Chapter 9

Use of Event Beds and Sedimentary Cycles in High-Resolution Stratigraphic Correlation of Lithologically Repetitive Successions

The Upper Ordovician Kope Formation of Northern Kentucky and Southern Ohio

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1.   INTRODUCTION

Thick, lithologically repetitive successions often present a challenge to the stratigrapher attempting correlation of such units at a regional scale. The recurrence of just a few rock types generally inhibits correlation solely on the basis of lithologic criteria, and gamma ray, stable isotope, or magnetic susceptibility patterns commonly provide inadequate resolution or insufficiently distinctive signals for high-resolution correlation work. Yet reliable fine-scale correlations are required in order to address many problems in paleoecology, taphonomy, and process sedimentology (e.g., community gradients, proximality trends in tempestites). Under such conditions, establishing a high-resolution stratigraphic framework requires cm-scale analysis of individual sections to identify local marker horizons of distinctive paleontologic, ichnologic, taphonomic, or sedimentologic characteristic from which regional correlations can be built up. Critical to the success of this approach is the increasing recognition of the highly episodic nature of sediment accumulation, such that single geologic events (e.g., storms, turbidity currents, sediment slumps, ashfalls, and earthquake shocks; Seilacher, 1982; 1991; Clifton, 1988) commonly yield an event layer of regional extent.

The Kope Formation (Upper Ordovician, Cincinnatian Series) of the Tristate (Ohio-Kentucky-Indiana) region comprises just such a lithologically repetitive succession, consisting of approximately 70-73 m of finely interbedded shales and limestones containing no lithologically unique marker horizons. Although these strata have been the subject of innumerable paleontologic investigations (see Davis and Cuffey, 1998, for references), they have only recently become the focus of high-resolution stratigraphic study (e.g., Dattilo, 1996, 1998; Diekmeyer, 1998; Holland et al., 2000). This is due in part to a widely prevalent view that the Cincinnatian Series displays complex lateral facies relationships, and the plethora of regional names (i.e., the differences in Ohio, Kentucky and Indiana) conveys the impression of a rather disorderly mosaic of facies. Although depositional sequences have been delineated regionally by Holland

(1993, 1998) and Holland and Patzkowsky (1996), it would appear from past literature that meter-scale correlation between outcrops more than a few hundred meters apart is impossible. But is this really the case? We tested this idea through high-resolution stratigraphic analysis of the Kope Formation in a series of closely spaced, relatively new roadcuts along the AA Highway (Alexandria-to-Ashland; KY Rte. 9) in northern Kentucky (Potter *et al.*, 1991; Brett and Algeo, 2001a, b; Fig. 1).
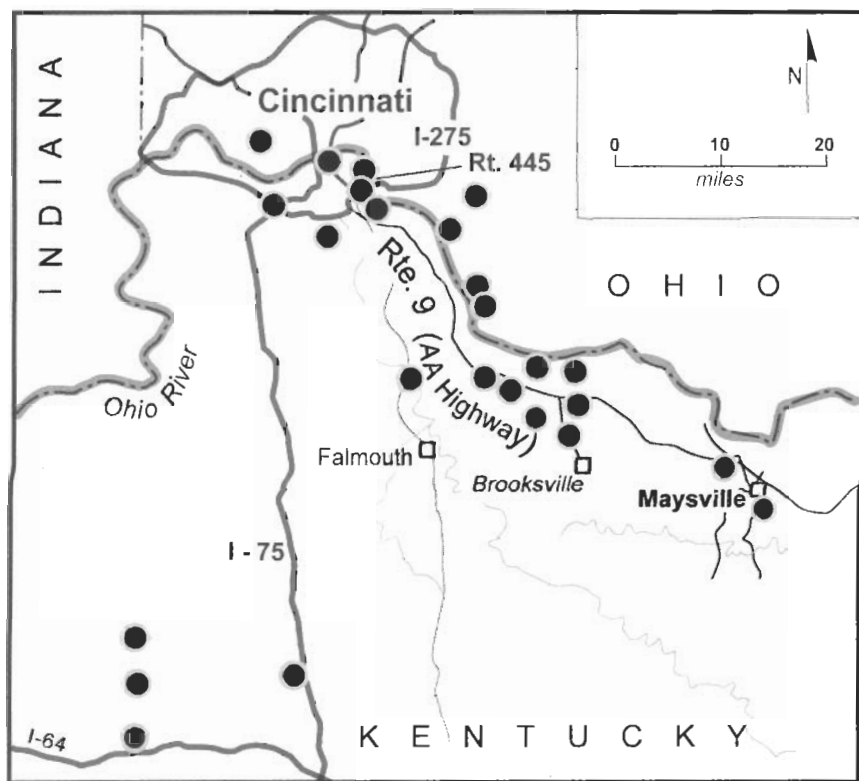

Figure 1. Location map of study locales in the Tristate area (Ohio-Kentucky-Indiana). Many good Kope Fm. exposures are found along the Ohio River and the AA Highway (KY Rte. 9) between Cincinnati and Maysville; somewhat sparser outcrops are present to the south in north-central Kentucky.

In this contribution, we will report on our studies of event beds and sedimentary cycles within the Kope Formation. We will: 1) describe types of event beds and meter- and decameter-scale cycles prevalent in the Kope; 2) demonstrate their utility for regional high-resolution stratigraphic correlation using the Fulton submember of the Kope as an example; 3) document our ability to establish a high-resolution (m-scale) correlation

framework for the entire Kope Formation along a ca. 80-km transect between Cincinnati, Ohio and Maysville, Kentucky (Fig. 1); and 4) propose a new subdivision of the Kope Formation into submembers based on this stratigraphic framework (see also Brett and Algeo, 2001b).   While this contribution focuses on the methodology of high-resolution stratigraphic correlation, the broader aims of our work are to develop a process-based model for deposition of mixed carbonate-siliciclastic successions of the type represented by the Kope Formation.

2.   REGIONAL GEOLOGIC SETTING

Upper Ordovician (Cincinnatian Series) strata in southern Ohio and northern Kentucky were deposited on the northern margin of the Lexington Platform, a carbonate-dominated feature of positive relief bounded by subsiding siliciclastic-dominated basins to the southeast (Taconic Foreland Basin) and northwest (Sebree Trough; Figs. 2-3; Rooney, 1966; Cressman, 1973; Keith, 1989; Mitchell and Bergström, 1991; Bergström and Mitchell, 1992).   The Sebree Trough was a shallow depression that developed during the Shermanian (late Chatfieldian) Age and disappeared by Richmondian time, existing for only about 7-8 Ma (Wickstrom et al., 1992; Kolata et al., 2001).   Its origin has been linked to subsidence associated with far-field stresses of the Taconic Orogen (Mitchell and Bergström, 1991; Ettensohn, 1992; Rast et al., 1999; Ettensohn et al., 2002), possibly compounded by upwelling of cool, corrosive deep waters along the trough axis (Cressman, 1973; Schwalb, 1980; Kolata et al., 2001).   On its eastern flank, an embayment known as the Point Pleasant Basin extended southeastward approximately along the line of the present Ohio River between Cincinnati, Ohio and Maysville, Kentucky (Fig. 3); formation of this embayment may have been controlled by subsidence along the Ironton-Vanceburg Fault (Ettensohn et al., 2002).   The boundary between the northern margin of the Lexington Platform and the Point Pleasant Basin (the area of this study) was a fairly uniform north-dipping ramp, as evidenced by a regionally consistent orientation of gutter casts in the Kope Formation (Jennette and Pryor, 1993, fig. 7).

The northern part of the Late Ordovician Lexington Platform was located in a subtropical climate zone, about 20-25° south of the paleoequator (Scotese, 1990; Ettensohn, 1992; Fig. 2).   With an extensive area of warm tropical seas to the north, the region was frequently affected by tropical storms (Fig. 3), as reflected in the prevalence of carbonate tempestites in the Cincinnatian Series (Tobin and Pryor, 1981; Jennette and Pryor, 1993;
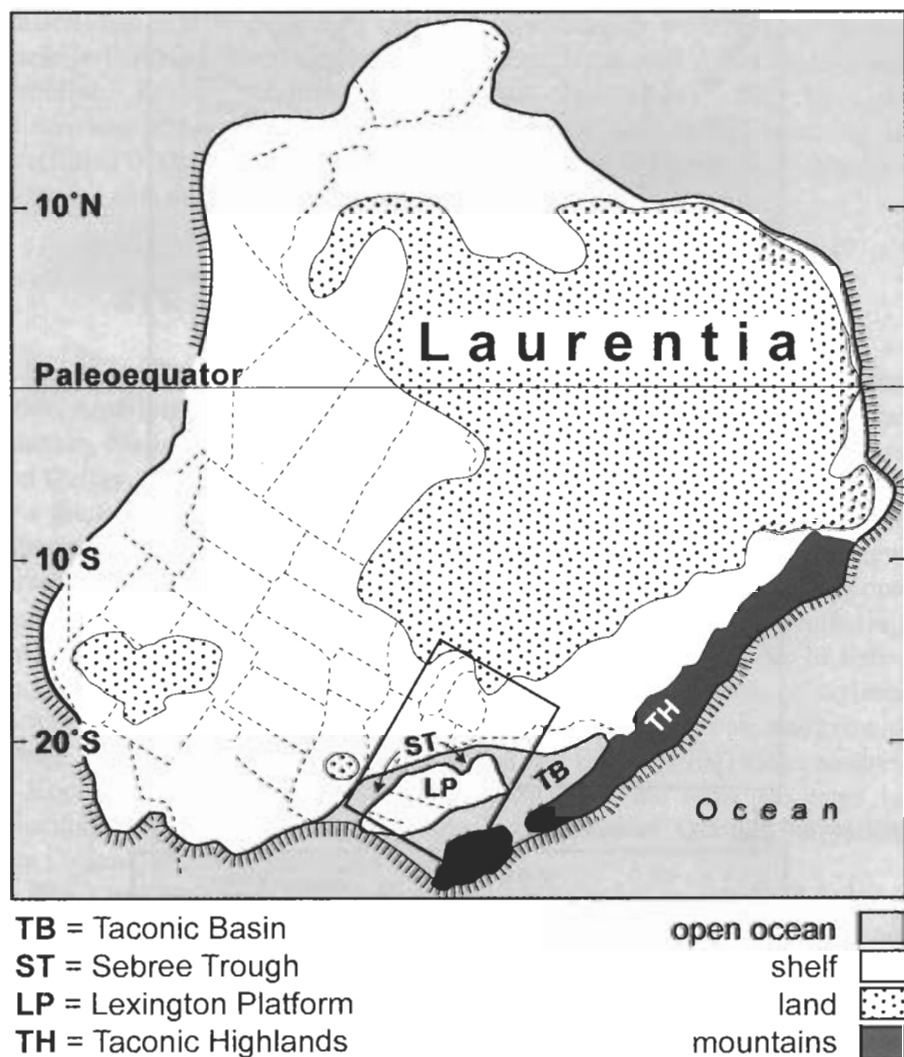
TB = Taconic Basin
ST = Sebree Trough
LP = Lexington Platform
TH = Taconic Highlands

open ocean
shelf
land
mountains

Figure 2. Paleogeography of Laurentia during the Late Ordovician. Note that the Lexington Platform is separated from cratonic shelf areas to the north and west by the Sebree Trough, and from the Taconic Highlands to the south and east by the Taconic Foreland Basin. Inset rectangle is area of Figure 3. Modified from Scotese (1990) and Blakey (2001).

Drummond and Sheets, 2001).   At the same time, large quantities of siliciclastic sand, silt, and mud were derived from upland areas to the northeast and east as a consequence of the Taconic and Blountian orogenies (Dewey and Kidd, 1974; Shanmugam and Walker, 1980; 1984; Shanmugam and Lash, 1982; Rowley and Kidd, 1991; Lehmann *et al.*, 1994).   During
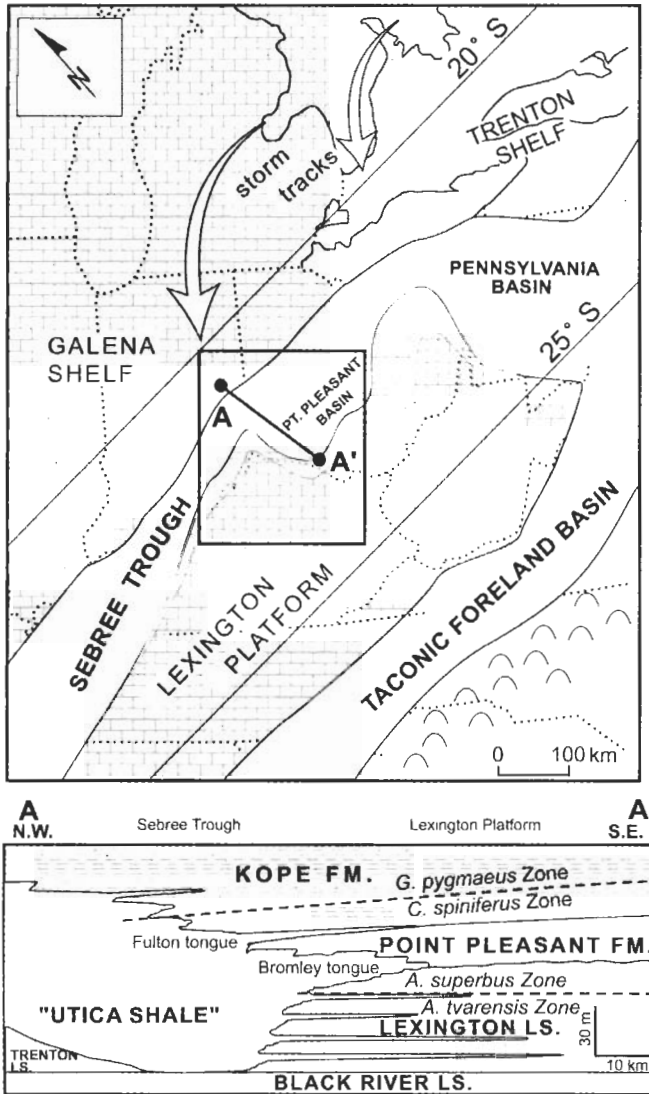
Figure 3. (top) Paleogeography of the greater Midwest region during the Late Ordovician. Note the Point Pleasant Basin, an embayment in the Lexington Platform, within the study area (inset rectangle, Figure 2). Tropical storms moved across the shallow Trenton/Galena shelves and intersected the northern margin of the Lexington Platform. Line A-A' gives location of cross-section (below). Regional cross-section, A-A', of Mohawkian- and Edenian-age strata from the Lexington Platform into the Sebree Trough. Approximate positions of graptolite (*C. spiniferus-G. pygmaeus*) and conodont (*A. tvarensis-A. superbus*) zonal boundaries are indicated. Note the change from platform carbonates into dark Utica-type shales in the trough; the Bromley and Fulton are dark-shale tongues that onlap the platform margin. Modified from Keith (1989), Mitchell and Bergström (1991), Ettensohn (1992), Jennette and Pryor (1993), and Ettensohn *et al.* (2002).

Chatfieldian and Rocklandian time, these sediments were trapped in the Taconic Foreland Basin as black shales (e.g., Utica and Antes shales) and turbiditic flysch (Martinsburg-Reedsville formations), but by late Mohawkian time sedimentation had outstripped subsidence, resulting in overfilling of the foreland basin and southwestward transport of siliciclastics along the axis of the Sebree Trough (Fig. 3).

3.   STRATIGRAPHY

The Kope Formation in northern Kentucky is part of the stratotype of the North American Cincinnatian Provincial Series, which is subdivided into the Edenian, Maysvillian, and Richmondian stages (see Davis, 1992, and Davis and Cuffey, 1998, for earlier references). The Edenian-age Kope Formation is a thick (70-73 m) package of shale-dominated strata between the older (Shermanian-age) Point Pleasant and younger (Maysvillian-age) Fairview formations, both of which are limestone dominated (Fig. 4). The Kope consists predominantly of soft, pale to medium gray, readily weathering mudstones or shales interbedded with abundant thin (<5 cm) beds of light-gray laminated calcisiltite, and medium to thick (5 to 60 cm) beds of skeletal packstones and grainstones dominated by brachiopod, bryozoan, and crinoid debris. The formation was named by Weiss and Sweet (1964) for exposures at Kope Hollow, near Levanna in southern Ohio; the term was used in substitution for the biostratigraphically based Eden or Latonia Formation (see Diekmeyer, 1998, for review).

The Kope has been biostratigraphically subdivided to a limited degree. Bassler (1906) recognized three members in the "Eden Shales" based on bryozoan assemblages (Fig. 4): (a) the Economy Member, characterized by *Aspidopora newberryi* (ca. 16 m thick; originally reported as 28 m thick owing to inclusion of the upper beds of the underlying Point Pleasant Fm.); (b) the Southgate Member, typified by *Batostoma jamesi* (ca. 36-37 m thick); and (c) the McMicken Member, marked by *Dekayella ulrichi* (ca. 16-21 m thick). Mitchell and Bergström (1991) recognized two graptolite biozones within the Kope, a lower *Climacograptus spiniferus* zone and an upper *Geniculograptus typicalis-Geniculograptus pygmeaeus* zone (Fig. 3); the contact is within the Middle Kope, near the base of the Grand View submember of Brett and Algeo (2001b). Limited faunal turnover within the Kope has precluded development of finer biozonation schemes.

Lithostratigraphy, in some cases combined with biostratigraphic criteria, has provided the basis for a more detailed subdivision of the Kope. Early workers recognized several lithologically and faunally distinctive intervals:
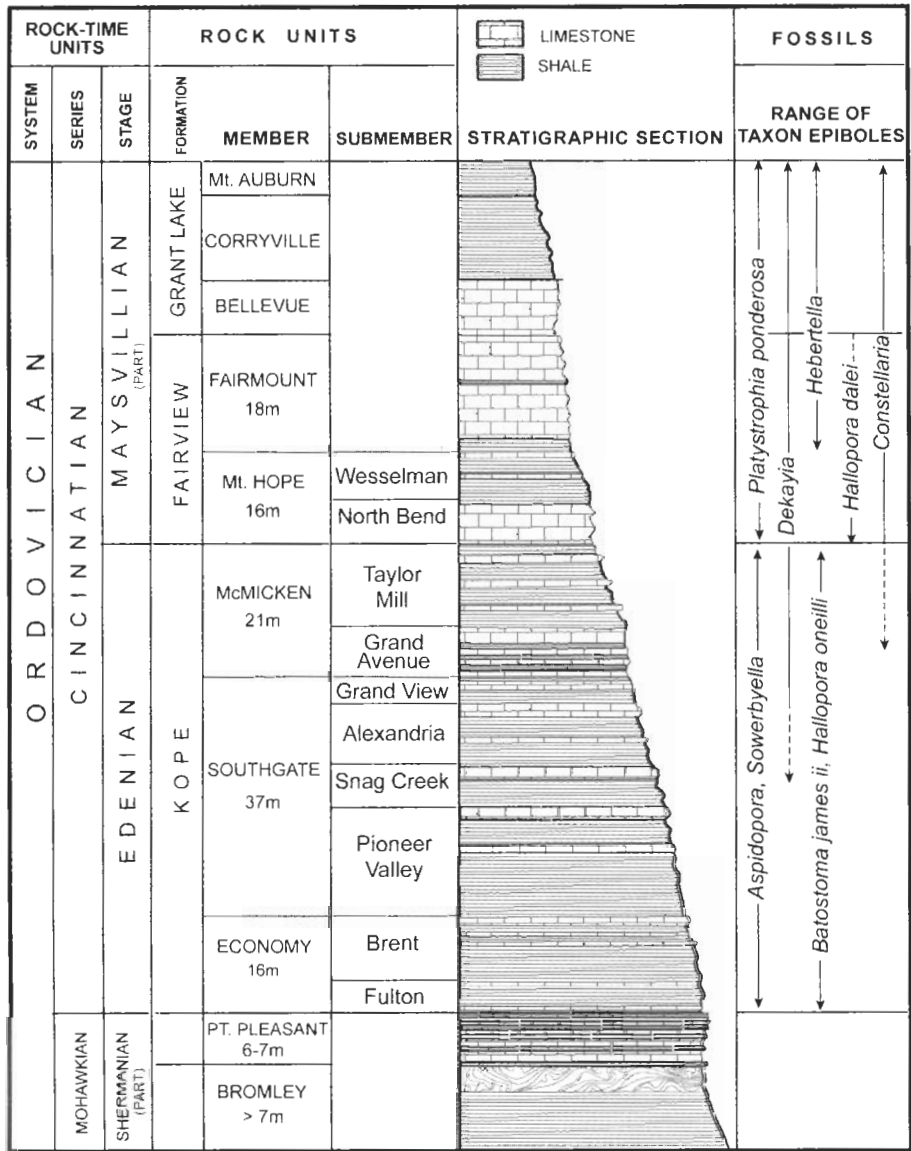
Figure 4. Stratigraphy of the Upper Ordovician in the Tristate area. Modified from Caster *et al.* (1955) with Kope Formation submembers introduced by Brett and Algeo (2001b). In this contribution, a high-resolution correlation framework will be established for the entire Kope Fm. in northern Kentucky, with a detailed example given for the Fulton submember.

(1) *Triarthrus*-bearing dark shale tongues in the basal 7 m of the Eden Shales (subsequently termed the lower Economy Member) were named the "Fulton beds" by Foerste (1905; Figs. 3-4); and (2) a 2.5- to 3-m-thick bundle of

limestones about 10 m below the top of the Kope Fm. was termed the "Grand Avenue Member" by Weiss and Sweet (1964; Fig. 4). More recently, Holland *et al.* (1997; 2001b) identified about 40 meter-scale cycles within a 60-m-thick composite section in northern Kentucky representing all but the lower 12 m of the Kope Formation. The most detailed subdivision of the Kope to date was proposed by Brett and Algeo (2001b), who combined Holland *et al.*'s section with the basal 12 m of the Kope from nearby Duck Creek to generate a complete reference section for the formation. Brett and Algeo retained the member names of Bassler (1906) and the cycle numbers of Holland *et al.* (1997) but proposed a further subdivision of the Kope into submembers (Fig. 4) based on thick, homogenous mudstone intervals ("Big Shales") that were shown to be traceable well beyond the Cincinnati area (see below).

4.   EVENT-STRATIGRAPHIC MARKERS

Event beds, recording geologically instantaneous events usually at a local to regional scale, are extremely useful in establishing high-resolution correlations. In the Kope Formation, such stratigraphic marker horizons may be recognized on the basis of: (1) distinctive faunal assemblages, (2) taphonomic features, (3) trace fossils, (4) sedimentary structures, mostly associated with storm sedimentation, and (5) other characteristics. In this section, we describe some of the more important types of event beds that proved useful in high-resolution correlation of the Kope Formation.

4.1   Event Beds with Distinctive Faunal Assemblages

Limited faunal turnover in the Kope Formation does not allow much biostratigraphic zonation beyond the three members identified by Bassler (1906) on the basis of bryozoan assemblages. However, distinctive faunal assemblages are nonetheless useful for intraformational correlation of the Kope (Holland, 1997). These fall into two categories: (1) faunal epiboles marked by very high concentrations of otherwise rare fossil types, including both proliferation and incursion epiboles (*sensu* Brett and Baird, 1997), and (2) shell beds containing a ubiquitous fossil taxon that exhibits an unusual taphonomic characteristic or morphotype.

Among the most useful epiboles are *Triarthrus* beds, which are typically composed of dark brownish gray, laminated shale beds containing abundant intact or fragmental molts of the trilobite *T. becki* (Fig. 5A; Whiteley *et al.*, 2002). Owing to similarities to *Triarthrus* epiboles in the Mohawkian-age
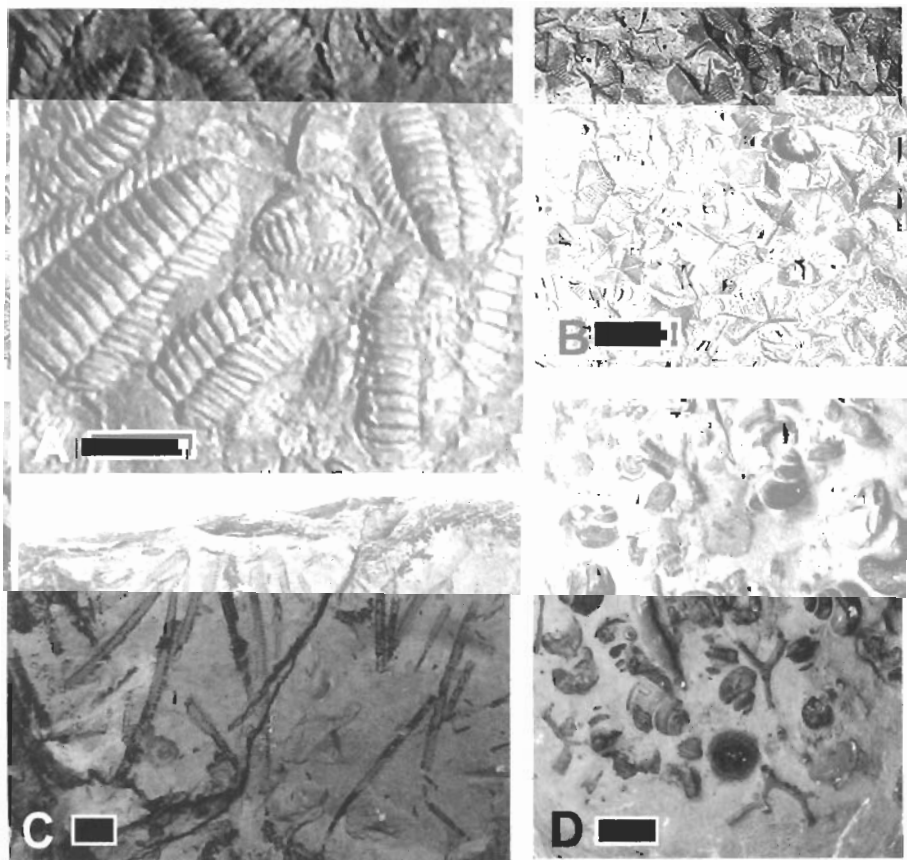
Figure 5. Faunal epibole event beds. (A) Cluster of articulated thoracopygidial molts of *Triarthrus becki*; from the Alexandria submember at Sycamore Creek, Cincinnati, Ohio. (B) Packstone containing large numbers of stellate plates of the rhombiferan *Cheirocystis fultonensis*; from Fulton submember, KY Rte. 8 roadcut, near Augusta, Kentucky. (C) Weakly aligned graptolites (*Geniculograptus* cf. *G. typicalis*) in calcareous shale; from Snag Creek submember, KY Rte. 17 ("White Castle site"), Covington, KY. (D) Gastropod-rich nodule in siliciclastic mudstone; from Alexandria submember, KY Rte. 9. All scale bars = 1 cm.

Bromley Shale of Ohio and Kentucky (Ulrich, 1888; Ulrich and Bassler, 1914) and to the Utica Shale of New York, these are thought to represent condensed beds formed during brief incursions of dysoxic water from the Sebree Trough onto the Lexington Platform. Some *Triarthrus* beds exhibit current-aligned columns of the cladid crinoid *Merocrinus curtus,* together with fully articulated *Triarthrus* exoskeletons; these appear to represent obrutionary deposits that terminated "incursion epiboles" (*sensu* Brett and Baird, 1997). In the Kope, *Triarthrus* beds are found in (1) cycles F2-F4 of

the Fulton submember, and (2) cycle H28 of the Alexandria submember.

There are several other types of epibole horizons of importance in the Kope Formation. First, an epibole of the rhombiferan cystoid *Cheirocystis fultonensis* (Fig. 5B) is found in cycle F1 of the Fulton submember, about 0.5 m above the base of the Kope; this bed has been found consistently over an area of ~500 km^2 in northern Kentucky and southern Ohio (Sumrall and Schumacher, 2002). Second, epiboles of current-aligned rhabdosomes of the graptolite *Geniculograptus typicalis* are found in calcareous siltstones in cycle H21 (Big Shale 3) of the Snag Creek submember (Fig. 5C). These beds may record incursions of graptolite swarms onto the Lexington Platform from the Sebree Trough, where graptolitic facies predominate, and represent "taphonomic epiboles" (*sensu* Brett and Baird, 1997). Third, concretionary siltstones with well-preserved molluscs, primarily gastropods, occur near the tops of·major limestones at several levels in the Kope (Fig. 5D). Several of these are named beds, including the Newport Plaza hiatus bed (cycle H12, Pioneer Valley submember) and the Carrolton gastropod bed (cycle H25, Big Shale 4 of the Alexandria submember).

The second type of faunal event bed useful in correlation is that containing common taxa exhibiting distinctive morphotypes. An example is provided by the strophomenid brachiopod *Sowerbyella rugosa*. While fairly ubiquitous in the lower half of the Kope Fm, *S. rugosa* nearly disappears at the Pioneer Valley-Snag Creek submember contact (top of cycle H20), only to reappear in abundance in a few beds of cycles H25-H28, where it displays an unusually elongated hingeline (Fig. 6A). With this exception, higher beds in the Kope are nearly devoid of *S. rugosa*, despite little apparent change in facies; its abrupt disappearance thus also represents a bioevent of regional significance within the Kope Formation.

4.2   Taphonomic Event Bed

Certain stratigraphic intervals are characterized by unusual taphonomic features. One example involves perhaps the most ubiquitous fossil in the Kope, the orthid brachiopod *Onniella* (Fig. 6B). Most *Onniella* are preserved as white to yellowish shells, but two horizons within the Kope contain distinctively colored shells: 1) the "black *Onniella* beds" (cycle H25, Alexandria submember), and 2) the "red *Onniella* beds" (cycles H27-H30, Alexandria submember). These discolorations may have a diagenetic (i.e., burial) origin, but the horizons containing the distinctively colored shells are traceable for 80 km across the study area, making them useful for correlation purposes.

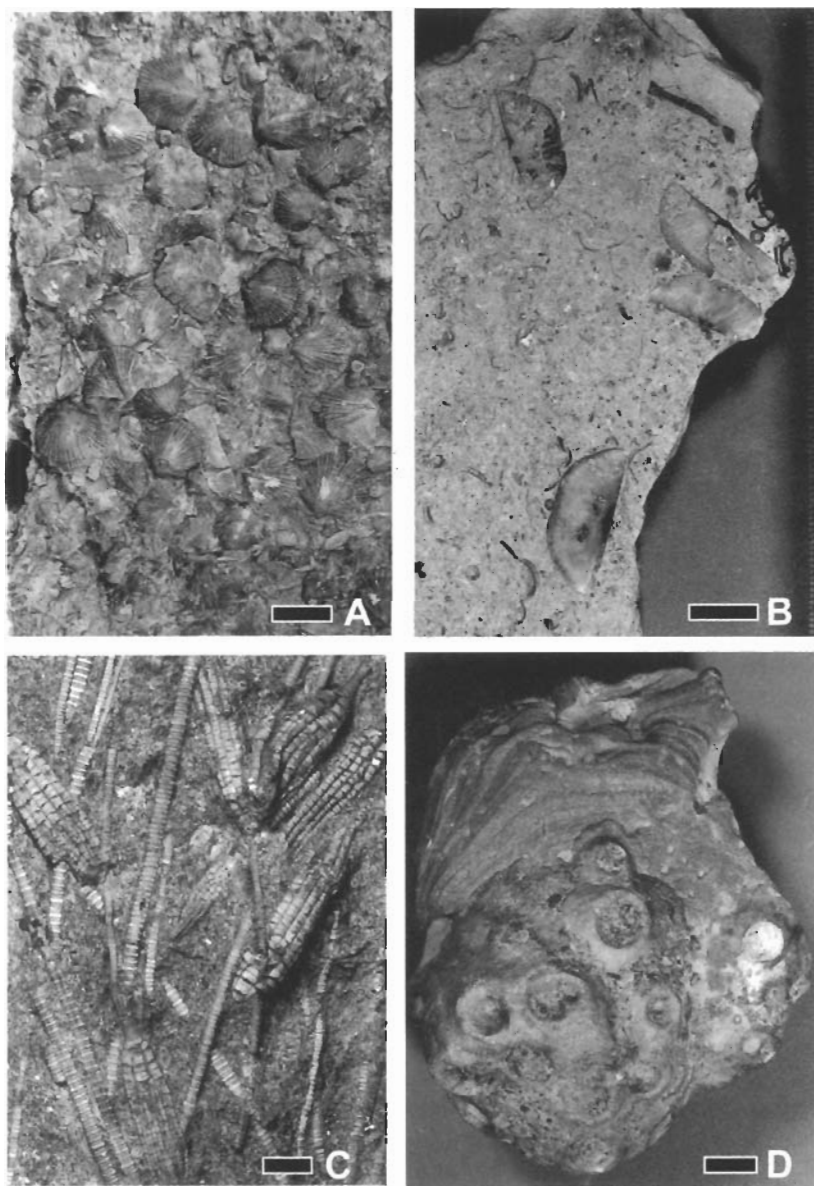A second type of taphonomic event bed is obrutionary lagerstätten, which

Figure 6. Other taphonomic event beds. (A) Wacke-packstone containing unusual *Sowerbyella rugosa* morphotype with an elongate hingeline, beds H23-H24 of Snag Creek submember; Rte. 6 roadcut northeast of Fosters, Kentucky. (B) Fossil grainstone with concentration of blackened *Onniella* forming an armored surface; from Alexandria submember, KY Rte. 9. (C) "Log jam" of oriented *Ectenocrinus* columns, note intact crowns; from Pioneer Valley submember, Alexandria, Kentucky). (D) Reworked siltstone concretion with encrusting bryozoans and crinoid holdfasts; from cycle H15 of Pioneer Valley submember, KY Rte. 17 ("White Castle site"), Covington, KY. All scale bars = 1 cm.

represent fossil assemblages that were rapidly buried, usually by smothering under a mud blanket. These deposits exhibit exceptional preservation of even fragile fossils (Brett and Seilacher, 1991; O'Brien *et al.*, 1994; Brett et al, 1997; Hughes and Cooper, 1999). The Kope contains several types of obrutionary deposit. "Butter shales" (any of several "Big Shales") are characterized by concentrations of enrolled or prone trilobites (Brandt, 1985; Schumacher and Shrake, 1997). Large numbers of articulated *Flexicalymene granulosa* are found in shales of cycle H16 of the Pioneer Valley submember (Hughes and Cooper, 1999), and this horizon has been traced for at least 10 km (Holland *et al.*, 2000). Abundant articulated specimens of the trilobites *Cryptolithus* and *Acidaspis* are found in cycle H25 (Big Shale 4) of the Alexandria submember, in a bed that has been traced approximately 20 km north-south through the Cincinnati area; at other levels in the Kope these trilobites are found only as disarticulated elements. Another type of lagerstätten is beds containing masses of parallel-oriented crinoid columns ("log jams"), probably formed through mass mortality associated with storm-generated currents. In some cases, crinoid columns at bed bases are oriented at approximately a right angle to those on the bed tops, indicating a change in current direction or a shift to wave-dominated flow. Some of these layers (e.g., an *Ectenocrinus* "log jam" in cycle H9, Big Shale 2 of the Pioneer Valley submember; Fig. 6C) have been found to persist over several outcrops (D. Schmidt, pers. comm.).

A third type of taphonomic marker horizon in the Kope is hardgrounds (Meyer, 1990). These commonly take the form of layers of nodules exhumed from underlying mudstones that were subsequently colonized by boring and encrusting organisms. Among the more commonly identifiable encrusters are crinoid holdfasts, edrioasterioids, and bryozoan protoecia (basal disks). For example, edrioasteroid holdfasts are prevalent in a bed of reworked and encrusted nodules in cycle H15 of the Pioneer Valley submember (Fig. 6D; Wilson, 1985). This bed is apparently traceable from near Big Bone Lick, Kentucky, northeast to the vicinity of Batavia, Ohio, a distance of about 50 km (S. Felton, pers. comm., 1999).

4.3   Trace-Fossil Event Bed

Certain beds contain an abundance of a characteristic, easily identifiable trace fossil that can be found at the same stratigraphic level in multiple, closely-spaced outcrops, reflecting occurrence of conditions particularly favorable to a certain behavior or its preservation. One such trace fossil is *Diplocraterion*, a distinctive U-shaped (or bell-shaped when larger) dwelling trace associated with hummocky cross-stratified siltstone beds (Fig. 7A). It
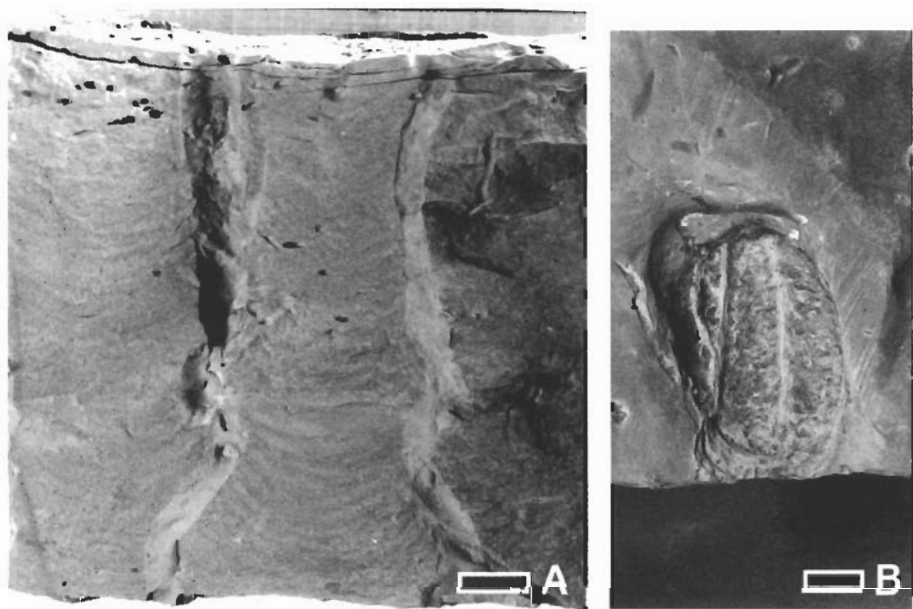
Figure 7. Ichnologic event beds. (A) Side view of laminated siltstone showing spreiten of the U-shaped burrow *Diplocraterion*; Taylor Mill submember, Mason/Reidlin Road, Taylor Mill, Kentucky. (B) The trilobite resting trace *Rusophycus*; from lower Kope Formation, KY Rte. 17 ("White Castle site"), Covington, KY. All scale bars = 1 cm.

is most common in cycles H38-H40 of the Taylor Mill submember but also occurs sporadically at other stratigraphic levels (e.g., H1, H24-H28). Evidently, the trace makers colonized storm silt layers in large numbers; thus, these beds represent a type of epibole or biotic event horizon (*sensu* Brett and Baird, 1997). A second trace fossil that occurs in locally correlatable horizons is *Rusophycus*, which is prevalent at several levels in the Kope (Fig. 7B). It was long considered to be a trilobite resting trace but has recently been reinterpreted on the basis of juxtaposition with other burrow types (e.g., *Planolites*) as a hunting trace (Brandt *et al.*, 1995). This suggests that concentrations of this trace represent enhanced opportunities for predation as, for example, after storm erosion has unroofed infaunal organisms such as worms in large numbers. Such behaviors are associated with specific events and, as such, commonly result in regionally correlatable marker horizons.

4.4 Storm-Event Beds

Beds containing unusual sedimentary structures have also proven to be useful in regional correlation. In the Kope Formation, storm sedimentation

processes are responsible for generating many of these features, including gutter casts, edgewise shell beds, megaripples, drag marks, among others (cf. Aigner, 1985; Nummedal, 1991; Brett, 1995). Other storm-related sedimentary structures have also proven to be traceable at a local to regional scale, including hummocky cross-stratification, graded bedding, intraformational scouring, and tool, flute, and prod marks, but as the general characteristics of these features are well known, they will not be discussed here.

Gutter casts are erosional features that form on the forward margin of storm-generated gradient currents, where fingers of sediment-laden water spiral downslope (Aigner, 1985); as a consequence, they form in parallel series at spacings of a few meters. Individual gutter casts are generally 5 to 10 cm in width and thickness, are asymmetric in cross-section, and have bases heavily ornamented by tool marks and flute casts parallel to the direction of current flow as well as by randomly oriented exhumed burrows (Fig. 8A). Jennette and Pryor (1993) documented a consistent orientation within a gutter cast bed in cycle H39 of the Taylor Mill submember (their cycle 20) at >20 localities across the greater Cincinnati area, demonstrating generation from a single flow down a north-northwesterly paleoslope. Gutter cast beds are found at more than a dozen horizons within the Kope, most abundantly within the Fulton, Brent, and Pioneer Valley submembers (see Algeo and Brett, 2001).

Distinctive coarse skeletal debris layers, such as beds of edgewise-oriented or shingled shells are also useful in correlation. In the Cincinnatian Series, beds of this type commonly contain edgewise *Rafinesquina* shells that, in some cases, are clustered at the bottoms of gutter casts (Fig. 8B). Three such horizons (called the "first, second, and third *Fracta* beds" by Des Jardins, 1933, and the "first, second, and third shingled beds" by Hyde, 1959) have been identified and traced regionally in the Maysvillian of the Tristate area (Dattilo, 1996). These particular event beds permitted identification of time lines 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 represent major storms or, possibly, seismic events (A. Miller, pers. comm., 1998) that aggregated the flattish to gently concavo-convex brachiopod shells and oriented them in edgewise clusters over a large area of seafloor. In the Kope Formation, shingled shell beds are found mainly within coarse grainstone beds at the tops of decameter-scale cycles, for example in cycles H23-H24, H28, H35-H36, and H39.

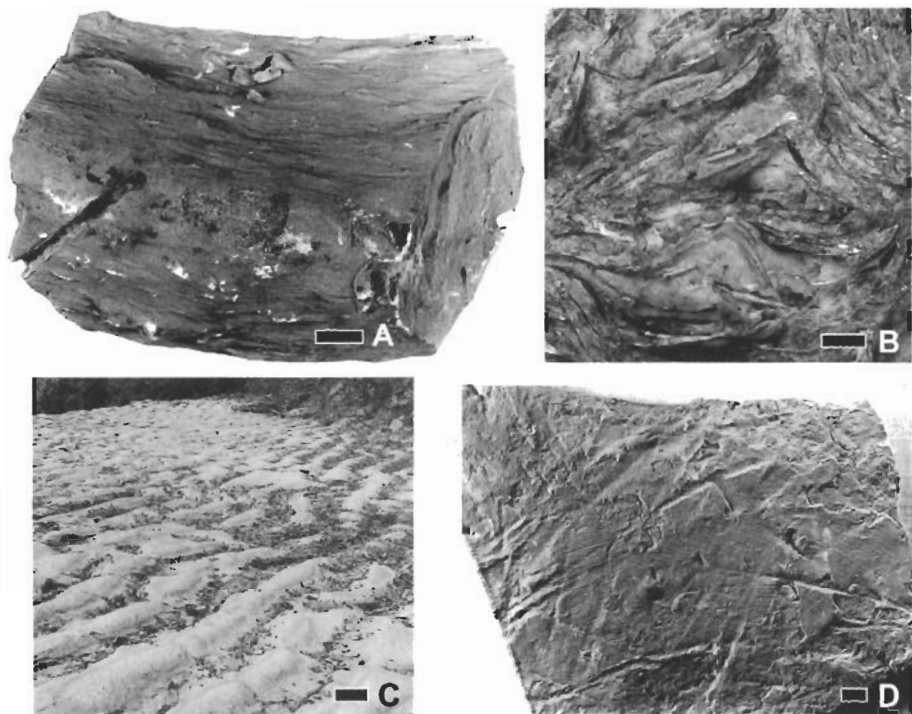Megaripples are generally found capping thick, fine- to medium-grained

Figure 8. Tempestite event beds. (A) Bottom side of gutter; note nearly rectangular cross section to left and well-defined lineations formed as tool, prod, and flute marks; from base of Pioneer Valley submember, KY Rte. 445, Brent, Kentucky. (B) Top view of edgewise coquina of *Rafinesquina* shells; note multiple orientations of shell sets; from Grand Avenue submember, Mason/Reidlin Road, Taylor Mill, Kentucky. (C) Megaripples on top of medium-grained fossil grainstone; crest-to-crest wavelength ca. 1 m; from Taylor Mill submember, US Rte. 50 West, 4 mi east of North Bend, Ohio; photo from Jennette and Pryor (1993). (D) Cast of crinoid stem drag marks; note arcuate character of grooves, probably due to columnals being rotated around a pivot point on soft silt; Alexandria submember, KY Rte. 17 ("White Castle site"), Covington, Kentucky. Scale bars in A, B, D = 1 cm; bars in C = 25 cm.

grainstone beds at the tops of m-scale cycles. They are usually symmetrical with amplitudes from 2 to 10 cm and wavelengths from 40 to 100 cm (Fig.8C). Prominent examples are found at several dozen horizons within the Kope Formation, but they can sometimes be uniquely characterized on the basis of ripple amplitude, wavelength, and orientation. They are inferred to have formed during the final stage of storm sedimentation, as storm waves or combined flows molded the surface of grainstone deposits for the last time.

Crinoid drag or roll marks represent a special type of tool mark found at certain stratigraphic levels in the Kope. These occur as a series of parallel

scratches in an arcuate configuration (Fig. 8D), formed as oscillating currents dragged crinoid columns over the seafloor about a fixed pivot point. These crinoids may have been living or dead, attached to the seafloor by their holdfasts or detached and rotating about a calyx embedded in the sediment. These relatively rare features are generally developed on the tops of hummocky cross-stratified calcisiltite beds, suggesting that strong storm waves played a role in knocking over or detaching the columnals and in dragging them across the seafloor. The best-documented example is from cycle H29 of the Alexandria submember.

4.5   Other Event Beds

Finally, several enigmatic sedimentary structures are encountered in the Kope, which, despite uncertainty about their genesis, are nonetheless useful for correlation purposes. One such feature, millimeter "ripples," consists of sets of parallel, closely spaced ridges with flattened crests and troughs that are found mainly in calcisiltites (Fig. 9A). Jennette and Pryor (1993) observed that these "ripples" are penetrative, occurring in nested sets in all laminae of a given bed up to several centimeters in thickness, and that the
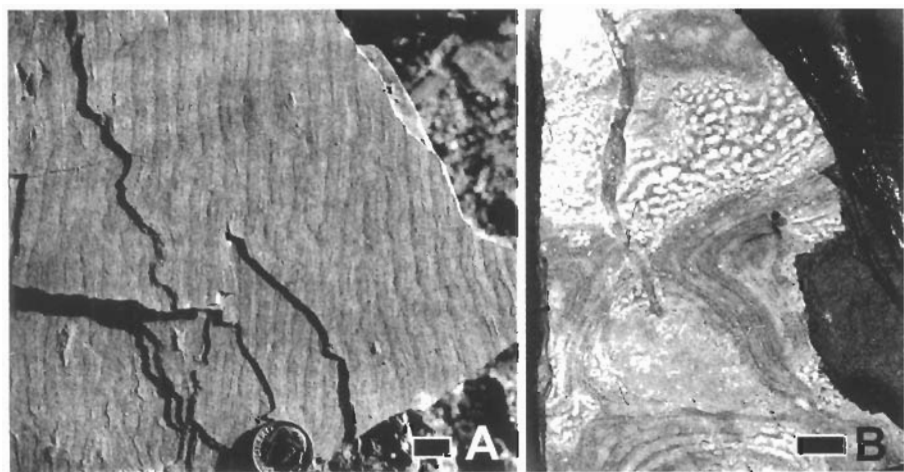

Figure 9. Other types of marker horizons. (A) Millimeter "ripples" in siltstone; note that the "ripples" occur in parallel, nested arrays on successive laminae of the siltstone (visible on broken edges); probably from Taylor Mill submember, Alexandria, Kentucky; photo from Jennette and Pryor (1993). (B) *Kinneyia*, an enigmatic feature that appears on the upper bedding surface of siltstones; note presence of *Kinneyia* only on crest of hummocky cross-strata and not in troughs; from Brent submember, KY Rte. 9 near Fosters, Kentucky. All scale bars = 1 cm.

"ripples" occasionally change spacing or amplitude upward within a bed in response to changes in grain size (Jennette and Pryor, 1993). Similar features have been attributed to wave rippling in very shallow water, but in the Cincinnatian Series these structures are found mainly in deeper-water facies, suggesting that another origin must be considered. Pflueger (1999) reviewed similar cases of "microripples" and concluded that they result from shearing within the sediment, i.e., below the sediment-water interface. Such shearing might, however, be induced by wave pounding of the seafloor or, perhaps, by seismic shocks. Millimeter "ripples" are found in a few beds (e.g., H40) and are commonly traceable over several outcrops.

A second enigmatic structure is runzel or wrinkle marks of a type known as *Kinneyia*, also found mainly in calcisiltites (Hughes and Hesselbo, 1997; Pflueger, 1999). Sometimes these consist of more-or-less regular patterns of shallow pits across the surface of a calcisiltite layer; in other cases, pitted areas abut areas of concentric but irregularly spaced laminae (e.g., Fig. 9B). Similar features have been interpreted as interference ripple marks, formed either subaqueously or subaerially (Klein, 1977; Allen, 1982; Seilacher, 1982; Hughes and Hesselbo, 1997). An alternative idea is formation in association with bacterial mats (Hagadorn and Bottjer, 1997). Pflueger (1999) presented experimental evidence that *Kinneyia* may form by the trapping of gas bubbles from organic decay, along the 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 or vertical dewatering, creating the wrinkle marks. *Kinneyia* structures have been found in just a few beds of the Kope Formation (e.g., H1, H40).

5.   CYCLE STRATIGRAPHY

The Kope Formation exhibits cyclicity at two readily apparent scales, a decameter (10-m) scale and a meter scale, both of which are useful in establishing a regional correlation framework (cf. Miller *et al.*, 1997; Holland *et al.*, 2000). The 70 to 73 m thickness of the Kope Formation is divisible into eight decameter-scale cycles that are easily correlatable along the Cincinnati-Maysville axis of the present study. These decameter-scale cycles are equivalent to the eight informal submembers of the Kope recognized by Brett and Algeo (2001b). Each decameter-scale cycle consists of multiple smaller, "meter-scale" cycles that may be correlatable at a regional scale (Brett and Algeo, 2001a; Holland *et al.*, 2000, 2001b).

5.1   Meter-Scale Cycles

The Kope Formation is characterized by a large number (>40; Holland *et al.*, 1997) of small-scale (typically 0.5 m to 3.0 m thick) alternations of recessive weathering shales (mudstones) and ledge-forming, medium- to thick-bedded skeletal packstones and grainstones (Fig. 10). The mudstones vary from light to dark gray, may be massive, finely laminated, or micrograded, and contain fossil concentrations along some bedding planes (e.g., Fig. 5). This hemicycle may exhibit an upward increase in skeletal content and in the frequency of thin calcisiltite and shelly packstone interbeds (Jennette and Pryor, 1993; but see Webber, in press, for a discussion of more random patterns). The calcisiltite beds commonly exhibit hummocky cross stratification, laminated or burrow-mottled ichnofabric, and well-preserved trace fossils such as *Diplocraterion*, *Planolites*, and *Chondrites* (Fig. 7). The bases of these beds are sharp, preserve tool and prod marks as well as gutter casts, and, sometimes, have thin basal lags of fossil debris. The tops of calcisiltite beds are normally gradational into the overlying mudstones but occasionally preserve oscillation or interference ripple marks, or "runzel marks" (*Kinneyia*) of probable dewatering origin (Fig. 9B). Layers of small (5-10 cm) carbonate nodules commonly occur just below the bases of the overlying limestone hemicycle (Fig. 10). These appear to represent diagenetic underbeds, formed during periods of sediment starvation (see Aigner, 1985).

The limestone hemicycles consist of one or more sharp-based, subtabular skeletal packstone or grainstone beds, generally 5 to 30 cm in thickness and separated by thin shales or calcisiltites (Fig. 10). Internally, many of these beds are amalgamated, as shown by internal truncation surfaces, sharp changes in shell size, color, or taxonomic composition, or shaly partings (Barbour, 2001; Drummond and Sheets, 2001). Local relief on the bases of shell beds may be as much as 5 to 10 cm with irregular lumps or mounds of mudstone projecting upward into the overlying limestones. The bed bases may show gutter casts, tool marks, or other sole features indicative of scouring and loading (Fig. 8A), and small (mostly 1 to 5 cm) buff-colored clasts of reworked mudstone are commonly present as a basal lag. The skeletal debris tends to be dominated by brachiopod valves, bryozoan fragments, and crinoid ossicles, and these tend to be heavily broken and abraded and may exhibit a dark reddish to blackish discoloration (Fig. 6). The thickest beds tend to be grainstones, and these have a tendency to be dominated by crinoid ossicles and small twiggy bryozoans, whereas large ramose bryozoans are more abundant in thinner layers with a packstone texture.   The tops of the limestone hemicycles may exhibit firm- or
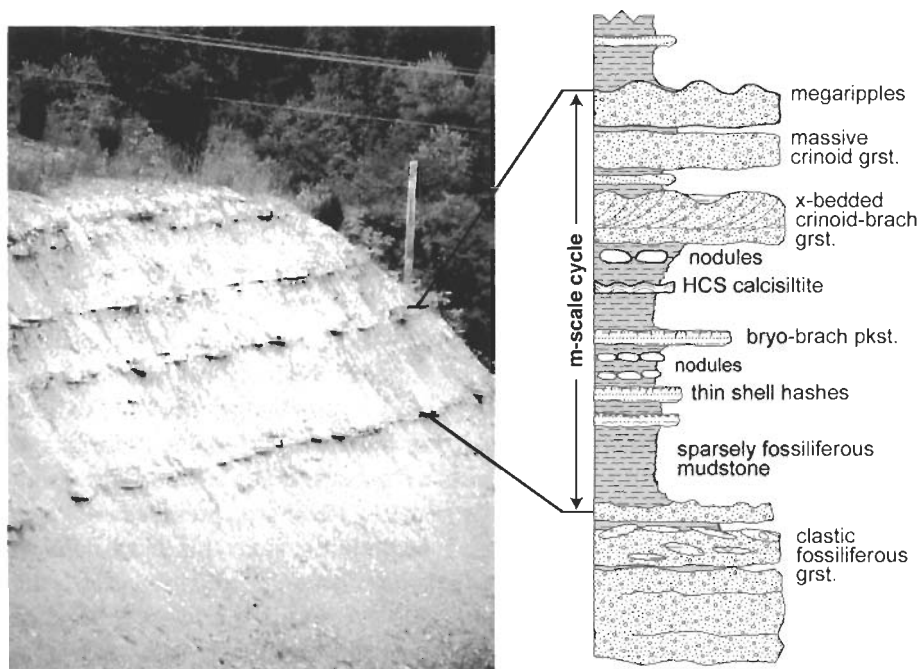
Figure 10. Meter-scale cycles; note sharp bases of limestone bed bundles, nodular underbeds, and rippled tops. Photo of Brent submember at KY Rte. 445 roadcut, Brent, Kentucky; approximately 9 m of section visible.

hardground development or molding into megaripples with a wavelength from 0.5 to 1.5 m (Fig. 8C).

The nature and interpretation of meter-scale cycles in the Kope Formation has long been debated (e.g., Tobin and Pryor, 1981), and current theory focuses on either eustatic fluctuations (Jennette and Pryor, 1993; Holland, 1997; Brett and Algeo, 2001a; Drummond and Sheets, 2001) or variable storm frequency or intensity (Holland *et al.*, 2001b). While it is not necessary to understand their genesis in order to use them for regional correlation purposes, their origin nevertheless has a bearing on lateral facies variation and degree of continuity. Relevant to the issue of their origin is that (1) Kope m-scale cycles are not simply random alternations of storm-influenced carbonate and background mud layers but, rather, represent an organized succession of lithologies, bedding patterns, and sedimentary structures and (2) shale hemicycles were deposited more rapidly than limestone hemicycles and, hence, are comparatively "time poor" (Brett and Algeo, 2001a). The mudstone intervals demonstrably do not represent gradual background accumulation but, rather, show evidence, such as micrograded beds and obrutionary (rapidly interred) fossil horizons, of accumulation as a series of episodic, rapid pulses. Conversely, most

limestone beds do not represent tempestites produced by single storm events but, rather, show evidence of long-term reworking of bioclasts and amalgamation of multiple storm-influenced layers (cf. Seilacher, 1985). Despite this, such beds frequently exhibit a signature (or "overprint") of the last event causing sediment mobilization. This includes basal lags of large, angular mudstone lithoclasts that would not withstand extensive reworking, as well as bedforms such as megaripples, hummocky cross-stratification, and millimeter ripples. Such beds are often laterally persistent and, in some cases, retain similar amalgamation patterns ("stratigraphic fingerprints") over distances of tens of kilometres. Such features suggest that m-scale cycles have an origin in extra-basinal mechanisms such as climate change or sea-level oscillation, rather than in intrinsic processes linked to the depositional system (Drummond and Sheets, 2001).

5.2   Decameter-Scale Cycles

Kope meter-scale cycles are organized into sets of thinning- and coarsening-upward units, yielding a readily apparent decameter-scale stacking pattern in outcrop (Fig. 11; Holland et al., 1997). The mudstone hemicycles (termed "Big Shales" by Brett and Algeo, 2001a) are composed of medium to dark gray shale and range from 1 to 7 m in thickness, comprising about 1/3 to 1/2 of a decimeter-scale cycle. They generally contain a sparse, low-diversity fauna of diminutive brachiopods, bivalves, crinoids, and trilobites, well-preserved pelagic taxa (e.g., graptolites and nautiloids), pyritized burrows, and plastically deformed mollusc shells. These features are consistent with low-oxygen bottom-water conditions, representing stressed environmental conditions, and early sulfide formation and dissolution of aragonitic shells in the sulfate-reduction zone. Toward their tops, the mudstone-dominated intervals contain increasingly frequent, thinly laminated calcisiltites and fossil packstones, many of which are lenticular and laterally discontinuous ("precursor beds" of Brett, 1995, 1998). The greater abundance and diversity of fossil faunas in these beds suggests better-oxygenated bottom-water conditions. Just below the base of the overlying limestone hemicycle, a carbonate nodule layer is often encountered (Fig. 10).

The limestone hemicycle of a decameter-scale cycle consists of several m-scale cycles (typically four or five) and ranges from 2 to 10 m in thickness. Limestone beds typically comprise about 30-70% of this interval and are generally grouped in bundles, representing the amalgamated caps of individual m-scale cycles. The uppermost, capping limestone beds of decameter-scale cycles frequently exhibit irregularly hummocky, stained
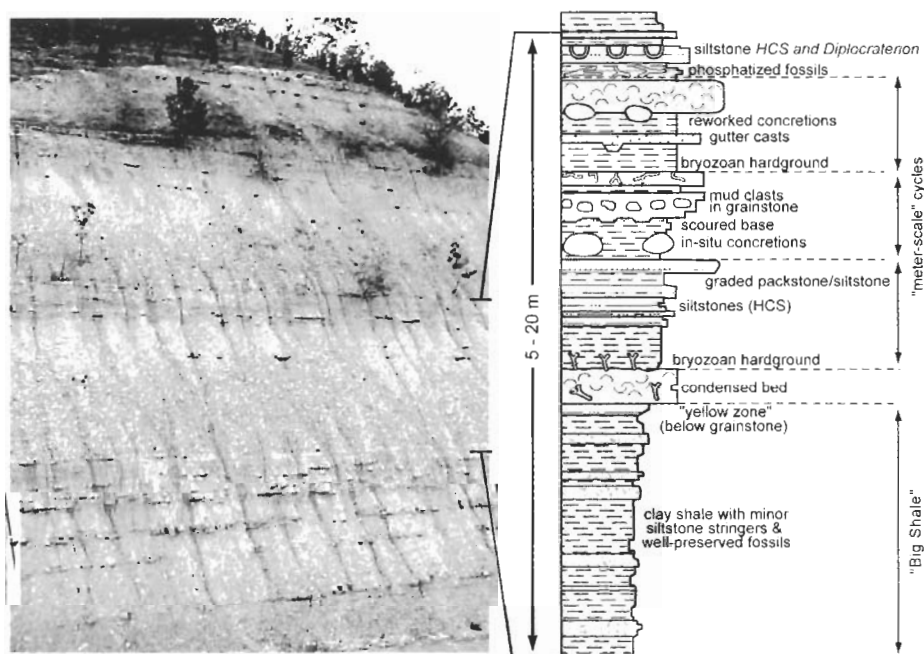
Figure 11. Decameter-scale cyclicity in Kope Formation. These larger stratal packages consist of a basal, 1- to 7-m-thick "Big Shale" overlain by a number of m-scale cycles; the latter tend to thin and become more amalgamated upward within each decameter-scale cycle. Seen here, from base to top, are the upper part of the Pioneer Valley submember, the complete Snag Creek and Alexandria submembers, and the lower part of the Grand View submember; from KY Rte. 445 roadcut, Brent, Kentucky. Diagram at right is an idealized decameter-scale cycle.

tops, darkened phosphatic- or pyrite-rich crusts as well as minor borings and encrusting organisms. Taphonomic features suggest that fossil debris in many beds has been subject to longer term reworking, marked by corroded fossil debris, hardgrounds, phosphatic staining, and other indications of an omission surface. The transition to an overlying "Big Shale" is typified by a thin bundle (0.1 to 0.5 m) of calcisiltites and/or packstones that shows excellent preservation of fossils, especially ramose bryozoans or, more rarely, a mollusc-dominated fauna.

As event beds are the building blocks of meter-scale cycles, the latter are the building blocks of decameter-scale cycles. Individual m-scale cycles tend to thin and become more carbonate-rich upward within decameter-scale cycles, so that the last few m-scale cycles may be represented by several closely stacked limestone bed bundles. The basal "Big Shales," ranging up to 7 m in thickness, may represent single, unusually thick and shaly m-scale cycles or, conversely, stacking of several thinner m-scale cycles lacking well-developed carbonate caps. In either case, the lower part of these "Big

Shales" clearly differs from the shale hemicycles of m-scale cycles toward the top of decameter-scale units in showing evidence of more dysoxic bottom-water conditions (e.g., impoverished biota, abundant pyrite) and containing fewer calcisiltite/packstone interbeds. These features suggest that the basal portions of "Big Shales" represent maximum highstand conditions. This is consistent with an analysis of Kope faunal patterns by Holland *et al.* (2001a), who inferred abrupt shifts toward deeper water biofacies and gradual transitions back toward shallower water facies within their "20 meter cycles."

6.   EXAMPLE OF DETAILED CORRELATION: FULTON SUBMEMBER OF THE KOPE FORMATION

To better illustrate the lateral continuity of cycles and component event beds in the Kope Formation, we will elaborate on the internal stratigraphy of one decameter-scale cycle, the Fulton submember, representing the basal 6 to 7 m of the Kope. The Fulton is bounded below by the limestone-dominated Point Pleasant Formation and above by Big Shale #2 (base of Brent submember) of the Kope; for this reason, it is easily identifiable throughout the study area. The Fulton displays excellent development of meter-scale cyclicity (four cycles averaging 1.5 m in thickness) and contains a number of highly distinctive, widely traceable event beds, providing the basis for high-resolution correlation at a regional scale (Fig. 12). On the basis of its composition and internal structure, each Fulton cycle is readily correlatable along the 80-km-long Cincinnati-Maysville axis.

6.1   Cycle F1

The first Fulton cycle starts in the upper half meter of the Point Pleasant Fm with a stack of compact *Merocrinus*-bearing skeletal grainstones including the uppermost "Sugar Creek bed." This distinctive bed is identifiable across the study area as it contains large platters as well as having a heavily mineralized upper surface. Near Cincinnati, the "Sugar Creek bed" is overlain by approximately 40 to 50 cm of pale-gray-to-green, yellow weathering, sticky clay shale containing only thin lamina of the otherwise rare brachiopods *Onniella emacerata* and *Leptaena*. These basal shales of the Fulton submember are overlain by a 20-cm interval containing two or three pale-gray concretion layers capped by a two-part concretionary packstone to calcisiltite. This bed contains dalmanellid brachiopods and
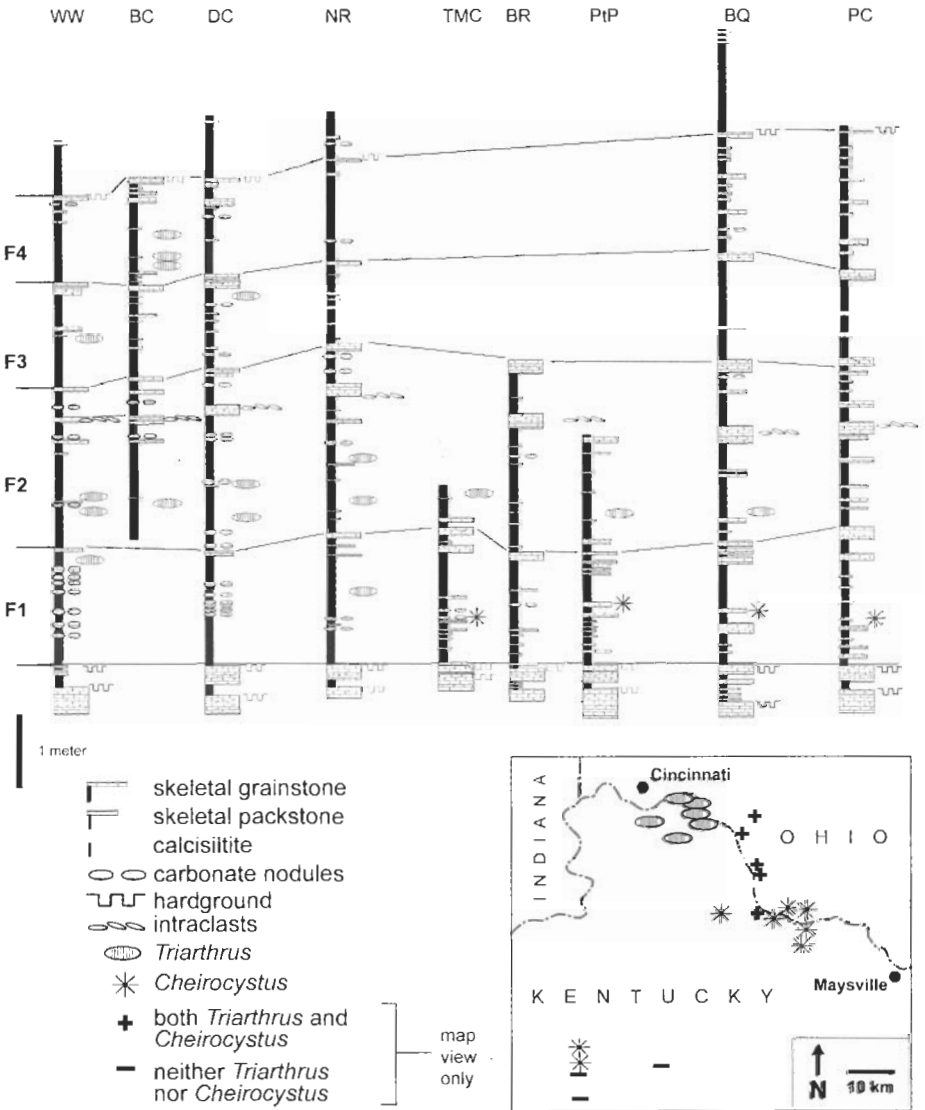
Figure 12. Detailed cross-section of the Fulton submember along the Cincinnati, Ohio-Maysville, Kentucky axis. The Fulton submember consists of four m-scale cycles, here numbered F1-F4 (the basal Kope is not exposed at KY Rte. 445 and, hence, was not numbered by Holland *et al.* (1997)). The distribution of *Triarthrus* and *Cheirocystis* beds in the Fulton submember is shown in the map inset at lower right.

crinoid fragments near Cincinnati, but passes laterally into a thin packstone containing abundant plates and columnals of the rhombiferan cystoid *Cheirocystis fultonensis* (Figure 5B), plus abundant brachiopods *Onniella,* and *Zygospira,* the trilobite *Flexicalymene,* and rare *Aspidopora* bryozoans.

This thin bed has a very distinctive taphonomic signature and can be traced over an area of at least 500 km in northern Kentucky (Fig. 12). It is consistently 50 to 60 cm above the base of the Kope.

6.2   Cycle F2

Packstones containing abundant fragmentary *Onniella*, *Cryptolithus*, and columnals of *Merocrinus* form the base of this cycle in the Cincinnati area. Southeastward, these muddy packstones grade into thicker (20-cm) *Merocrinus*-rich grainstones. Near Cincinnati, the upper grainstone is overlain by two concretionary, rusty weathering calcisiltites that mark the base of the overlying shaly interval. These are interbedded with pale olive gray to dark brownish gray shales, which contain lenses of packstone or fossiliferous mudstone with *Merocrinus* columns. Articulated specimens of the trilobite *Triarthrus* found within this interval are widespread and may be current aligned. Complete *Onniella* and a small number of articulated *Isotelus* and *Cryptolithus* also occur at this level. These are followed by over 1 m of nearly pure claystones that vary in color from pale olive gray to dark brownish gray. Particularly notable is a zone from 12 to 20 cm thick of dark brownish gray, slightly platy shale containing abundant cranidia of *Triarthrus* plus the small inarticulate brachiopod *Mesobolus*. A thin *Merocrinus*-bearing calcareous siltstone may occur within this band. This is the thickest dark brownish gray unit and *Triarthrus* have been found rarely in this interval as far to the southeast as Holst Creek (Fig. 12). Locally, at "Waterworks Creek," near Fort Thomas, Kentucky, the lower portion of the dark brownish gray shale fills a gutter-like scour cut some 10 cm into the underlying olive mudstone. Near Cincinnati the *Triarthrus* beds pass upward into about 50-80 cm of variegated olive to dark gray sparsely fossiliferous shales. However, tracing this interval to the south, thin calcisiltites give way to more prominent skeletal wackestones and packstones. This interval is capped by a weakly developed crinoidal pack- to grainstone, which breaks locally into several thin packstones and varies from 0 to 10 cm; locally it is represented by a series of starved ripples. A distinctive feature of this bed near Cincinnati is the presence of ellipsoidal concretions at its base; where the bed is missing in starved ripple troughs, the concretions are still present.

6.3   Cycle F3

The base of this cycle is a 60- to 80-cm-thick interval composed of two *Merocrinus*-bearing grainstones. The lower one is a thick, megarippled, fine-grained, crinoid-brachiopod grainstone and is typically the thickest and

we studied more than 60 sections in northern Kentucky representing all submembers of the Kope Formation (Algeo and Brett, 2001). Each section was measured and described at a centimeter scale, noting lithology, fossil content, taphonomic features, sedimentary structures, bedding characteristics, and other salient features. Certain event beds were collected and slabbed for detailed petrographic examination. Measured sections were then compared, and field sections revisited as needed, in order to verify correlations.

In general, we established regional correlations proceeding from larger-scale features (e.g., the "Big Shales" and decameter-scale cycles) to smaller-scale features (e.g., m-scale cycles and event beds; Figs. 13-14). Each decameter-scale cycle (or submember of the Kope) exhibits a highly distinctive succession of beds, based on lithology, bed thickness, and spacing, that provides a "bar code" unique to that stratigraphic interval. These characteristic bedding patterns were generally identifiable in a succession of outcrops, changing only gradually if at all across the 80-km-wide study area. Although individual beds are sometimes visibly discontinuous at an outcrop scale, we observed that these beds were commonly present at the same stratigraphic level in the next outcrop a few kilometers distant. From this, we concluded that such apparently discontinuous beds are generally persistent as a series of lenses over a broader area.

Other researchers have used different approaches for regional correlation of the Kope Formation. Correlations based on generalized stratigraphic trends in lithology are possible where stratigraphic sections are converted to running averages of percent shale. This procedure, which has a ca. 1-meter scale of resolution, was applied to the Fairview Formation and Miamitown Shale by Dattilo (1996, 1998) and to the Kope Formation by Webber (2001). Another approach is statistical cross-correlation of shale-limestone "bar codes" for pairs of stratigraphic sections to establish the best match. Holland *et al.* (2000) employed this approach to correlate the Kope in the White Castle section of Hughes and Cooper (1999) with the KY Rte. 445 reference section of Holland *et al.* (1997). Both of these approaches have yielded reasonable results, but we think that neither is superior to our method of comparing event beds and cycles in high-resolution (cm-scale) measured sections.

7.2   Implications

High-resolution regional correlation of the Southgate and McMicken members, representing the middle and upper Kope, respectively,
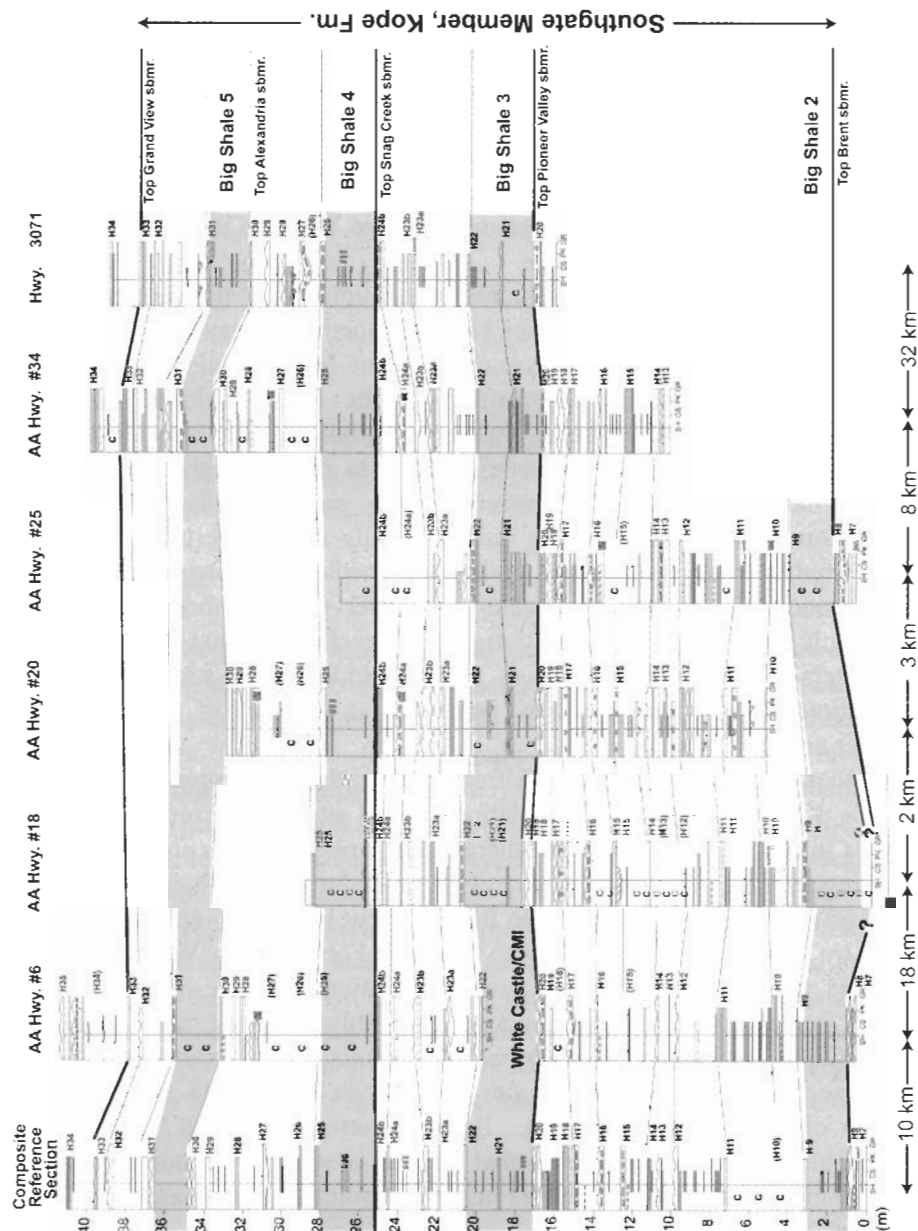
Figure 13. Generalized correlated cross-section of the Southgate Member (Pioneer Valley, Snag Creek, Alexandria, and Grand View submembers) of the Kope Fm. along the Cincinnati, Ohio-Maysville, Kentucky axis. Lithologic key: SH = shale, CS = calcisiltite, PK = packstone, and GR = grainstone; C = covered. Big Shales 2-5 are shaded. Cycle numbers are those of Holland *et al.* (1997), prefixed with an "H" to distinguish them from cycles of the Fulton submember of the Kope and those of other Edenian-Maysvillian formations in the Tristate area.
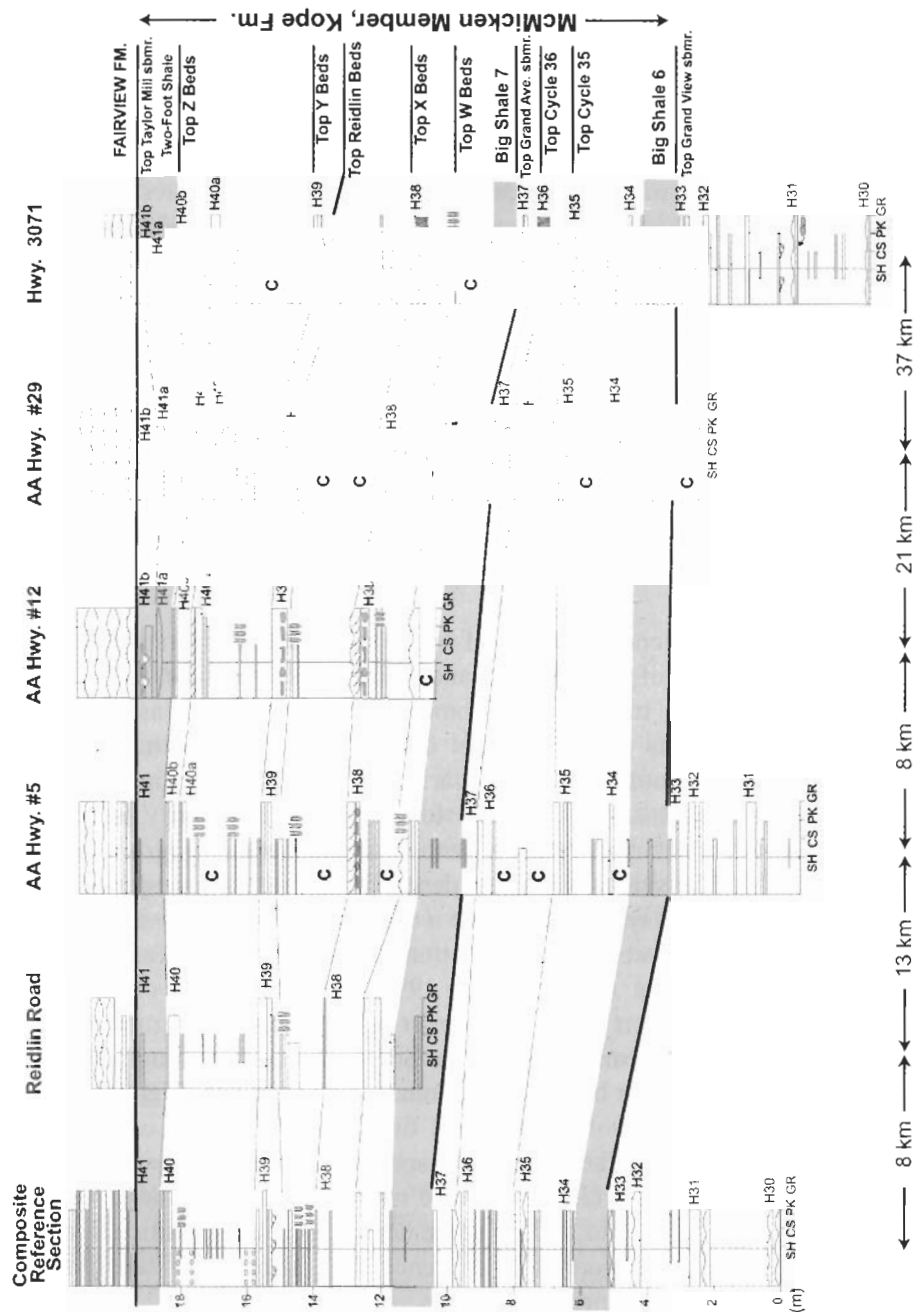
Figure 14. Generalized correlated cross-section of the McMicken Member (Grand Avenue and Taylor Mill submembers) of the Kope Fm. along the Cincinnati, Ohio-Maysville, Kentucky axis. See Figure 13 caption for more information.

demonstrates the regional continuity of all decameter-scale and most m-scale stratal packages (Figs. 13-14). Almost all cycle-capping limestone beds are continuous across the study area (possibly excepting H26), in many instances exhibiting similar thicknesses and sedimentary structures from Cincinnati to Maysville, a distance of 80 km. In some cases, even single event beds (e.g., distinctive calcisiltites containing gutter casts or *Diplocraterion* such as those in cycles H38-H40) can be traced over this distance. Furthermore, changes in thickness and lithofacies across the study area are small. The Kope Formation exhibits no discernible change in thickness regionally, a slight thinning of the middle Kope being compensated by a slight increase in thickness of the upper Kope at Maysville. Facies within any single cycle are also quite similar regionally, although capping limestones tend to be slightly thicker and calcisiltites slightly more numerous at Maysville than at Cincinnati (Figs. 13-14). Thus, the empirical evidence suggests that the internal stratigraphy of the Cincinnatian Series hews more closely to a "layer-cake" model than to the local facies mosaic that has been depicted in recent publications (e.g., Davis and Cuffey, 1998).

The strong lateral correlatability of meter-scale and finer stratal packages and the uniformity of thicknesses and lithofacies over the 80-km-long Cincinnati-Maysville transect are somewhat surprising in as much as preliminary work on a north-south Cincinnati-Lexington transect has revealed more pronounced lateral variation within the Kope. These observations strongly suggest that the former transect is nearly parallel to regional depositional strike, possibly with a slight increase in proximity in the direction of Maysville. Other evidence for an increase in depositional proximity toward Maysville includes a faunal gradient analysis (Webber, in press) as well as lateral facies relations in the overlying Fairview and Grant Lake formations (Schumacher, 1992, 1998). These observations provide empirical support for Wickstrom *et al.*'s (1992) reconstruction of an east-southeast-oriented embayment in the Sebree Trough, running parallel to the axis of the Ohio River between Cincinnati and Maysville (Fig. 3).

A further implication of the regional fine-scale correlation of the Kope demonstrated here is that the processes responsible for producing decameter- and m-scale patterns of cyclicity operated over wide areas of the Lexington Platform, at least parallel to and, to some degree, across depositional strike. This result strongly supports the inference that patterns of stratigraphic accumulation in the Cincinnati Series were controlled by allocyclic processes (e.g., eustatic or climatic changes) as opposed to strictly local autogenic phenomena.

8.   SUMMARY

A regional high-resolution correlation framework has been developed for the Upper Ordovician (Edenian) Kope Formation on the basis of event beds and sedimentary cyclicity. The correlation framework comprises eight decameter-scale and forty-one meter-scale cycles along a ca. 80-km transect from Cincinnati to Maysville, Kentucky. In addition, many individual event beds containing faunal epiboles or distinctive ichnofossils, taphonomic features, or sedimentary structures can be traced at a local to regional scale. Thus, the recent paradigm of the Cincinnatian Series as a complex facies mosaic is incorrect. Rather, the Kope Formation displays a very predictable, layer-cake-like stratigraphy, at least parallel to depositional strike. The wide correlatability of small-scale stratal packages suggests ultimate control of Kope sedimentation by allocyclic forcing mechanisms, possibly glacio-eustasy. This study demonstrates that accurate high-resolution regional correlation of thick, lithologically repetitive successions is possible given sufficiently detailed stratigraphic observations.

ACKNOWLEDGMENTS

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