of Edenian and lower Maysvillian strata of northern Kentucky.

Tempestites

Storms produce a distinctive suite of sedimentary deposits that range from coarse, amalgamated skeletal debris beds to hummocky laminated siltstones and sandstones, to distal mud layers (Aigner, 1985). In some cases, particular conditions associated with a given storm bed may make it distinctive and usable for local or regional event correlation. This applies to certain coarse skeletal debris layers such as beds of edgewise oriented or shingled shells. In the Cincinnatian Series, beds of this type commonly contain edgewise *Rafinesquina* shells that, in some cases, are clustered in gutter casts (Fig. 2). At least three such

Figure 2. Edgewise coquina of *Rafinesquina* shells filling a gutter; Miamitown Shale, Galbraith Road exit of Ronald Reagan (Cross-County) Highway, Springfield, Ohio; X1.

horizons (called the "first, second, and third *Fracta* beds" by DesJardins, 1933, and the "first, second, and third shingled beds" by Hyde, 1959) have been identified and traced regionally in the Upper Ordovician (Maysvillian) Miamitown Shale and its lateral correlatives in the upper Fairview Formation of southern Ohio to northernmost Kentucky (Datillo, 1998; Fig. 10, p. 42, this volume). These particular event beds have permitted identification of timelines cutting across facies contacts, as they are present in lithofacies mapped as Fairview Formation in Kentucky, while the second shingled *Rafinesquina* bed was used by Ford (1967) to define the base of his Miamitown Shale at the type locality in southwestern Ohio. The shingled brachiopod beds appear to reflect extremely major storms or, possibly, seismic events (A. Miller, personal communication, 1998) that aggregated the flattish to gently concavo-convex brachiopod shells and oriented them in edgewise clusters over a large area of seafloor.

Many skeletal debris layers show evidence of intense reworking in the form of megaripples, graded bedding, and caps of fine laminated silt (Fig. 3). Such episodes of intense reworking are likely to have been brief, e.g., the duration of a major storm, although the sediments themselves may have accumulated over a much longer period of time. Such graded beds may be persistent through outcrops over a wide area. A particularly notable example of such a complexly graded shell bed was documented by Miller (1997) and is presently under detailed study by S. Barbour (see contribution this volume).

Several types of more distal tempestites have proven to be regionally extensive and traceable (Jennette and Pryor, 1993). These include (1) distinctive graded beds (e.g., one such layer in the upper Kope Formation that grades upward from shell hash to a thick hummocky laminated calcisiltite has been found in most outcrops within the Cincinnati area), and (2) beds of distinctive gutter casts and/or well-preserved hypichnial trace fossils (Fig. 4). Jennette and Pryor (1993) sampled a gutter cast marker bed in the upper Kope Formation at some 20 localities covering tens of square kilometers near Cincinnati (Fig. 5). They found a rather consistent northwesterly orientation to the gutters and suggested that they formed from gradient currents associated with a single storm. The gutters are normally parallel to one another and oriented parallel to inferred paleoslope.

The fact that gutters are typically undercut on one side and show very well-defined flute marks, tool marks, and trace fossils in their bases (Fig. 6) indicates that these scours were eroded into a firm, semi-compacted mud. Clearly, these scours would not be capable of preserving such features if the mud were not already quite firm at the time of erosion. For this reason, gutter cast beds probably do not represent a common product of storms. Rather they probably occur at diastems, at which repeated seafloor erosion removed surficial sediment layers down to the level of compacted mud. Moreover, in some cases there appear to have been multiple events of erosion and filling within the same gutter. Large

Figure 3. Megaripples in the "Z bed" of the Taylor Mill submember. Wavelength about 0.5-0.8 m. From Jennette and Pryor (1993).

Figure 4. Gutter cast showing tracks (T) and possible prod marks (P) on sole. Front of cast is on left; solid lines indicate internal laminae. Note that gutter cast is asymmetric in cross-section and that internal laminae slope upward to right; both of these features indicate that gutter was formed by a spiralling flow in the CCW direction (from perspective of photo; arrow). Lower Kope Formation; Rte. 445 roadcut, Brent, KY; X0.5.

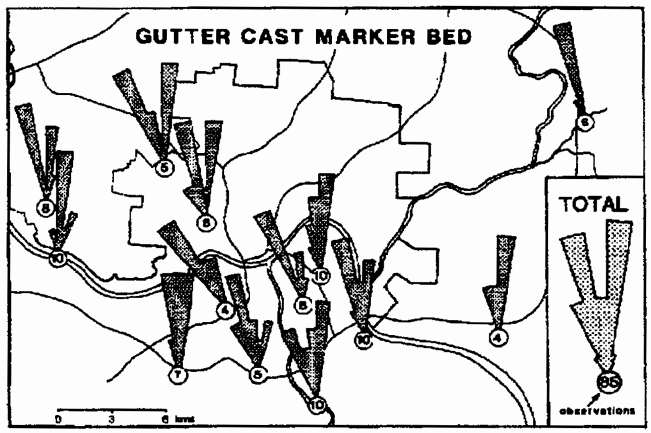

Figure 5. Rose diagrams of a gutter cast marker bed in the upper Kope Formation (Taylor Mill submember); note consistent northward orientation, toward the Sebree Trough (from Jennette and Pryor, 1993).

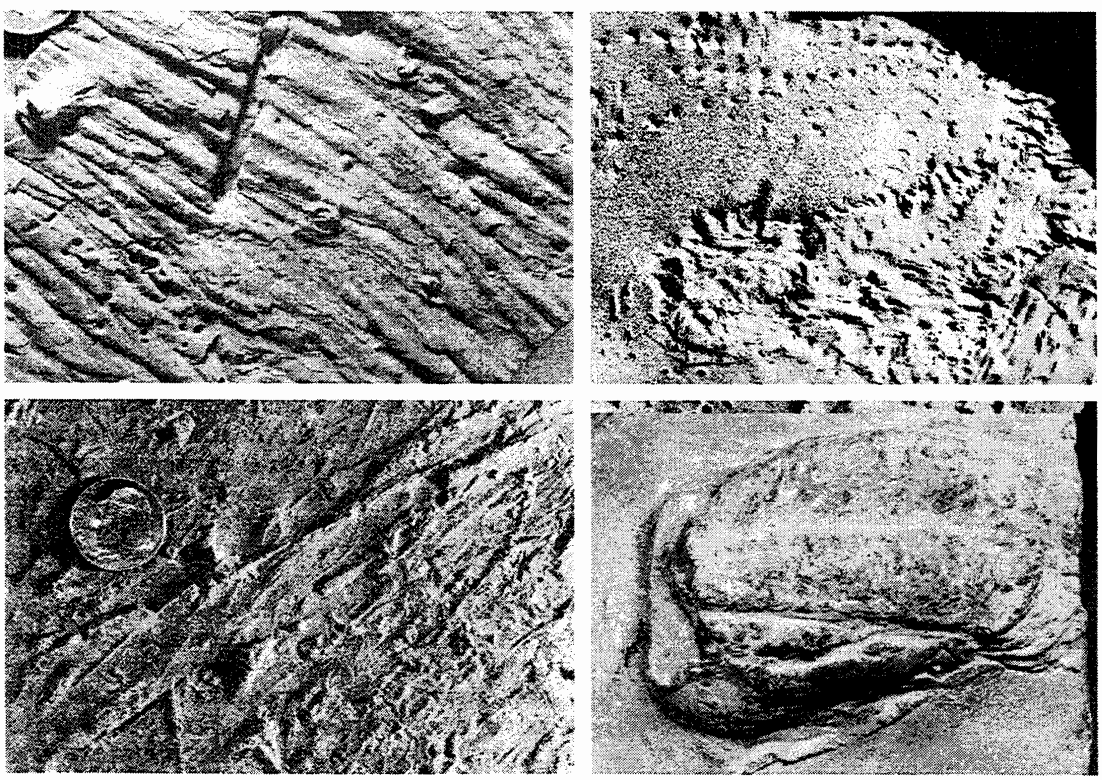

Figure 6. Bed-sole features, common in both gutter casts and tabular calcisiltite beds: (A) Flute marks. (B) Tool marks. (C) Well-preserved trilobite tracks. (D) *Rusophycos*, trilobite resting trace. All from the Kope Formation, Cincinnati area.

Rusophycus with deeply incised scratch marks occur in the bases of some gutters (Fig. 6D), indicating that there may have been some time separation between the scouring event and deposition of sediment on these surfaces.

Single event mud and silt layers are recognizable within mudrocks by a series of subtle but recognizable features. Some of these show slight color banding and or size grading from silt to fine mud on the scale of laminae (typically millimeters to a few centimeters). Such beds may overlie burrowed mudstone or shell-rich horizons or limestones, and the most diagnostic feature of these beds is the excellent preservation of fossils contained within them. Such beds may include obrution layers in which fragile, readily disarticulated fossils are preserved intact, indicating rapid or even live burial of the organisms. These are recognized taphonomically and may be traceable, at least locally. Such layers are not uncommon within the Cincinnatian Series and include the famous enrolled or prone trilobite layers often referred to as "butter shales." (Brandt, 1985; Shrake, 1997; and Hughes and Cooper, 1999). More common are beds of intact, unbroken or relatively little disturbed bryozoan colonies. Although they do not per force indicate instant burial, they do indicate relatively rapid sedimentation under quiet-water conditions, preventing the rather fragile branching bryozoan colonies from becoming pulverized. Such beds are frequent at the tops of small scale cycles or even some major limestone beds. Excellent examples of obrution events are provided by layers of crinoid column "log jams," i.e., parallel-oriented columns that probably reflect mass mortality and gradient current alignment during storms (Fig. 7). These layers appear to extend over several outcrops and record unusually violent events that uprooted and oriented masses of crinoids.

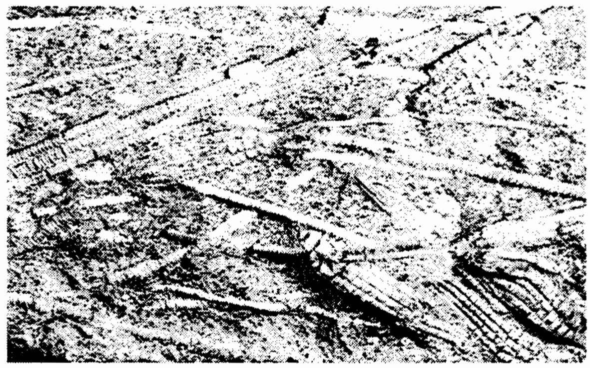

Figure 7. "Log jam" of oriented *Ectenocrinus* columns, note crowns intact; lower Kope Formation, location unknown; X1.

Trace Fossil Horizons

Likewise, certain horizons carry particularly well-preserved trace fossils, such as *Rusophycus*. These also can be found in more than one outcrop and indicate conditions particularly favorable to formation and/or preservation and of such traces. Rapid removal of surficial sediments during storm erosion might expose infaunal organisms such as worms providing a potential food source for predators such as trilobites. Traces showing interception of a horizontal burrow (*Planolites*) intercepted by a *Rusophycus* suggest hunting behavior on the part of the trilobites (see Brandt et al., 1995). Such foraging might have gone on particularly intensely following a storm unroofing of worm burrows.

Another distinctive bed (or set of beds) present in the upper Kope Formation contains an unique, bell-shaped morphotype of the trace fossil *Diplocraterion* (Fig. 8). This bed has proven to be similarly widespread throughout the Greater Cincinnati region. Evidently, the tracemakers colonized a storm silt layer very broadly and adapted to an unique set of conditions, perhaps including low oxygen, that favored lateral flaring of the u-tube. In a sense, these represent a type of epibole or biotic event horizon (see Brett and Baird, 1997, for further details and discussion).

Shell Pavements/Hardgrounds

Shell pavements (e.g., of brachiopods) and hardgrounds also provide correlatable horizons. In some cases, these rapidly buried surfaces have been correlated for tens of kilometers along outcrop strike. For example, Wilson (1985) described a bed of reworked and encrusted concretions in the middle part of the Kope Formation (Fig. 9). In some cases, the final generation of encrusters, including intact edrioasteroids,

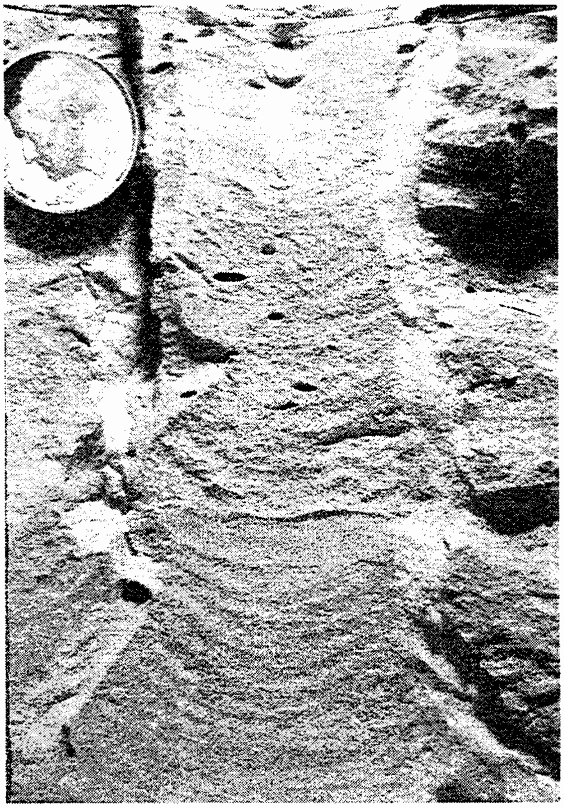

Figure 8. Side view of laminated siltstone/calcisiltite showing distinctive spreiten of *Diplocraterion*; upper Kope Fm. (Taylor Mill submember); Reidlin Road, Taylor Mill, Kentucky; X0.5.

Figure 9. Hardground surface on limestone from upper Kope Formation; note encrusting crinoid holdfasts and bryozoans; Montana Avenue exit of I-74; Cincinnati, Ohio, X1.

was preserved by rapid burial. This bed is apparently traceable from near Big Bone Lick to the vicinity of Batavia, Ohio (S. Felton, pers. comm., 1999). The bed displays much the same unusual characteristics over this area, suggesting that the smothering mud blanket was very extensive following a particular storm, resulting in mass mortality and burial on a regional scale. Another example of such a bed is a hardground covered that is presently under study in the lower Grant Lake Formation from the new Route 3071 cut near Maysville (Sumrall et al., this volume; Stop 3 on Saturday).

Beds Containing Unusual Sedimentary Structures

Beds containing unusual sedimentary structures have also proven to be traceable, at least within closely spaced outcrops. An example of this is distinctive millimeter ripples (Fig. 10) found in a few beds in the middle and upper Kope. Jennette and Pryor (1993) observed that they are penetrative, occurring along all laminae of a given bed and typically in the same orientation. The ripples may also change spacing and amplitude upward in a given bed in relation to changes in grain size (Jennette and Pryor, 1993). In the past, millimeter ripples were attributed to wave rippling in very shallow water; but in the Cincinnatian Series, these structures are common in presumably deeper-water facies such as the Kope Formation. Pflueger (1999) reviewed similar cases of microripples and concluded that they result from shearing within the sediment rather than being formed at a sediment-water interface by waves. Such shearing might, however, be induced by wave pounding of the seafloor or perhaps seismic shocking. In any, event we have found that millimeter-rippled siltstone beds

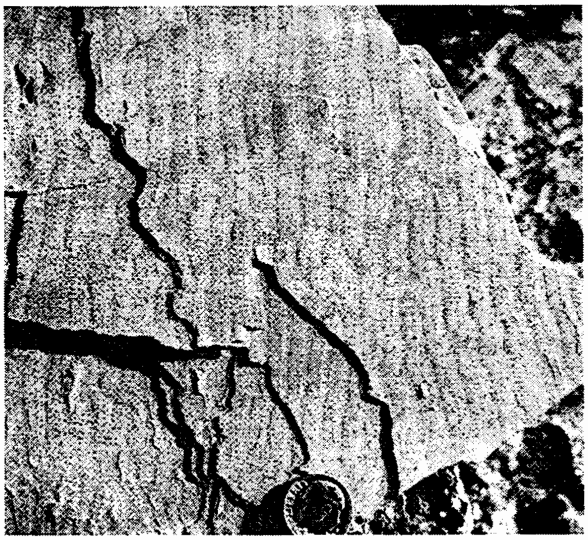

Figure 10. Millimeter ripples in siltstone from upper Kope (Taylor Mill submember); note that the ripples occur in parallel arrays on successive laminae of the siltstone; Alexandria, Kentucky; X1. From Jennette and Pryor (1993).

in the Kope Formation are laterally extensive over several outcrops and provide an unique type of marker bed.

Another unusual sedimentary structure that appears to require the interaction of several phenomena are "*Kinneyia* structures" (Fig. 11). These are shallow pits and grooves that generally occur in large numbers in a quasi-hexagonal closest packing arrangement on the upper surfaces of some siltstone beds in the Kope Formation. Pflueger (1999) presented experimental evidence that *Kinneyia* may form by the trapping of gas bubbles from organic decay, along flattened upper surfaces of truncated ripples that were coated by microbial mats. Agitation of the sediment, again possibly seismically induced, may cause lateral migration of bubbles and or dewatering and create these marks on the former bed tops . *Kinneyia* structures have been found in just a few beds of the Kope Formation and may provide another useful marker horizon.

A distinctive feature found at certain horizons in the Kope Formation are a series of parallel scratches often in an arcuate configuration (Fig. 12). By direct evidence these were tool marks formed by dragging of nodal crinoid columns over the seafloor. Wherever they have transcribed an arc, there is evidence of pivoting of the column around an anchored point. Possibly the heavier crown or holdfast end of the column was lodged in the sediment, and the stem was free to rotate back and forth in response to somewhat oscillatory currents. In some cases, bedding planes heavily marked by crinoid stem toolmarks have been found by splitting shaly calcisiltite beds. This proves that there was some separation between

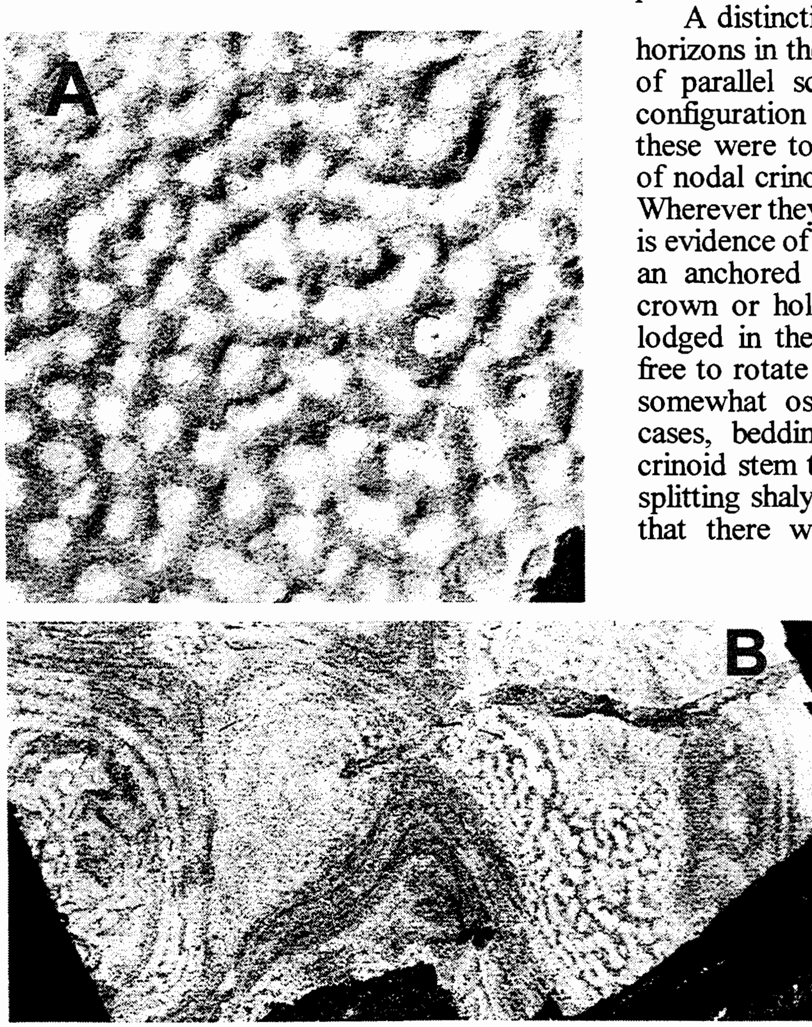

Figure 11. *Kinneyia*, enigmatic features on upper bedding planes of siltstones. (A) Slab showing typical appearance of *Kinneyia*; X1. (B) Siltstone with interference ripple marks; note *Kinneyia* structure only on flattened ripple crests, not in troughs; X1.5. Lower Kope (Brent submember), AA Highway Outcrop 27, near Fosters, Kentucky.

Figure 12. Crinoid stem drag marks; note arcuate character of grooves, probably due to columnals being rotated around a pivot point on soft silt; middle Kope Formation (Southgate Member); "White Castle site," Pioneer Valley industrial mall; Covington, KY; X0.75.

pulses of sediment deposition even within the event layers and during these times the crinoid columns rolled about on the seafloor prior to being entrained in the current.

Seismites

Recently, a number of authors have begun to recognize zones of widespread deformation that may be attributable to seismic shocking (Pope et al., 1997; Ettensohn, in review). These intervals are typified by beds of ball-and-pillow deformation that extend for tens to hundreds of square kilometers (Schumacher, 1992 and this volume; Pope et al, 1997). Careful observation of these deformed intervals demonstrates that they resemble beds known to have been deformed seismically, e.g., by liquefaction of muds and foundering of overlying coarser sediments ("seismites," *sensu* Seilacher, 1982). The larger deformed masses show overturned folds and flame structures, but most deformed zones do not show consistent orientation of fold axes (Pope et al. 1997; DeJong et al., this volume). Such evidence is consistent with deformation induced by liquefaction rather than by slumping. Basal surfaces of the pillows display small load casts, striations, deformed burrows and load casts, indicating deformation of semi-plastic muds by loading. Commonly, the deformation appears to have been concentrated in thickened portions of siltstone beds, which may represent submarine channel fills. A deformed channel-fill like feature that cuts some 2 m down into underlying strata is found locally along one of the ball-and-pillow horizons on the Rte. 3071 roadcut near Maysville (Stop 4 on Saturday).

Excellent examples of possible seismites are the ball-and-pillow layers of the upper Fairview Formation in the Maysville area (Fig. 22, p. 27, this volume). These have been studied extensively by Schumacher (1992; this volume), who has mapped the deformed horizons for about 700 km^2 in northern Kentucky and adjacent Ohio. These deformed strata were clearly formed on the seafloor (as opposed to intrastratally) because the upturned edges of disturbed beds are crosscut by overlying horizontal (non-deformed) skeletal limestone beds. Also, clasts of deformed sediment with load cracks occur within the overlying limestone bed.

Schumacher (1998; this volume) suggested that the three ball-and-pillow horizons in the upper Fairview Formation may also correlate with more extensive zones of convolute bedding in the correlative Garrard Siltstone tongue in central Kentucky. Pope et al. (1997) inferred that these and similar occurrences of widespread deformed horizons in the Ordovician of Ohio, Kentucky, and Virginia may have formed in response to large earthquakes, e.g., possibly with magnitudes in excess of 7 on the Richter scale.

More dramatic evidence for deformation, probably associated with some lateral sliding, occurs in a thin interval (ca. 1.0-1.5 m) in the upper Point Pleasant Ls. near Brooksville, KY (DeJong et al., this volume). Here, the presence of rotated blocks, brecciation, and small-scale thrusts indicates more severe deformation of indurated sediment, possibly accompanied by slumping. Angular discordance between the deformed and broken strata and the overlying limestones indicates that slumping was synsedimentary and occurred on the seafloor (rather than intrastratally). The lateral extent of this zone is presently unknown.

Pope et al. (1997) suggested that the Maysville ball-and-pillow horizons and related slumps might have been triggered by earthquakes in the Taconic Orogen or by movements of local basement faults associated with the Kentucky River Fault System. Numerous small faults cut the Ordovician strata in northern Kentucky, including some in the vicinity of the Rte. 3071 seismite beds (Grover et al, 1998; Stop 4 on Saturday), but these appear to be of late Paleozoic (Alleghenian) origin and probably are unrelated to synsedimentary deformation (DeJong et al., this volume). In any case, these dramatically deformed intervals provide excellent stratigraphic markers.

CYCLES IN THE KOPE AND FAIRVIEW FORMATIONS

The Kope and Fairview formations are divisible into bundles of limestone beds separated by comparatively shaly intervals at several scales. Such rhythmicity, or cyclicity, exists: (1) at a ca. 100-m or formation scale, between carbonate-rich units such as the Point Pleasant and Fairview formations and the intervening shale-dominated Kope Formation; (2) at a ca. 10-m or submember scale, in which each submember is composed of a basal 1- to 6-m-thick "Big Shale" and an overlying 2- to 6-m-thick bundle of limestone beds; and (3) at a ca. 1-m or bed scale, as reflected in shale-limestone couplets that are best developed within the limestone-rich upper portions of submembers.

These patterns hold remarkably well through most of the Cincinnatian Series, although cycles at the formation scale do not correspond exactly to formational contacts, and, hence, are probably best viewed as "subformational" in scale (see 2nd Brett and Algeo paper, this volume). For example, the Kope-Fairview interval consists of three broad shale-limestone cycles, the first from the Fulton submember (base of Kope Fm.) to the top of the Grand Avenue submember (Kope Fm.), the second from the base of the Taylor Mill submember (Kope Fm.) to the top of the North Bend submember (Fairview Fm.), and the third taking in the Wesselman submember and Fairmount Member of the Fairview Formation. Each subformational cycle grades upward from a shaly base to a more carbonate-rich cap, reflecting a shallowing upward trend.

The next smaller scale of cyclicity in the Kope is on the order of 5 to 20 meters in thickness ("decameter-scale cycles"). At this scale, bundles of subtabular, skeletal limestones are overlain by relatively thick intervals of shale-dominated strata capped by an interval of more closely bundled limestones. In turn, these larger cycles are made up of smaller 0.5-to 1.5-m-thick alternations of thick limestone beds and intervening shales, calcisiltites, and thin packstones (see Fig. 3, p. 5, and Fig. 16, p. 15, this volume). The meter-scale bundles of shale and thin- to medium-bedded limestone have been interpreted as small-scale (ca. "fifth-order") depositional cycles. Tobin (1981) termed these bundles "megacycles", while Jennette and Pryor (1993) interpreted them as shallowing-upward cycles, or parasequences. We follow Holland et al. (1997) and simply refer to them as "meter-scale cycles."

Decameter-Scale Cycles

We recognize eight large (5-20 m) or "decameter-scale" cycles within the Kope Formation (Fig. 13; see also CRS, Fig. 5, p. 51-52, this volume); these are equivalent to the informal stratigraphic submembers that we defined herein (see 2nd Brett and Algeo paper, this volume). Holland et al. (1997) used Fischer plots to break out a similar series of four "20-meter scale cycles" (numbered C1-1 to C1-4); the boundaries of the decameter-scale cycles (or submembers of Kope Fm.) defined by us coincide with the boundaries recognized by Holland et al., but in some cases (notably in C1-3) we recognized internal subdivisions of Holland et al.'s 20-meter stratal packages. Although these "decameter-scale" cycles differ somewhat in detail, they have some important features in common.

Defining cycle boundaries is somewhat subjective, depending upon the degree of symmetry in the sedimentary pattern. For completely symmetrical cycles the choice of cycle base would be arbitrary, whereas for highly asymmetrical successions the boundaries may be more clear. Thus, for proximal depositional sequences, the basal sequence boundary is a sharp lowstand erosion surface and a transgressive-regressive pattern is evident, whereas for shallowing-upward parasequences, flooding surfaces provide objective cycle (or hemicycle) boundaries. Decameter-scale cycles in the Kope Fm. actually show some aspects of both sequence and parasequence motifs (Fig. 14). For example, some of these cycles, e.g., the Grand View submember of the Kope, show the abrupt superposition of a bundle of amalgamated limestones with sharp facies dislocation (i.e., evidence for abrupt shallowing) over more distal shaly facies. In such cases, one might place a lowstand sequence boundary at this juncture. Others, however, seem to show a more gradual upward increase in the thickness and coarseness of "capping" limestone beds, and therefore, more resemble parasequences. These, too, are not completely asymmetrical and may show a minor retrogradational (upward-deepening) component. In this respect, decameter-scale cycles in the Kope Fm. closely resemble classic Klupfel cycles described by Bayer and McGhee (1985). However, all of the successions that we recognize as submembers of the Kope Fm. share the feature of

Figure 13. Decameter-scale cyclicity in Rte. 445 reference section, Brent, KY. Seen here are upper part of 16-m Pioneer Valley, 7-m Snag Creek, 8-m Alexandria (to just above dark band near top of outcrop face), and base of 5-m Grand View submembers of the Kope. Note meter-scale rhythms within each larger stratal package.

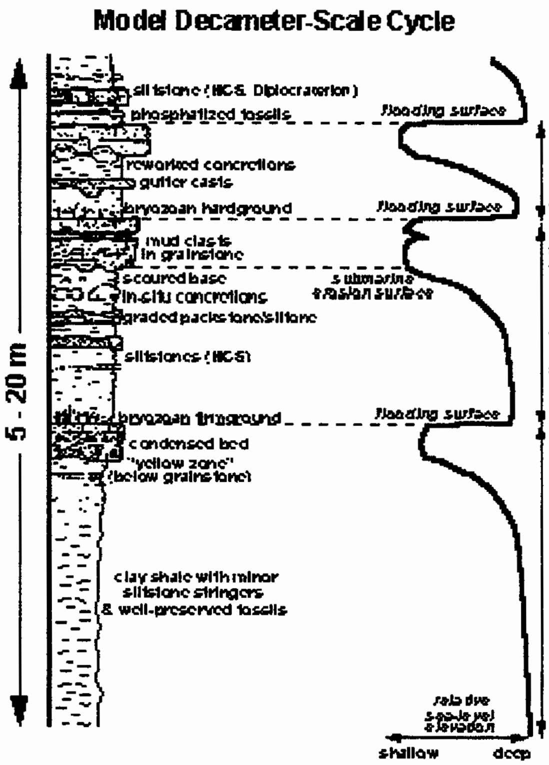

Figure 14. Model of decameter-scale cycle. Limestones are marked by scoured bases and rippled and burrowed calcisiltite caps showing evidence of condensation (firm- or hardground development). Typically, "meter-scale" rhythms become thinner and limestone beds more amalgamated upward within dm-scale cycles. Inferred changes in relative sea-level elevation and maximum flooding surfaces shown at right.

an abrupt (generally less than 0.5 m transition zone) of relatively thick shale and thin siltstones over bundles of limestone beds. Vertical faunal patterns documented by Holland et al. (this volume and in press) also show more abrupt shifts toward deeper water biofacies and more gradual drifts toward shallower water facies upward within their 20 meter cycles. In these respects, decameter-scale cycles consistently show a shallowing-upward or parasequence-like character. For these reasons, we have chosen to define decameter-scale cycles (and Kope submembers) as starting at the bases rather than the tops of the thicker, relatively pure shale-silt intervals (Fig. 14), making them similar to "shallowing-upward parasequences." However, we emphasize that a case could be made for recognizing minor, transgressive systems tracts near the tops of the cycles.

As thus defined, each decameter-scale cycle has a relatively sharp lower boundary at the base of a thick shale typically exceeding a meter in thickness (Figs. 13-14). The upper contact of the last thick limestone bed (packstone or grainstone) may be sharp and feature phosphatic staining, corroded fossil debris, hardgrounds, and other indications of an omission surface (Fig. 8). The transition into this lower shale-dominated portion of each decameter-scale cycle is typified by a thin bundle (0.1 to 0.5 m) of calcisiltites and/or packstones and typically shows excellent preservation of fossils at several levels. In particular, clusters of in-situ, well-preserved bryozoans are common at and near the tops of the carbonate bundles. It is noteworthy that several of the Kope cycles show the incursion of an unusual mollusc-dominated fauna at approximately this position of the cycle.

Such thin, transitional facies tend to be abruptly overlain by 1 to 3 meters of medium to dark gray claystone with few interbeds except for very thin beds or laminae of siltstone/calcisiltite. This clay shale interval typically forms approximately half of the thickness of the overall cycle. It is generally sparsely fossiliferous, but the occurrence of minor, pyritic thread-like burrows and a diminutive fauna of a few species of brachiopods, small bivalves, crinoids, and trilobites suggests dysoxic, stressed environmental conditions. Presence of graptolites and nautiloids in some of the mudrocks indicates an input of pelagic organism remains (Fig. 4, p. 50, this volume). The preservation of fossils tends to be very good, with at least partially articulated crinoids, rolled-up small trilobites, and intact graptolites. Such taphonomic evidence tends to support an interpretation of rapid and episodic accumulation of muds. Slight thinning or "ghosting" of some calcitic shells and plastic deformation of aragonitic mollusc shells indicates some early dissolution of carbonates. The upper portion of the thick, mudstone-dominated interval becomes increasingly silty and displays increased frequency and thickness of thin-laminated siltstones/calcisiltites and fossil-rich packstones (Fig. 14). Thicker (7 to 10 cm) lenticular, typically bryozoan-rich packstones occur near the tops of the decameter cycles.

The siltstone- and packstone-rich interval is generally sharply overlain by a thick (10- to 30-cm-thick), sub-tabular grainstone bed that bounds the overlying interval carbonate-rich interval, generally marked by upward coarsening and increasing bed thickness (Fig. 14); these may be equivalent to the "precursor beds" discussed by Brett (1995, 1998; see below). Bases of these beds are sharp and may show evidence for truncation of underlying shale and reworking of firm mud clasts or even carbonate concretions into the overlying basal unit. They may, in turn, be overlain by a relatively thick (0.5 m) shale.

Upward within each decameter-scale cycle, the proportion of shale decreases and limestone becomes increasingly dominant (to about 30-40% of section; Figs. 13-14). The upper carbonate-rich portion of each decameter-scale cycle is 2-3 m thick and commonly represents several (up to as many as ten) limestone-shale rhythms equivalent to the "meter-scale" cycles of previous workers (Tobin and Pryor, 1981; Jennette and Pryor, 1993; Holland et al., 1997; see below). Carbonate beds toward the tops of bundles, in particular, tend to show irregularly hummocky, stained tops that represent minor diastems. These are characterized by distinctly sculptured surfaces and commonly darkened phosphatic- or pyrite-rich crusts as

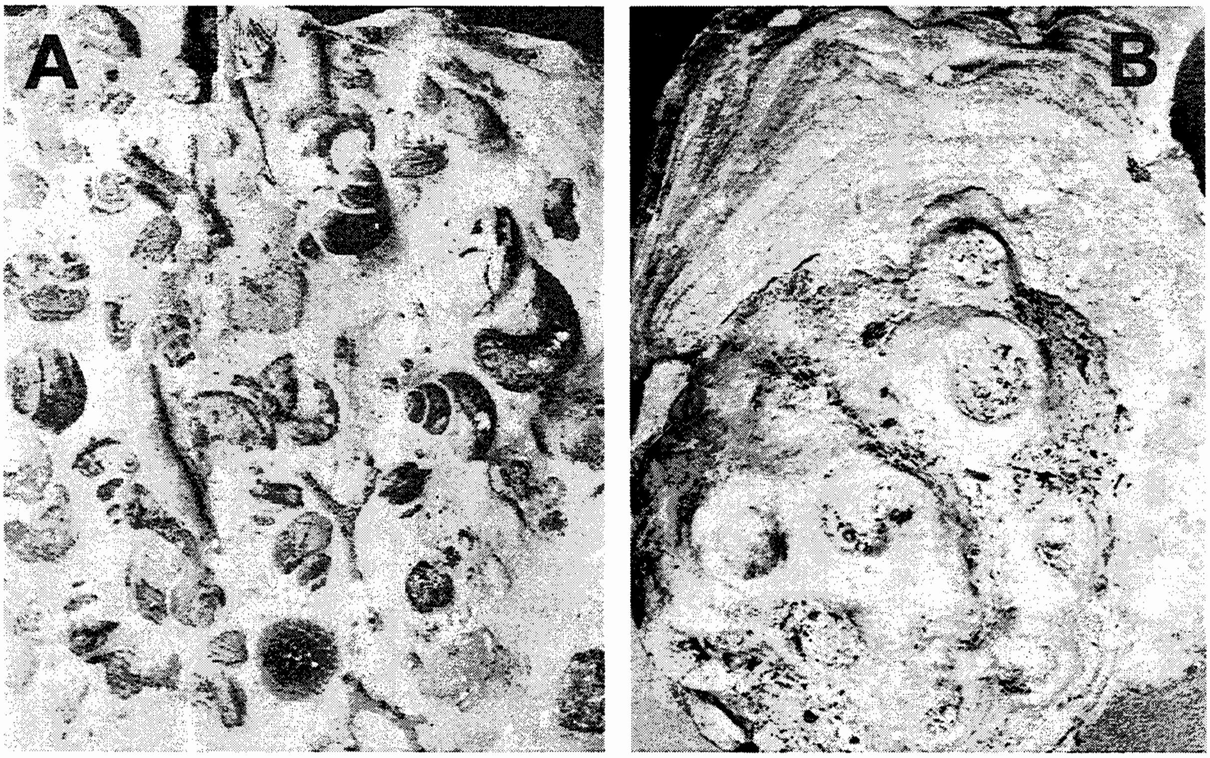

Figure 15. Carbonate nodules from mudstones in Kope cycles. (A) Non-reworked nodule developed in gastropod-rich mudstone. (B) Reworked siltstone concretion with encrusting bryozoans and crinoid holdfasts. From bed 15 of Pioneer Valley submember of Kope Fm.; "White Castle site" off Rte. 17, Covington, Kentucky.

well as minor borings and encrusting organisms (Fig. 8). The upper limestones may have associated concretionary "under-beds" or even reworked concretions (Fig. 15; see discussion below). Fossils in the thicker beds are typically small rounded fragments or whole valves of brachiopods, many of which are darkened or appear reddish in weathered outcrops, probably due to shell impregnation by limonite or pyrite (Fig. 6B, p. 53, this volume). Taphonomic features suggest that fossil hash in many beds has been subject to longer term reworking.

Temporal Constraints on Decameter Scale Cycles: The approximate duration of the decameter-scale cycles is difficult to estimate. At present, we recognize eight such cycles in the Kope Formation, but the second and third cycles (Brent and Pioneer Valley submembers) require further study; each could perhaps be further subdivided. The Edenian Stage, which comprises the Kope and lower Fairview formations, has a duration of some 3 to 4 million years. Thus, the eight decameter-scale cycles in the Kope Fm. have an average duration of ca. 400-500 ky. Obviously, there is no reason to assume *a priori* that the cycles are of equal duration; these numbers simply are meant to give an order-of-magnitude estimate for the time represented by these units. These calculations also assume that the lower sequence boundary, a subtle discontinuity within the Point Pleasant Ls., does not occupy a large fraction of the total time span of the C1 sequence (see Holland and Patzkowsky, 1996).

Genesis of Decameter Scale Cycles: As noted by Holland et al. (1997), the decameter-scale cycles are widely traceable, at least in the Tristate area. Our correlation studies show that these packages can be traced readily at least along depositional strike (Brett and Algeo, this volume). Because of this Holland et al. (1997) inferred that these cycles reflect allocyclic processes, probably eustatic sea-level fluctuations.

Tempestite beds within the decameter-scale cycles show a general increase in "proximality" upward within each package, from predominantly distal mud flows to increasingly greater proportions of hummocky laminated siltstones, graded shell-silt beds and, finally, amalgamated shell-hash beds toward the top (Fig. 1; Aigner 1985). This pattern is complicated by possible smaller scale cyclicity but indicates a general shallowing trend from environments below storm wavebase to those affected by frequent storms. Moreover, the faunal surveys of Holland et al. (this volume and in preparation) clearly demonstrate that widespread shifts in biofacies coincide with the decameter-scale cycles. The species associations are fairly consistent, suggesting the presence of environmentally zoned biofacies (Holland et al., in preparation). Regional studies and ordination of these faunas suggests that the biotas are, at least indirectly, related to depth. Low-diversity, deeper water, dysoxic biofacies typical of basin-center deposits occur in the shale-rich portions of the cycles. These give way upward to increasingly diverse faunas of shallower water aspect in each case. In summary, multiple lines of evidence suggest that the decameter-scale packages reflect widespread fluctuations of relative sea level on the order of several tens of meters.

In defining submembers, we have treated these packages as shallowing-upward cycles bounded by flooding surfaces. However, as noted, they are not wholly shallowing upward, and, in a sequence stratigraphic context, these decameter-scale cycles may actually represent distal manifestations of "fourth-order" sequences. The shaly intervals at the bases of decameter cycles ("Big Shales" of the Kope Formation) may be interpreted as early highstand systems tracts. The common appearance of a few thick and highly persistent siltstones/calcisiltites near the bases of the shales may indicate the onset of sediment progradation following prolonged sequestering in coastal areas. The upper portions of these intervals, which contain abundant calcisiltites and thin, condensed, and often channelized packstones, may signal a phase of more rapid sea-level drop and seafloor erosion that was not accompanied immediately by progradation of coarser sediments (the "precursor beds" of Brett, 1995, 1998). The tops of these 10-20 m cycles show minor evidence for progradation of coarser sediments and are interpreted as the late highstand or regressive phase of these "fourth-order" sequences.

Sequence boundaries, as such, are not readily identified, but could be placed at the bases of the first thick subtabular limestones. As noted above, these may show abrupt facies dislocations indicating abrupt shallowing and/or erosive loss of transitional facies (Fig. 14). The uppermost interval of each, consisting of alternating bundles of skeletal limestones and thin shales and having sharply defined bases, can interpreted as a distal representation of lowstand to transgressive systems tracts (TST). In these offshore facies the exact position of a transgressive surface is typically unclear. However, the uppermost portions of at least some of the decameter cycles show evidence of a retrograding pattern indicative of a TST. In three of Holland's four cycles, the presumed shallowest water faunas appear at or near the tops of the limestone dominated bundles. The upper portion of Holland's C1-1 cycle, however, shows an apparent retrograding pattern opposite to that of the other cycle tops. Thus, a deepening upward portion of this cycle may be indicated. Typically, the "caps" of the uppermost meter-scale cycles are more weakly developed than those below as might be expected in a retrograding pattern. The evidence for intense reworking of fossils and clasts and development of heavily burrowed firmgrounds near the tops of the limestone bundles (Figs. 8, 15) suggest a degree of condensation towards the tops of these cycles. This is also in line with interpretation of these portions of the cycles as minor TSTs. Hardgrounds, and thin beds of highly comminuted phosphatic debris at the tops of limestone bundles may mark a surface of maximum sediment starvation (Fig. 14).

Meter-Scale Cycles

The Kope Formation is characterized by a large number (>45) of small-scale (typically 0.5 m to 1.5 m thick) alternations of recessive weathering shales (mudstones) and ledge-forming, medium- to thick-bedded skeletal packstones and grainstones (Figs.

16-17). These smaller scale bundles in some way mirror the large 10 to 20 meter cycles: both are commonly composed of sharp-based, subtabular skeletal limestone beds (commonly amalgams of thinner beds), alternating with shale-rich portions that tend to exhibit an upward increase in the frequency of thin- to medium-bedded calcisiltites and minor packstones.

There has been a good deal of debate as to the nature and interpretation of these and similar lithologic patterns encountered frequently in mixed carbonate-siliciclastic successions (e.g., Tobin and Pryor, 1981; Jennette and Pryor, 1993; Holland et al., 1997). In this section, we will review the anatomy of these small-scale bundles, consider time constraints on their accumulation, and conclude with analysis of their genesis and significance. This discussion incorporates details from the excellent descriptive work of Tobin and Pryor (1981), Jennette

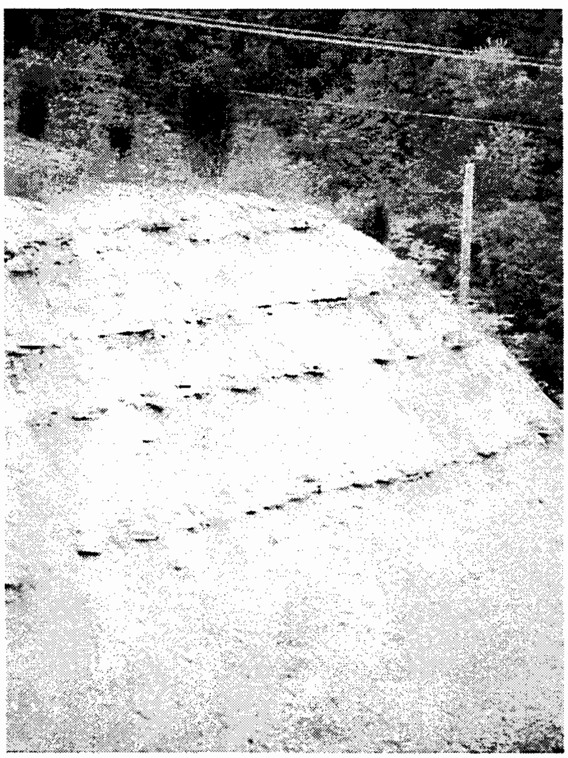

Figure 16. Meter-scale cycles in Brent submember of Kope Fm. Note sharp basesof limestone bed bundles, nodular underbeds, and rippled tops. Outcrop is "White Castle site" off Rte. 17, Covington, Kentucky.

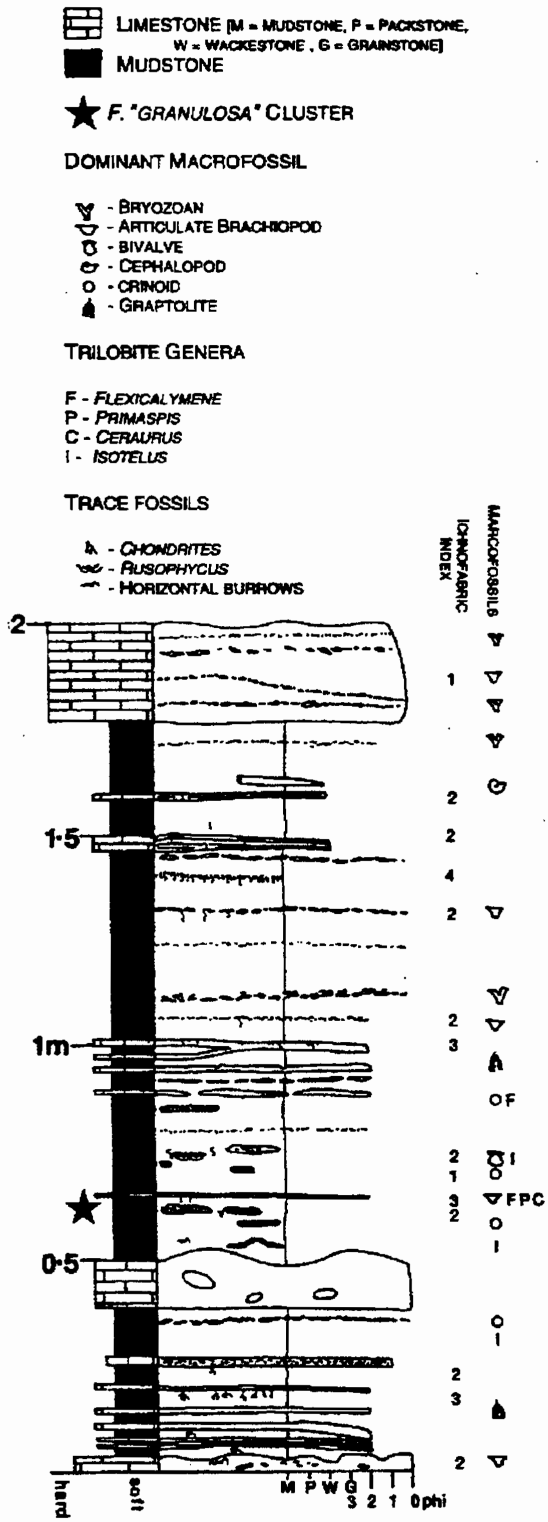

Figure 17. Stratigraphic log of a single meter-scale cycle in the middle Kope (Pioneer Valley submember; beds 15-16) at the "White Castle site." From Hughes and Cooper (1999).

and Pryor (1993) and Holland et al. (1997), as well as our own observations.

Shale Hemicycle: Generally, meter-scale cycles are composed of a shaly lower portion and a carbonate-rich upper portion, the latter consisting of one or, commonly, several amalgamated packstone or grainstone beds (Figs. 16-17). However, it is important to note that the portion of the meter-scale shale-limestone couplets identified as "shale" is actually more complex than this term implies and consists of a number of beds ranging from nearly pure dark gray claystones, to medium gray mudstones, silty shales, thin siltstones and shell beds. The mudstones are typically nearly barren of fossils, but may display thin laminae with fossil fragments, particularly brachiopods remains. Toward their tops, the shales may become more heavily fossiliferous and include fragmentary or intact bryozoans. Near the base of the mudstone interval, siltstones or calcisiltites are typically thin, planar laminated beds that display small trace fossils, especially *Chondrites*. Silty beds higher within the shale tend to be thicker and to exhibit hummocky cross stratification and laminated or burrow mottled ("lam-scram") ichnofabric. Such beds may display large well-formed *Diplocraterion* (Fig. 8), in addition to the nearly ubiquitous *Planolites* and *Chondrites*. These clearly represent post-depositional burrowers; however, some larger near-vertical burrows that disrupt or cause upwarped laminae within the siltstones appear to represent escape burrows. Bases of the calcisiltites are sharp and typically show thin lags of fossil debris that may be current aligned. The bases also commonly show prod and tool marks (Fig. 6). Some calcisiltites contain well-formed gutter casts, typically up to 10 cm in diameter across and 5 cm deep, with tool marks on their exteriors (Fig. 4). In some cases, discrete silt-filled gutters occur isolated from any continuous tabular bed at particular horizons. Silt-filled gutter casts tend to be especially common immediately below the capping skeletal limestone bundles of decameter-scale cycles (Fig. 14). Hummocky cross-laminated calcisiltites pass upward into graded packstone to calcisiltite beds. These show lag deposits up to several centimeters thick composed of graded skeletal material, e.g., crinoid ossicles, brachiopod fragments, and bryozoan debris (e.g., Fig. 6, p. 53, this volume). The tops of calcisiltite beds are normally gradational into the overlying mudstones. In some cases, however, the tops are sharp and may show oscillation or interference ripple marks (Fig. 10). Dewatering "runzel marks" or *Kinneyia*-type structures may be present on the tops of rippled silty beds (Fig. 11).

Mudstones, particularly within the Lower Kope (Economy Member), may contain horizons of small (2 to 5 cm thick and up to 20 cm long), ellipsoidal carbonate nodules or concretions (Fig. 15). In many instances, these nodules show a central core of a slender, cylindrical pyritic burrow fill. In rare instances, the nodules are laterally amalgamated or interlocked to form a semi-continuous calcareous layer (Fig. 15A). The nodules appear to have formed primarily within claystones but may show bedding features, including fossil debris layers. Such shelly laminae may be partly adherent to the lower or upper surfaces of the nodules or run through the middle of concretions. Nodules may also incorporate thin calcisiltite laminae. Some concretions contain oriented, well-preserved, non-compressed, graptolite fossils. A distinctive feature of the nodule horizons is that they tend to occur approximately 5 to 20 centimeters below thick capping limestones (Fig. 14; see discussion below). In rare instances, the concretions may occur immediately below or even within the skeletal limestone beds.

Limestone Hemicycle: The upper part of meter-scale cycles is carbonate rich, consisting of compact single beds, or closely spaced bundles of beds, of skeletal packstones and grainstones (Figs. 14, 18). Evidence of amalgamation is abundant, with amalgamated beds most commonly consisting of two to six discrete layers separated by thin (often <1 mm) shaly partings. These skeletal carbonates typically weather to slightly to strongly rust-stained ledges (probably owing to oxidation of pyrite) that project up to several tens of centimeters outward from the outcrop surface. Bases of the beds or bed bundles are characteristically sharp and may be undulatory with a relief of 5 to 10 centimeters (rarely more; Fig. 18). Irregular lumps or mounds of mudstone may project upward into concavities on the bases of the beds. The bed bases may show gutter casts, tool marks, or other sole features indicative of scouring and loading (Fig. 6). The beds themselves are composed of skeletal debris, particularly of whole and broken valves of brachiopods, bryozoan fragments, and crinoids ossicles. This fossil material may appear crudely, normally graded with a decrease in the average grain size upward through the thickness of the bed. Capping beds or bed bundles range from 5 to over 30 centimeters.

Limestone beds, especially thicker grainstones, commonly contain small to large (1 to 20 cm) clasts of buff-weathering dolomitic mudstone. These appear to have been derived from the immediately underlying sediment, which commonly also appears somewhat altered and buff-colored in a zone that typically penetrates 2 to 5 centimeters downward from the bases of the limestones (Fig. 18). In addition, a small number of thicker limestone beds exhibit reworked concretions that were evidently exhumed from underlying mudstones (Figs. 15, 18). The concretions are usually embedded within a matrix of coarse skeletal grains and may be bored and/or encrusted by fossils such as crinoid holdfasts and bryozoans, although clean, non-encrusted concretions are also present in some limestones.

Internally, the capping limestones commonly display crude normal grading as well as cross-stratification. Hummocky cross-stratification is less common within these coarser beds, while small-scale, planar cross-bedding is common. Clasts may be aligned along foreset beds within the thicker skeletal limestones. The thicker limestone beds are dominated by fossil fragments, which are commonly heavily abraded and rounded and may exhibit various degrees of staining manifested as dark reddish to blackish discoloration. It is noteworthy that the thickest beds are typically skeletal grainstones and that, counter to common belief, these are not composed of large intact valves but of finely milled fragments. Large intact valves occur most abundantly in thinner grainstone and packstone beds (Fig. 6, p. 53, this volume). There is also some differential distribution of fossil types between the thicker grainstone beds (representing higher energy conditions) and thinner grainstones and packstones (representing lower energy conditions): crinoid plates and small twiggy bryozoans are more abundant in the former, and large ramose bryozoans more abundant in the latter. However, this observation holds only for limited stratigraphic intervals, as there is also an overall change in the biotic content of limestone beds as one moves from the base to the top of the Kope Formation.

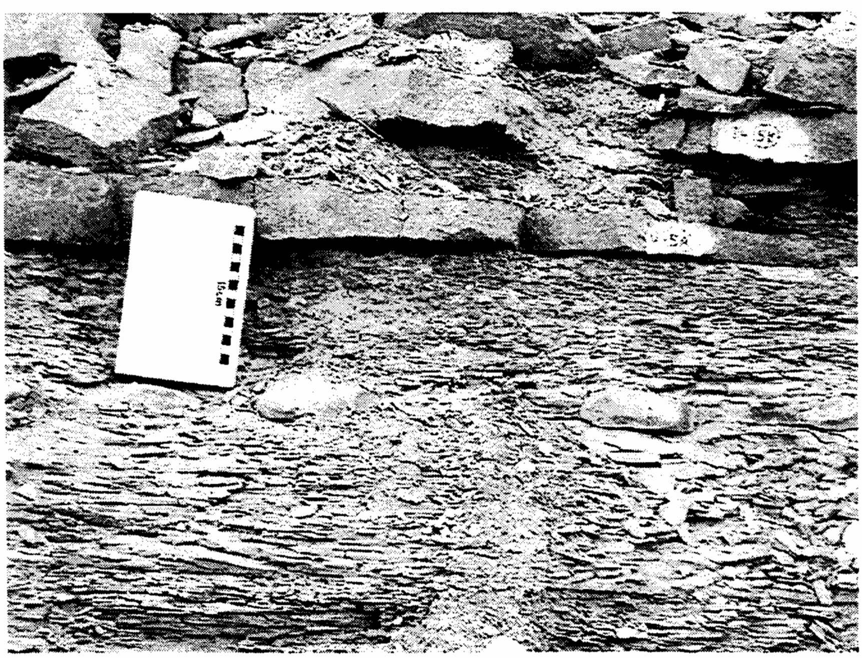

Figure 18. Profile of limestone bed (crinoid-brachiopod grainstone showing sharply defined base, nodular underbed, reworked nodules, and rippled top. Bed 15 of Brent submember, Kope Fm., "White Castle site," Covington, Kentucky. Cf. Figs. 16-17.

The tops of thicker limestone beds may be gradational with thin caps (typically less than one centimeter) of laminated muddy calcisiltite which are often intensely burrowed; in other cases, such caps are missing. The top surfaces of limestone beds may also exhibit nearly symmetrical megaripples with trough to crest heights of approximately 2 to 10 centimeters and spacing of ripple crests from 40 to 80 centimeters apart (Fig. 3). In many instances, the rippled or planar tops of the skeletal limestone beds were apparently exposed as firmground or hardground surfaces on the seafloor (Fig. 8). Such surfaces have a relief of 1 to 3 centimeters and contain linear horizontal depressions that represent partially exhumed current-enlarged burrows.

Temporal Constraints on Meter-Scale Cycles: As interpretations of cycle genesis hinge on the temporal significance of particular beds and microfacies, a critical question is "How much time do individual beds, bundles of beds, and cycles represent?" This question was considered by Brett and Baird (1993) and relevant points will be reviewed here.

The first issue relevant to the distribution of time within cycles is rates of accumulation of shale and carbonate beds within meter-scale cycles. A majority of the *thickness* of meter-scale cycles is taken up by the mudstone- and calcisiltite-rich interval. A common view has been that the mudstones represent gradual buildup of "background" sediments, while shell beds record episodic winnowing or importation of shells by storm waves and currents. However, a variety of lines of evidence suggest that this is not necessarily so, and that, in fact, the situation may be nearly opposite to this. Indeed, one may argue on the basis of empirical evidence that some of the shell-rich limestones (especially the grainstones) may represent the majority of the time taken up by the cycle as a whole, while the much thicker mudstones record minimal time.

The basal portion of the shaly hemicycle of most meter-scale cycles consists of fossiliferous mudstones with a few thin skeletal limestones. Small, refractory phosphatic and organic fossils such as scolecodonts and conodonts are abundant in these basal shales, while thin interbedded packstones commonly contain a "microhash" of finely comminuted, blackened (phosphatized?) shell fragments and ostracodes. Such evidence suggests that this portion of the cycle represents a relatively condensed interval.

Conversely, much of the higher mudstone interval is composed of discrete beds representing depositional pulses rather than "background sedimentation," as might be assumed (cf. Tobin and Pryor, 1981). Most of the mudstone is massive, structureless, and non-laminated, and lacks obvious burrows. In some cases, fine-scale lamination or micrograding is evident on clean weathered surfaces. Fossils are present on some bedding planes and include a variety of strophomenid brachiopods, small bivalves, ramose bryozoans, and trilobites, especially *Flexicalymene*. Entire, outstretched or rolled-up trilobites are found within the mudstones or at the junctions between the tops of the shell beds and overlying mudstones. Long segments of crinoid columns as well as delicate portions of crinoid cups and crowns are also common in mudstone intervals. Overall, the low density of fossils may not be attributable entirely to oxygen stress but to relatively rapid sedimentation as well. The occurrence of patches of well-preserved fossils, such as bryozoan colonies and crinoids, in sparsely fossiliferous mudstones indicates preservation of patchiness in the original benthic communities and an absence of time-averaging. Such evidence, again, suggests relatively rapid mud aggradation.

The second issue relevant to the distribution of time within cycles is the significance of taphonomic characteristics of the tempestite beds. Many of the skeletal limestones, especially the grainstones, are complexly amalgamated and might be described as condensed or time-rich deposits. Even single (i.e., non-amalgamated) tempestite beds that might be casually interpreted as the depositional record of a single storm event may, in fact, represent the end product of a substantial interval of reworking by multiple storms. Several lines of taphonomic evidence point toward substantial reworking, condensation, and "time enrichment" of storm beds and bed sets.

First, skeletal elements such as brachiopods exhibit wide variability in preservational grade with respect to degree of both comminution and phosphatization. Limestones are composed of variably articulated, disarticulated, and, in some cases, fragmented and abraded remains. The fact that many of the thicker skeletal grainstones appear to contain more highly comminuted fossil debris suggests longer periods of reworking for these beds. Phosphatization of shell material most commonly occurs at or just below the sediment-water interface under conditions of slow sedimentation, and this, too, is consistent with extended reworking of fossil debris.

Second, shell-rich beds contain remains of species that are also found in the enclosing mudstones, although much more sparsely and typically in much better condition. This suggests that the tempestite fossil assemblages are not transported but, rather, parautochthonous in origin, i.e., they represent skeletal debris reworked from underlying mudstones that is undoubtedly time-averaged but not transported laterally to any great extent.

Third, if tempestite fossil assemblages are indeed parautochthonous, then the relative density of fossils in these beds versus in the underlying shales becomes an important consideration. Specifically, limestone beds exhibit a fossil density that is typically several hundred-fold greater than subjacent mudstones, most of which contain only isolated shells and widely scattered thin shell concentrations. In this case, the interpretation of shell beds as simple winnowed storm lag deposits (e.g., Jennette and Pryor, 1993) would necessitate an extraordinarily high degree of winnowing and concentration of fossil debris. As with Devonian shell beds studied by Parsons et al (1988), it is evident that some tens of meters of muds would have to have been removed by winnowing in order to create shell beds as dense and thick as those commonly seen in the Kope successions. It is most unlikely that single storms processed such a large volume of sediment. Moreover, if shells had been recently released from enclosing sediment and concentrated during a single event, it is likely that many or most of them would remain intact, which is inconsistent with the degree of disarticulation, fragmentation, and synsedimentary mineralization characteristic of many of these beds.

Fourth, most tempestites are composed primarily of the remains of organisms whose skeletal morphology suggests that they were adapted to soft muddy substrates rather than nestling within shell gravels. This is particularly true of the abundant strophomenid brachiopods, such as *Sowerbyella*, which make up a great many of the Kope shell beds (Fig. 6A, p. 53, this volume). Many studies (e.g., Alexander, 1978; Richards, 1975) indicate that these concavo-convex shells were adapted to resting in rather soft, non-gravelly sediment, and rare in-situ occurrences of these species indicate that they did live in this manner. The fact that the remains of these organisms are packed tightly together in some shells beds would seem to imply repeated episodes of mud sedimentation, colonization and winnowing, as in Seilacher et al.'s (1985) model of shell bed formation (Fig. 19). In Seilacher's model, based on studies of modern shell gravels in the south Pacific island of Jeram, shell lags accrete through "event condensation." Much of the time they lie buried by a thin layer of mud colonized by organisms adapted to a soft substrate, but episodically storm waves winnow away the "background mud" causing accretion of a shell lag onto an older underlying pavement. Once such a pavement begins to form, it armors the seafloor and serves to collect many generations of shells. New episodes of erosion strip away muds down to the level of the older shell horizon and lower a new generation of shells down onto this surface. Rare, very high intensity storms may actually rework or resuspend the entire deposit, at least locally, and produce erosional effects such as the incorporation of mud clasts. The process may continue until a mud blanket (often deposited as a single-event mud tempestite) of sufficient thickness accumulates to permanently seal off the shell layer.

Fifth, the association of shell beds with carbonate nodules is further evidence of time-averaging. As noted above, these small nodules tend to lie within a few centimeters of the sharp bases of skeletal packstone or grainstone beds. We suggest that they are associated causally with this same sharp surface. Both are apparently the response

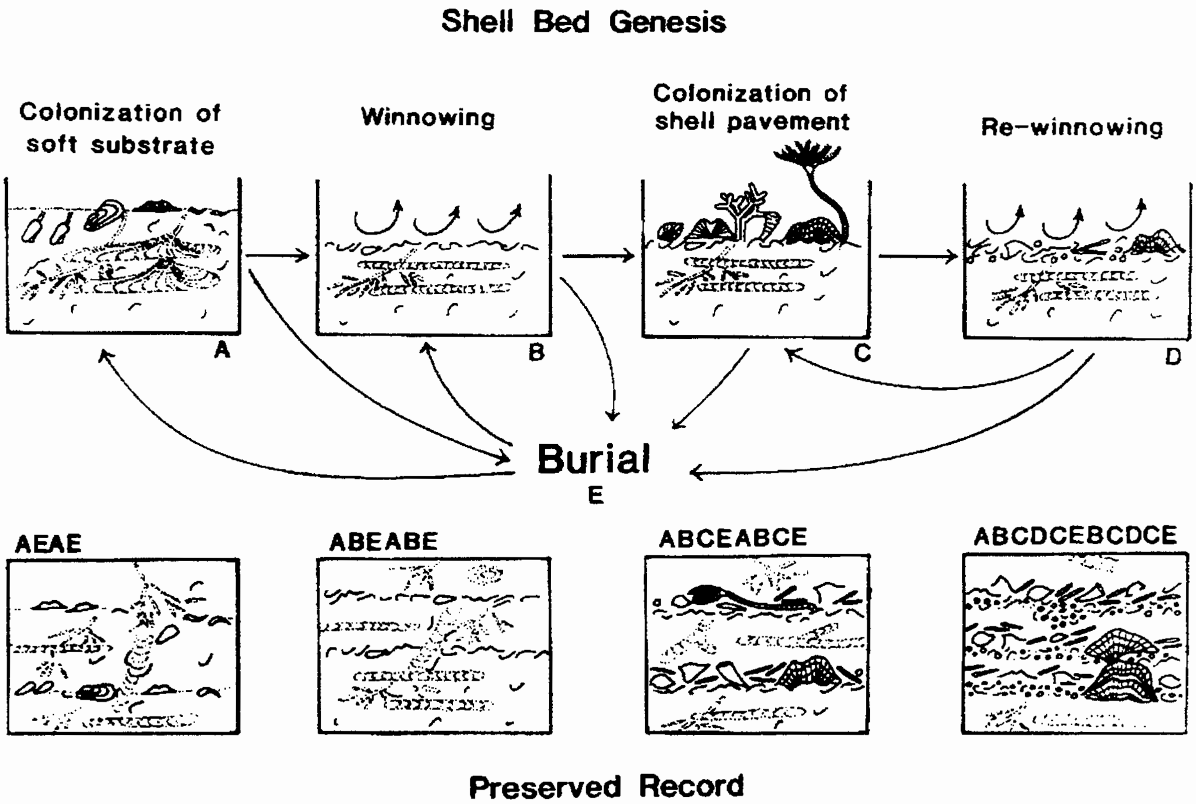

Figure 19. Jeram model of complex series of winnowing and blanketing events, ultimately yielding highly condensed, amalgamated shell beds. From Miller et al. (1988).

to long-term sediment starvation and/or erosion, which may have maintained particular increments of sediment within the zone of sulfate reduction for a sufficient period to allow growth of small nodules or semi-continuous concretionary limestone beds. Although the precise timing of such phenomena is difficult to judge, there is reason to believe that carbonate nodules require a substantial time period for formation. Mass balance calculations of Raiswell (1976) suggest that the radial growth of small concretions requires a period of time on the order of one to five thousand years. This implies a stable sediment-water interface well above, but spatially related to the concretionary horizons. Excellent candidates for just such a position are the sharp basal contacts of complex limestone beds that lie small distances above the concretionary horizons. In some instances, erosion later cut down through mud layers, exhumed pre-lithified carbonate nodules onto the seafloor, and incorporated them into shell-rich lag beds. Again, this is further evidence that shell-rich limestones may represent substantial amounts of time. Not only may the first of the shelly deposits have begun accumulating during times of slow sedimentation when concretions were forming in the underlying sediment, but later generations of shell debris came to incorporate the reworked concretions. Occasionally, concretions in lag deposits show evidence of differential erosion and/or encrustation on one side (presumably the upper) that indicates prolonged exposure of the exhumed nodules on the sea floor. Thus, concretion growth and reworking would have require a substantial amount of time, at least on the order of several millennia.

Sixth, development of bored and encrusted hardgrounds at the tops of some limestone bundles indicates a hiatus in sedimentation prior to burial by overlying mudstones. These hardgrounds are commonly marked by the appearance of specialized communities of organisms, e.g., edrioasteroids, which attached directly to the hardgrounds or to shells in stabilized shell pavements. In several instances, these final hard substrate communities were buried abruptly by pulses of mud, again, showing the obrutionary or rapid depositional character of some of the mudstones that overlie the tops of major shell beds.

The final line of evidence supporting prolonged build-up of the thicker shell beds is their lateral persistence. Whereas individual event beds, e.g., calcisiltites with distinctive faunal elements such as *Diplocraterion* burrows, may be traced for a few kilometers, many of the complex shell beds or shell-rich intervals can be traced for tens or hundreds of kilometers, both along and to some degree across depositional strike. Careful section measurement has revealed that details of bed sequencing ("stratigraphic fingerprints") are retained over long distances. Hence, there is reason to believe that the alternation of shale-rich and limestone-rich intervals reflected in decameter-scale cycles may well reflect an extra-basinal forcing function such as climate change or sea-level oscillation.

Yet in spite of long-term reworking, condensation, and erosion of many shell beds in the Kope Formation, such beds frequently exhibit a signature (or "overprint") of the single event responsible for final mobilization of the sediment. First, shell beds containing large, angular lithoclasts of mudstone are likely to represent such events, as these objects presumably could not withstand prolonged reworking on the seafloor and remain intact. Some of the clasts are bent, suggesting a semi-plastic condition at the time of burial. Second, well-preserved delicate fossils in some shell beds, such as complete bryozoan colonies, intact crinoid columns, and articulated trilobites, also suggest rapid burial. Third, the tops of many of the thicker shell beds display megaripples, the symmetrical shape of which indicates that they were formed by deep storm waves that reworked the sediment one final time. The fact that the ripples are preserved and sometimes show development of hardgrounds on their upper surfaces indicates that the turbulence took place in a normally low-energy environment, in which tractional movement of sediment was rare and out-of-equilibrium with normal conditions.

Genesis of Meter-Scale Cycles: Interbedded mudstone and limestone layers in the Kope Formation show certain regularities of pattern which suggest that they are, in fact, representations of a cyclic phenomenon. A simplistic view is that the limestone-shale couplets are merely random alternations of storm-influenced deposits and "background" mudstone deposition. Based on evidence discussed above, this "model" is insufficient to account for many observations. Specifically, the "shale" portions of the couplets demonstrably do not represent gradual background accumulation but, rather, show evidence, such as micrograded beds and obrutionary (rapidly interred) fossil horizons, that indicates accumulation as a series of episodic, rapid pulses. Indeed, the primary evidence of slowed sedimentation occurs near the tops of shaly intervals and is an indirect one: the formation of carbonate-cemented concretions within mudstone layers. Also, the limestone-shale couplets do not simply consist of a simple rhythmic alternation, but, rather, show regular stacking patterns of claystone, thin to thicker siltstone beds, packstones and fossil-rich packstones, and grainstones. Further, many of the limestones do not represent single-event storm beds. They frequently show evidence of local amalgamation of two or more beds, long-term reworking of bioclasts, and coherent lithoclasts and reworked nodules that indicate erosion down to levels of compacted muds or diagenetic concretions. Also, such amalgamated limestones are traceable, directly for up to a half kilometer in individual outcrops and indirectly for tens of kilometers by careful outcrop-to-outcrop correlation.

Tobin and Pryor (1981) were among the first researchers to specifically address the cyclic nature of meter-scale couplets. These authors interpreted them as fining (deepening) upward small-scale cycles, in which time-rich amalgamated shelly layers were overlain by fossil packstones, and these, in turn by claystones. Tobin thought that the mudstones were event beds and represented rapid deposition of muds associated with storms that brought up mud-laden currents from deeper portions of the basin. We concur that at least some mudstones were deposited rapidly, although the immediate source of the mud remains ambiguous. We also agree that many of the limestones are amalgamated units and, hence, are "time-rich," as inferred by Tobin and Pryor.

Jennette and Pryor (1993) came to a contrasting conclusion, namely, that meter-scale limestone-shale bundles in the upper Kope and Fairview formations represent shallowing-upward cycles, comparable to parasequences. In their view, cycle deposition commenced at flooding surfaces, on which deeper water mudstones were deposited, followed by a gradual upward increase in the thickness and proximality of individual event layers and decrease in shaliness as a function of overall shallowing. This trend was thought to culminate in the compact skeletal limestones that Jennette and Pryor interpreted as amalgamated proximal tempestites or storm winnowed shell beds. In addition, they demonstrated that meter-scale cycles and some of their component beds could be traced laterally for several kilometers in the Cincinnati area. This was an important observation that we herein extend to argue that cycles and individual beds can be correlated for at least tens of kilometers, supporting Jennette and Pryor's allocyclic interpretation for these beds.

Recently, Holland et al. (1997) reexamined a large number of meter-scale Kope and Fairview limestone-shale alternations. In the process, they documented much greater variability in the motifs of these cycles than had previous authors. Although a majority of cycles showed a predominantly shallowing-upward pattern, most cycles also showed some deepening-upward component. Further, some cycles were more nearly symmetrical, and a few were predominantly upward deepening. Indeed, only a few of the more than 50 cycles studied by Holland and his colleagues displayed the asymmetric shallowing-upward pattern typical of "parasequences," and the stratigraphic architecture of many is more reminiscent of "small-scale sequences." Another alternative considered, though not embraced by Holland et al., is that the alternations were not truly cyclic but rather random fluctuations of sea-level elevation or storm intensity.

We concur with Holland and colleagues that the meter-scale limestone-shale bundles are not merely random occurrences of storm beds but represent variably preserved and distorted cycles. Holland et al. (1997) argued that the cycles do not show regular, predictable changes in motif in relation to the larger decameter-scale cycles. However, they also recognized these latter cycles using Fischer plots that show regular stratigraphic variation in the thickness of the smaller, meter-scale cycles. Furthermore, we would note that, in at least some cases, the small-scale cycles show regular upward thinning (condensation) patterns as well as overall shallowing and backstepping patterns in relation to the larger cycles.

If the shale-limestone bundles do, in fact, represent regular oscillations in the intensity of some depositional process(es), what forcing functions were responsible for their genesis? Any explanation must account for several facts: (1) cycles or their component beds are regional in extent; (2) most show a regular increase in proximality upward within the shaly portion; (3) major limestone bundles extend basinward as thinning and fining tongues, while major shales thin in the opposite (shoreward) direction; (4) cycles thus show some degree of cross-cutting to facies; (5) many of the thicker limestones are condensed; (6) bases of most amalgamated limestones or bundles of limestones are sharply erosional and incorporate lithoclasts or concretions that indicate substantial erosion of underlying mudstones; (7) some limestone bundles are associated with underlying concretion horizons; and (8) many limestone bundles also exhibit sharp upper surfaces that, in some cases, have developed hardgrounds.

One possibility is that meter-scale couplets are the product of an oscillation in sediment supply caused by climatic factors, e.g., variable precipitation. Mud-rich and seemingly time-poor portions of the sections could represent times of enhanced runoff and terrigenous sediment supply, while shell-rich beds might record dryer and possibly warmer times of limited sediment supply. This model might explain some features in the Kope such as evidence for condensation in limestone bundles, but it fails to account for stratigraphic variation in faunal assemblages or proximality patterns of storm beds documented by Jennette and Pryor (1993). Additional factors seem necessary to explain these phenomena.

A second, and related, notion is that the cycles reflect climatic alternations between times of greater and lesser storm frequency and/or intensity. Such a mechanism would account for amalgamated limestone bundles as storm beds deposited during times of greater storminess and mud-rich intervals as aggradation of finer sediment during times of lower storm intensity (Holland et al., this volume). This mechanism accounts for changes in proximality within meter-scale cycles and requires no changes in sea-level elevation. If sediment bypass is invoked, it can also account for observations related to sediment starvation, such as early diagenetic concretionary layers. However, this model less readily accounts for other features of meter-scale cycles. For example, this model lacks a mechanism for development of diastems at the tops of limestone bundles. Moreover, the downslope thinning and gradation of limestone beds into nodular calcareous intervals is not explained: since this model invokes no temporal change in sediment supply, the pattern should be one of basinward thickening wedges of sediment rather than the thin tongues of nodular limestone actually observed.

A third possibility, favored by Jennette and Pryor (1993) and suggested by Holland et al. (1997), is that meter-scale cycles represent minor oscillations in sea-level elevation. Since most such cycles exhibit a mainly shallowing-upward pattern, they would then be interpreted as parasequences. As a slight modification of this view, we would suggest that many cycles take on the aspect of "small-scale sequences": the sharp erosive bases of limestone bundles may be small-scale analogs of sequence boundaries, and the limestone bundles thus resemble small-scale transgressive systems tracts culminating in flooding surfaces at their tops. Overlying shales thus represent relative highstand to regressive conditions. In this model, the strongly proximal nature of shell gravels in the thicker limestone bundles is explained by shallow-water conditions. Conversely, the mud- and silt-rich portions of the package reflect deeper water conditions and less frequent stirring of sediments. More importantly, the amalgamation of limestone beds and other indications of condensation may be explained as the result of low rates of sediment input associated with an initial sea-level rise following relative lowstands. This would explain the basinward thinning, rather than thickening (per the Holland et al. model above), of finer-grained carbonate bundles. In this model, limestone bundles in both proximal and distal areas would be expected to exhibit a response to basinwide intervals of sediment starvation. This model would also explain the sharp, diastemic tops of limestone bundles and the apparent abrupt transitions to mud-rich, seemingly deeper water facies, because these represent flooding surfaces followed by renewed aggradation of sediment. The increasingly silty character of the upper parts of shale hemicycles would reflect seaward movement of coarser-grained, more proximal facies. This model seems to account for most observed features of the Kope Formation, although it does not offer any specific mechanism to explain short-term sea-level oscillations. Nonetheless, the possibility of Late Ordovician glacio-eustasy cannot be dismissed, and there is strong evidence for such eustatic variation in the Hirnantian (latest Ordovician; xxxx).

Invocation of eustatic fluctuations (especially glacio-eustasy) invariably implies that the ultimate forcing mechanism for cyclic sedimentation might be orbital. However, in view of (1) the absence of a regular bundling pattern, such as the 5:1 precession:eccentricity ratio observed in certain other stratigraphic successions (e.g., DeBoer and Smith, 1997), and (2) the absence of sufficient temporal resolution to constrain the amount of time represented by individual decameter- and meter-scale cycles in the Kope Formation, further speculation on this possibility would be fruitless.

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