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SUBSURFACE CORRELATION AND PALEOGEOGRAPHY OF A MIXED SILICICLASTIC-CARBONATE UNIT USING DISTINCTIVE FAUNAL HORIZONS: TOWARD A NEW METHODOLOGY

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ABSTRACT

Regional correlation of mudrock-siliciclastic units is challenging, largely owing to the apparent featurelessness of fine-grained intervals. This difficulty is multiplied when subsurface correlation is necessary for paleogeographic reconstruction. In this study, faunal-marker tracing and limestone-pattern matching have permitted subsurface correlation of the Alexandria submember of the Kope Formation (Edenian Stage, Upper Ordovician) over a 193-km transect in southwest Ohio. The faunal markers are thin (<10 cm), widespread deposits of skeletal debris exhibiting faunal associations, degrees of preservation, or both, that distinguish them from other fossil deposits in host mudrocks. Subsurface correlations corroborate interpretations of southwest Ohio paleogeography and demonstrate the usefulness of techniques presented here. Geographic trends in the data indicate that the average seafloor slope over much of the Cincinnati region was near zero. Evidence also indicates a northwest-dipping paleoslope approximately normal to the study transect; this is likely a transition from the Kope environment into the Sebree Trough, a narrow basin with poorly understood morphology. A change from limestone-rich to limestone-poor facies, accompanied by replacement of oxic by dysoxic fauna, takes place over a maximum distance of 40 km between two localities along the transect. This represents improved constraint on the Kope–Sebree Trough boundary.

INTRODUCTION

Meaningful reconstruction of depositional and paleoecological dynamics and detailed paleogeography require precise stratigraphic correlations between measured sections, typically over long distances (tens to hundreds of kilometers). Correlation of repetitive alternations of thin limestones and thicker mudrocks is especially challenging owing in large part to the apparently featureless nature of mudrock intervals. Outcrop-based tracing of biostratigraphic zones has been the conventional correlation tool used in offshore marine successions. Stratigraphies constructed solely on this basis, however, tend to have resolutions of a few meters at best, and facies change can make matching uncertain on regional scales.

Cross-correlation techniques (*sensu* Anderson and Kirkland, 1966), supplemented by paleoecological analysis, have also shown some promise (Holland et al., 2000), as have biostratigraphic studies of units in Australia, Mississippi, and Wyoming (George et al., 1997; Puckett and Mancini, 1999; Saltzman, 1999; Gallagher and Holdgate, 2000), although biostratigraphic techniques have their problems as well. The stratigraphic range of a species whose occurrence is facies controlled can become truncated at its upper and lower ends with even relatively small environmental changes along depositional dip, creating the potential for incorrect regional scale correlation (Holland et al., 2000); moreover, zonal species may be absent in local sections. Additionally, the precision in resolving correlations with biostratigraphy is typically low and permissive of more than one scenario in terms of correlating beds or small cycles.

These problems are multiplied when it becomes necessary to work in the subsurface, as is frequently the case when paleogeographic studies on a regional scale are being conducted. Cores and drill cuttings are the only resources available that allow direct examination of the rock, and only cores preserve the vertical succession of the unit under investigation. The small size of a typical core (usually <8 cm in diameter) severely restricts sedimentologic and taphonomic analyses and completely rules out the use of many destructive analyses, such as conodont extraction. In addition, the great expense of drilling cores limits their number and availability. In many situations, however, the use of cores is critical to a complete reconstruction of a depositional environment, especially in areas where outcrops are limited or nonexistent. Thus the worker analyzing a unit in the subsurface faces a dilemma: how to correlate across a region that is possibly hundreds of square kilometers in size using only pinpoint samples of a unit that is difficult to correlate even in outcrop? Is it possible to recognize and trace markers at meter, decimeter, or even centimeter scale in cores?

Stratigraphers studying the well-known Kope Formation (Edenian Stage, Cincinnatian Series, Upper Ordovician; see Fig. 1), a mixed siliciclastic-carbonate unit in southwest Ohio and northern Kentucky, have made significant progress in developing high-resolution correlations in outcrops (e.g., Jennette and Pryor, 1993; Miller et al., 1997; Diekmeyer, 1998; Brett and Algeo, 2001; Brett et al., 2003). The methods and results presented in this paper offer further promising solutions to the problems of regional-scale subsurface correlation at high resolution (<1 m) of mudrock-dominated, siliciclastic-carbonate units and new insights into the paleogeography of the Cincinnati, Ohio, area during the Late Ordovician. The use of faunal-marker horizons as correlation tools has provided at least a partial solution to this problem in the Kope Formation. The mudrocks of the Kope are for the most part only sparsely fossiliferous (Weiss and Sweet, 1964) but contain thin (generally <10 cm thick), fossil-rich beds with unique assemblages or taphonomies at various horizons (Jennette and Pryor, 1993; Brett and Algeo, 2001; Brett et al., 2003). These deposits are faunally and taphonomically distinct from one another, and it has been shown that the same assemblages with the same preservation states can be found at the same stratigraphic levels consistently throughout many Kope outcrops in northern Kentucky and the Cincinnati vicinity (Brett and Algeo, 2001).

A high-resolution (<1 m) outcrop-based stratigraphy has evolved from previous studies using both faunal-marker horizons and stratigraphic pattern matching of lithologies (Holland et al., 2000; Brett and Algeo, 2001), but a complete picture of the Kope depositional environment depends upon extending this outcrop-based stratigraphy into the subsurface north of Cincinnati. This paper presents a case study of the application of event-bed correlation for developing high-resolution correlation of a single decameter-scale

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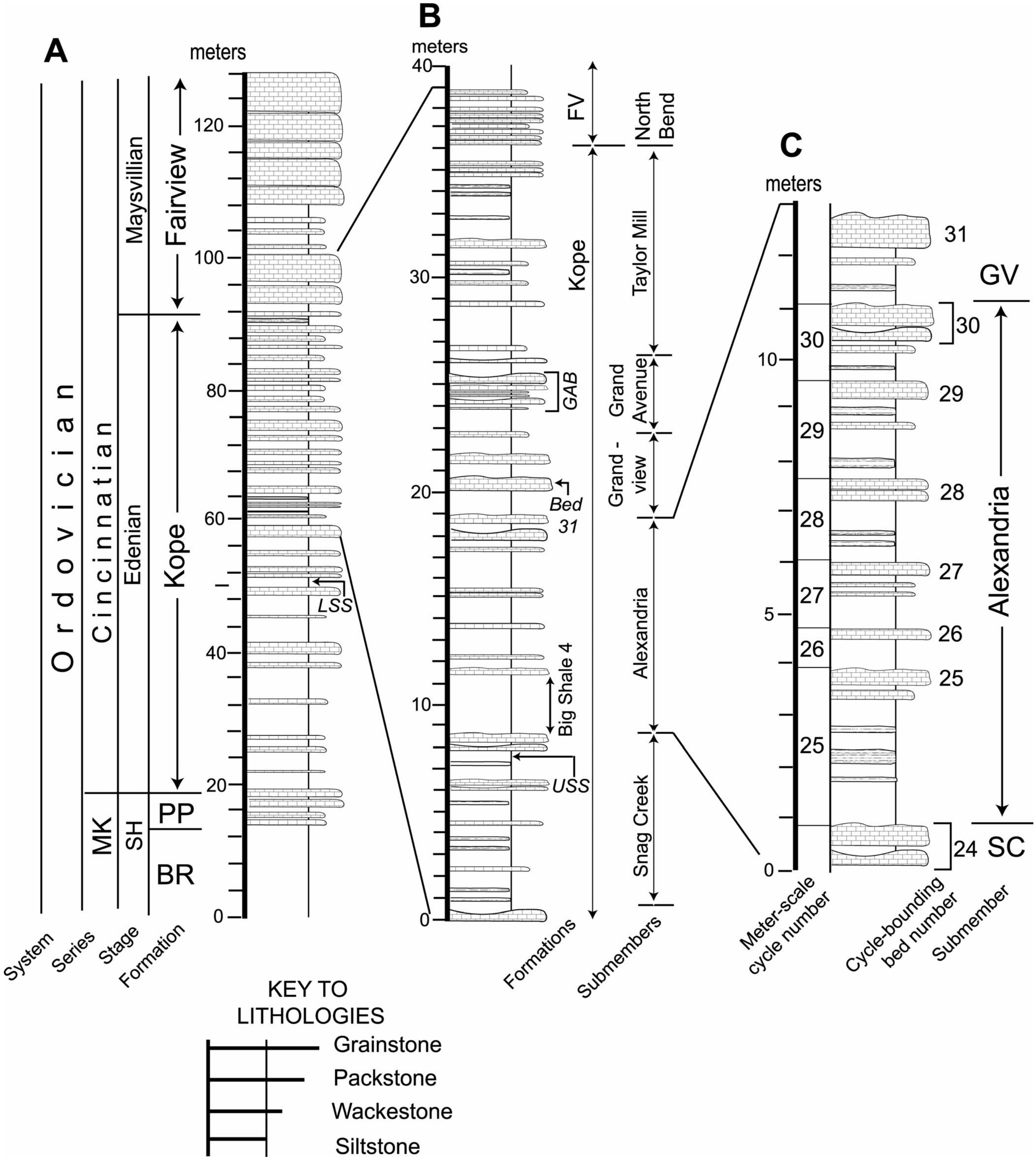

FIGURE 1—Upper Ordovician stratigraphy of the Cincinnati, Ohio region. A) Generalized stratigraphy of uppermost Mohawkian and lower Cincinnatian Series. BR = Bromley Shale; LSS = lower strophic *Sowerbyella rugosa* interval (see Results section for discussion); MK = Mohawkian Series; PP = Point Pleasant Formation; SH = Shermanian Stage (after Caster et al., 1955). B) Stratigraphy of middle and upper Kope and lower Fairview Formations, showing Kope submembers as designated by Brett and Algeo (2001). See text for discussion of Big Shale 4. USS = upper strophic *Sowerbyella rugosa* interval; GAB = Grand Avenue Beds; FV = Fairview Formation (after Brett and Algeo, 2001). C) Detailed stratigraphy of the Alexandria submember and the upper Snag Creek (SC) and lower Grandview (GV) submembers. Numbers immediately to left of column are meter-scale cycle designations; numbers to right are designations of cycle-bounding limestone beds (adapted from Brett and Algeo, 2001).

submember the Kope Formation in the subsurface to test the efficacy of this method. These correlations were constructed using lithologic pattern matching and fossil event beds in combination. On the basis of refined correlations, the depositional setting and paleogeography can also be reinterpreted. Results presented here demonstrate that a correlation method involving lithologic pattern matching and unique fossil event beds can be used successfully in cores, thus overcoming many of the problems that plague regional-scale correlations in mudrock-dominated units.

BACKGROUND

General Description of the Kope Formation

The Kope Formation in southwestern Ohio and northernmost Kentucky consists of an average of ~80% mudrock interbedded with 20% limestone and siltstone (Weiss and Sweet, 1964; Jennette and Pryor, 1993); it is made up of eight decameter-scale cycles, defined as informal submembers by Brett and Algeo (2001). Each of these, in turn, is subdivided into a number of meter-scale cycles composed of mudrock and limestone hemicycles (Jennette and Pryor, 1993; Holland et al., 1997; Brett and Algeo, 2001); the mudrocks are generally ~0.5–1 m thick, and the limestone hemicycles usually between 5–15 cm in thickness. The meter-scale cycles in actuality range in thickness from 0.5 m to 3 m (Jennette and Pryor, 1993).

The limestone hemicycles occur either as bundles of limestone beds interbedded with thin mudrocks or as single limestone beds of varying thickness. Individual limestone beds are highly fossiliferous packstones and grainstones with occasional wackestones, ranging in thickness from <1 cm to >30 cm in some northern Kentucky and Cincinnati localities (Brett and Algeo, 2001). Fossils in the limestones consist in large part of disarticulated brachiopod valves (e.g., *Dalmanella*, *Sowerbyella*), trilobite fragments (e.g., *Isotelus*, *Flexicalymene*), crinoid columnals (mainly *Cincinnaticrinus* and *Ectenocrinus*), and ramose, encrusting, and bifoliate bryozoans (Caster et al., 1955; Brett and Algeo, 2001; Webber, 2002). Also present in lower abundances are varied gastropods, bivalves, and graptolites (Brett and Algeo, 2001).

Mudrocks of the Kope initially appear to be nearly featureless packages of blocky, light-gray-to-gray-green mudstones with occasional sparse fossil debris beds. Under close inspection, however, they reveal a variety of sedimentological features, including laminations, burrows, fossil debris (either concentrated on bedding planes or scattered through mudrock intervals as isolated fragments), and erosional mud- or silt-filled scours that may be storm related (Hughes and Cooper, 1999). Taxa typical of the Kope mudrocks in outcrop include *Isotelus*, *Zygospira*, *Flexicalymene*, *Cincinnaticrinus*, *Ectenocrinus*, and graptolites, with occasional *Dalmanella*, *Iocrinus*, bryozoans (usually ramose), bivalves, and gastropods (Caster et al., 1955; Holland et al., 2000; Brett and Algeo, 2001). The taphonomic character of fossil debris in the mudrocks varies widely, from fragmented brachiopod valves to completely articulated trilobite exuviae and crinoid stalks.

Description of the Alexandria Submember

One decameter-scale interval of the middle Kope was selected for study. This interval, informally designated the Alexandria submember (Fig. 1) by Brett and Algeo (2001), was chosen for correlation because several key marker beds have previously been identified and traced in its mudrocks (Brett and Algeo, 2001). In the sections used in this study, the Alexandria submember ranges from 6 m to 9 m thick and consists of six meter-scale cycles, designated cycles 25–30 (Holland et al., 1997; Brett and Algeo, 2001; see Fig. 1). Each cycle consists of a mudrock interval topped by a bed or bed bundle of packstones and grainstones. The thickest meter-scale cycle in the submember is the lowest, cycle 25 (averaging ~2 m thick), and the thinnest lies at the top, cycle 30, which averages only ~75 cm thick (Brett and Algeo, 2001). In this paper, the capping limestone beds of each cycle are given the number of the cycle itself; for example, cycle 30 has bed 30 at its top.

Paleogeography of the Study Area

The Kope Formation was deposited in an epeiric sea in a transition zone between a carbonate-dominated shallow platform to the south and southeast, the Lexington Platform, and the Sebree Trough, a narrow basin to the north and northwest (Fig. 2; see Mitchell and Bergström, 1991). During Edenian time, the region was situated 300–500 km west of the western margin of Laurentia at about 20°–25° S latitude (Scotese, 1990),

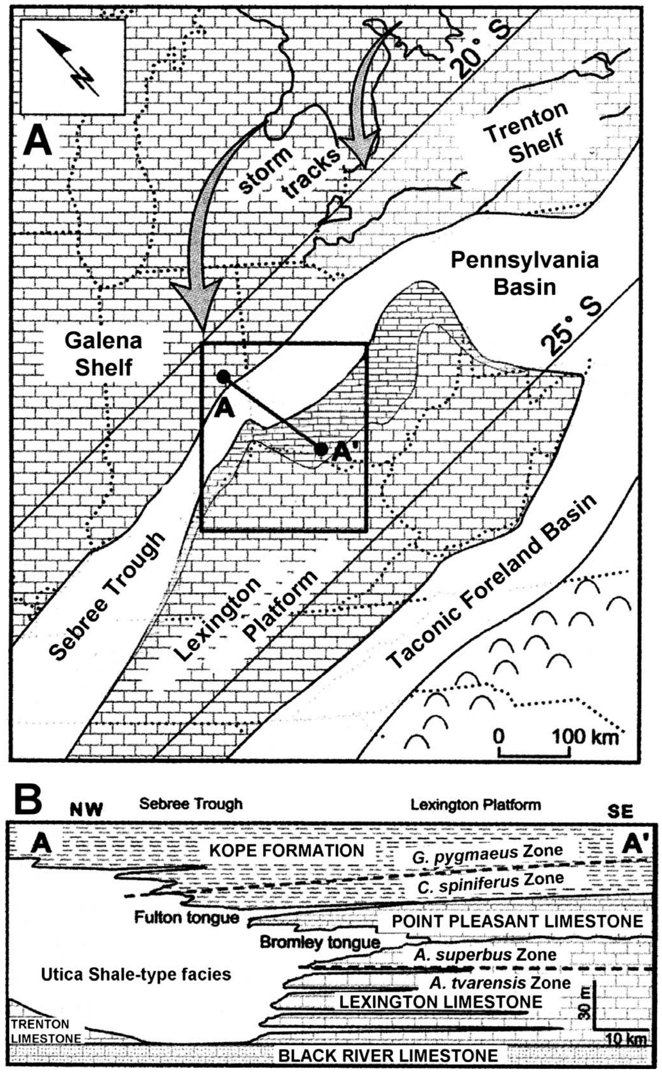

FIGURE 2—Paleogeography of the Cincinnati Arch region. A) Overview of the tristate area showing the major facies belts and latitudinal position during Late Ordovician (Edenian) time. Rectangle = study area; arrows = probable hurricane tracks through region. B) Facies changes of cross section A–A′. Note transition of Kope into dark gray Utica Shale–type facies to the northwest.

a likely major tropical storm and hurricane track (Marsaglia and Klein, 1983). This inference is strongly supported by the presence of numerous storm-related sedimentologic features throughout the Kope, including reworked and amalgamated limestones, scours, gutter casts, hummocky cross-stratification, erosive bed bases, and edgewise deposits of brachiopod valves (Jennette and Pryor, 1993; Holland et al., 1997; Brett and Algeo, 2001). Storms may have played a major role in Kope deposition by winnowing and redepositing fine-grained siliciclastic and carbonate sediments (Jennette and Pryor, 1993). The Taconic (Vermontian or Taconian phase) orogenic belt to the northeast and east was active during the Edenian Stage (Ettensohn, 1991) and was probably the major source for siliciclastic sediment. The Sebree Trough is thought to have been connected at its northeastern end to the Taconic foreland basin (Mitchell and Bergström, 1991); isopach patterns from that study suggest that Kope mudrocks of Taconic origin were transported from the foreland basin southwestward down the trough to the distal (north and northwestern) part of the Kope ramp. Minor amounts of mud and silt from the older Blountian highlands to the east and southeast may also have been transported across the Lexington Platform into the Kope depositional setting.

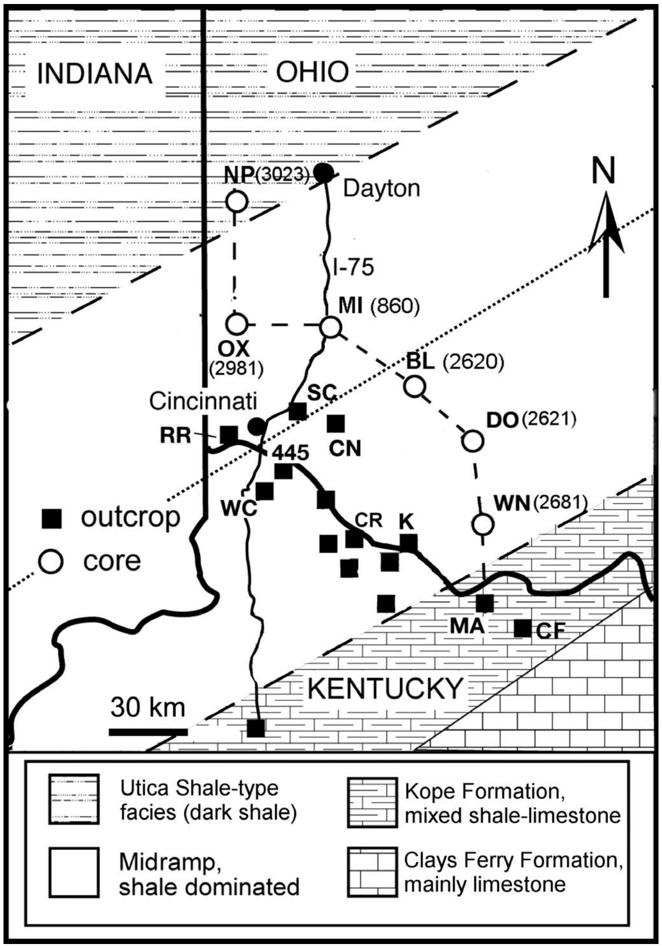

FIGURE 3—Location of outcrops and drill cores used in this study projected onto a facies schematic for the Kope Formation. Note transition from limestone-rich shelf deposits in the SE into dark, graptolitic shale in the Sebree Trough to the NW. Sections shown have entire Kope Formation or its equivalents exposed, approximately 75–80 m of section. Dotted line = furthest SE extent of *Triarthrus* in study sections; open circles = key drill cores (numbers in parentheses = Ohio Department of Natural Resources core numbers); solid circles = outcrops. Core abbreviations: BL = Blanchester (2620); DO = Dodsonville (2621); MI = Middletown (860); NP = New Paris (3023); OX = Oxford (2981); WN = Winchester (2681). Outcrop abbreviations: 445 = Route 445 roadcut; CF = Clays Ferry; CN = Cincinnati Nature Center; CR = Carntown; K = Kope Hollow; MA = Maysville; RR = Rapid Run; SC = Sycamore Creek; WC = White Castle Distribution Center.

METHODS AND MATERIALS

Seven stratigraphic sections form the basis of this study. Six cores from southwest Ohio were examined, designated here as Winchester, Dodsonville, Blanchester, Middletown, Oxford, and New Paris (Ohio Geological Survey core nos. 2681, 2621, 2620, 860, 2981, and 3023, respectively). For all cores, closely spaced surfaces were exposed by breaking cores crosswise along as many bedding planes as could be readily split. All lithologies, bed thicknesses, sedimentary structures, and faunal assemblages were logged at centimeter scale for the entire Alexandria submember. All specimens are deposited in the collections of the Cincinnati Museum Center, Cincinnati, Ohio. Lithologic and faunal data from Kohrs (2003) and Webber (personal communication, 2003) were included for an outcrop section at Maysville, Kentucky (Fig. 3). These seven sections were correlated, with the Maysville section serving as the proximal (upramp) end member for the cross section. The correlated sections form a transect designed to allow direct observation of facies changes in the subsurface and characterize the transition into the Sebree Trough. The transect extends from Maysville, Kentucky, northwestward, with a total length of ~193 km (Fig. 3).

Correlation Methods

The correlation technique employed in this study integrates visual matching of lithologic patterns in cores with the use of widespread faunal marker horizons. This method has shown promise in recent work (Brett et al., 2003) and is further extended here by application to subsurface investigation. This extension represents an important step in developing a more generalized correlation methodology applicable to other units.

The most reliable method for locating the Alexandria submember in each core was to use the base of the Kope Formation as a reference point, then move upward until the base of the Alexandria was found. The base of the Kope was pinpointed by locating the underlying Point Pleasant Limestone bundle (Fig. 1), which was generally distinctive and easily located in the cores, and by referring to lithologic descriptions of each core provided by the Ohio Geological Survey. Once this was accomplished, the overlying core was examined for distinctive lithologic patterns that could be matched with known patterns in the outcrop-based Kope stratigraphy of Brett and Algeo (2001). Distinctive lithologic successions and faunal occurrences in thin intervals were especially helpful. The basic procedure used is as follows: (1) locate the Alexandria submember unambiguously in each core, (2) identify marker limestone beds and meter-scale cycles, and (3) examine intervening shale intervals for faunal markers (epiboles, event beds) as a test of pattern-matching correlations.

Once the Alexandria submember was found, delineation of the meter-scale cycles within it could begin. This phase consisted of making cycle boundary picks for the submember on the basis of (1) the locations of major limestones, (2) the proportional spacing of limestones and mudrocks compared with known patterns from other sections, and (3) the positions of all faunal markers found during logging. Cores were examined multiple times during this phase, with faunal-marker locations being checked against the lithologic patterns of the intervals in which they were found, and vice versa. At least three of these examinations were carried out on each core before cycle boundary picks were finalized.

Faunal-abundance data were collected for three environmentally diagnostic taxa through all six cycles in all study sections. The taxa are *Leptobolus insignis* (a lingulid brachiopod) and *Triarthrus* sp. (an olenid trilobite), both indicative of a restricted circulation, dysoxic environment (generally deep basins), and *Rafinesquina* sp. (a strophomenid brachiopod), indicating a shallow-water setting. Visual estimation and a semiquantitative scale were used to assess relative specimen abundance on each bedding plane where a particular taxon was found. The categories used in the abundance scale were 0 (absent), 1 (rare; <5 individuals found in submember interval), 2 (common; 5–10 individuals found), and 3 (abundant; >10 found), following the basic procedures of Holland et al. (2001).

RESULTS

Correlation of Marker Limestone Beds

Results of this study indicate for the first time that all major limestone beds used to delineate decameter- and meter-scale cycles in the Kope Formation of the Cincinnati area by Holland et al. (1997) can also be traced regionally throughout the outcrop belt and subsurface (Fig. 4). Three particular features were very helpful in locating the Alexandria submember during this phase of correlation (Fig. 1):

1. The brachiopod *Sowerbyella rugosa* occurs abundantly in two intervals in the middle Kope; both intervals serve as useful landmarks in locating the basal Alexandria submember. The first occurrence is in the upper Pioneer Valley submember, approximately 8 m below the Alexandria (Brett and Algeo, 2001), and was found in several of the cores; the base of the Alexandria could be located with relative ease by search-

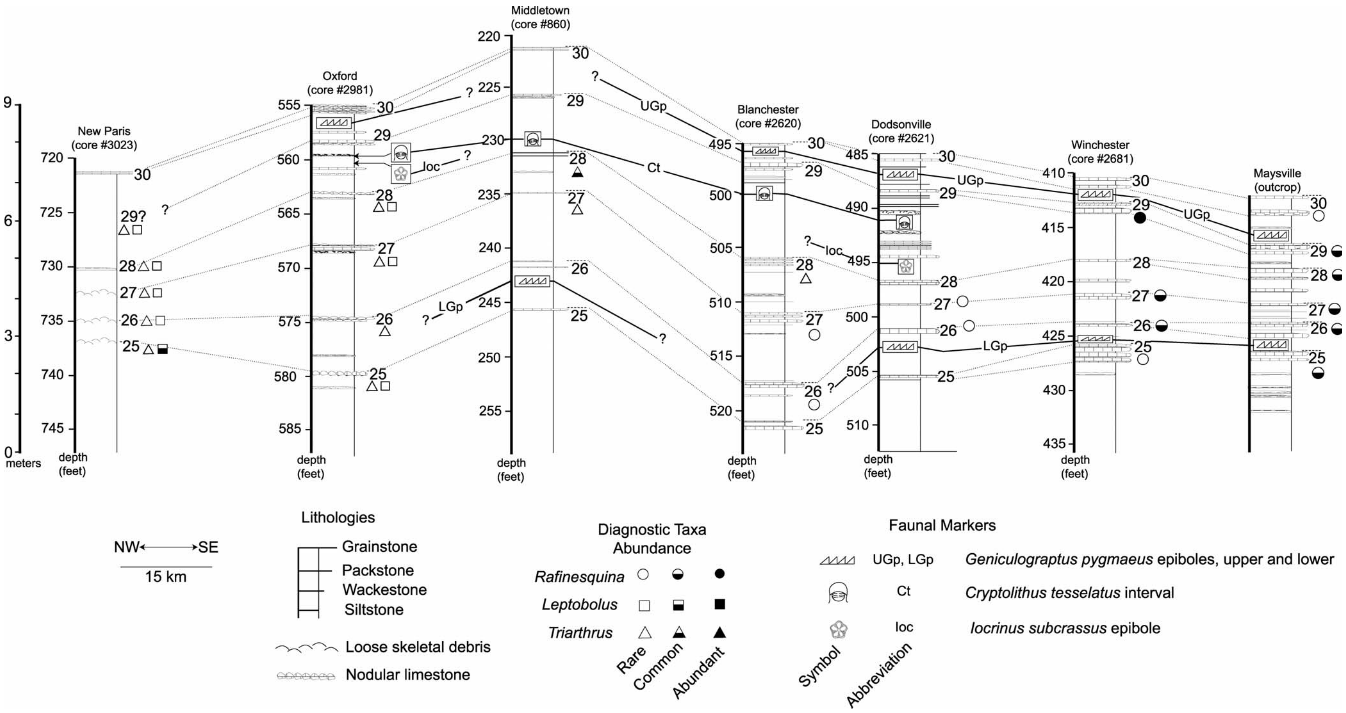

FIGURE 4—Stratigraphic sections for all study locations showing correlations using cycle-bounding limestones and faunal markers. Faunal symbols = locations of key faunal markers; geometric shapes = per-cycle average abundances (by visual estimate) of three environmentally diagnostic taxa. Cycle-bounding limestone beds are marked by numbers 25–30 next to each bed. See Figure 3 for section locations and other abbreviations. Datum for all sections is the base of the Alexandria submember. For the Maysville section, lithologic data from Kohrs (2003); data for *Triarthrus* and *Leptobolus* from C.E. Brett (personal communication, 2003); and data for *Rafinesquina* from A.J. Webber (personal communication, 2003).

ing upward for a particularly thick mudstone interval. The second occurrence is near the top of the Snag Creek submember, just below the Alexandria.

2. At the base of the Alexandria submember are 2–3 m of relatively pure mudrock (Big Shale 4 of Brett and Algeo, 2001), which stand out from the thinner mudrock intervals above and below it. This package was frequently used in conjunction with the aforementioned upper interval of strophic *Sowerbyella* to pinpoint the base of the Alexandria.

3. The upper Kope contains a distinctive limestone-rich interval termed the Grand Avenue beds (Brett and Algeo, 2001). This cluster of beds is 2.5–3.0 m thick, easily recognized in outcrop and core, and consists of a large number of closely spaced lenticular grainstones and packstones. The Grand Avenue beds occur about 8 m above the top of the Alexandria and provide a reliable stratigraphic reference. Moreover, a single, especially thick limestone bed, bed 31, is typically found between the Alexandria and the Grand Avenue beds, separated by about 2 m of pure shale (Big Shale 5 of Brett and Algeo, 2001) from the top of the Alexandria.

The number of these beds is retained over the entire study area, although the beds become thicker and more complex in up-ramp sections near Maysville and substantially thinner in more distal sections (Fig. 4). Marker beds are most difficult to identify in cores of proximal sections where they range from 10 cm to 50 cm thick and evidently comprise several stacked beds. Additional limestone beds appear above certain of the major limestone markers in proximal sections—for example, Maysville—as well as in proximal cores, such as those at Dodsonville and Blanchester; these are absent in the Cincinnati outcrop area where the cycles were defined—for example, the Kentucky Route 445 reference section studied by Holland et al. (1997). Careful study, however, shows that these beds correspond to thin intervals of fossiliferous shales in more distal sections. In addition, observations of outcrops in proximal facies, such as the one at Maysville, show an increased frequency of discontinuous lenticular limestone beds. These beds, which may represent starved ripples or fills of small scours, are easily distinguished from the continuous major limestone beds in outcrops but can be difficult to recognize in cores, where they add noise. Major marker beds are most readily identified in drill cores of proximal sections by locating sharp, basal contacts of thick, compact limestones with underlying relatively thick shales that lack interbedded carbonates.

The major cycle-bounding beds persist and are more readily recognizable in distal sections, such as at Middletown and Oxford. The beds do not feather out into interbedded successions of shell layers and mudstone but, rather, are represented by thinner limestones in otherwise noncalcareous dark shale. In the New Paris core, only beds 28 and 30 are present as lithified strata; beds 25, 26, and 27 are represented by minor, thin shell-hash beds but do retain their relative stratigraphic spacing and occur as discrete layers within otherwise nearly barren, dark mudrock (Fig. 4). Bed 29 was not found in the New Paris core. This may be the result of bed patchiness in the distal Kope facies and the core having missed bed 29. Given that beds 25–27 were found in this section despite their thinness, however, a more likely scenario is that bed 29 simply pinches out between Oxford and New Paris. This interpretation is also supported by the observation that bed 29 is one of the thinner cycle-bounding limestones in the Oxford and Dodsonville sections (Fig. 4). At Oxford, all six cycle-bounding limestones consist partially or completely of a distinctive nodular fabric characterized by limestone fragments with a wide range of sizes intimately commingled with pods, lenses, and stringers of mud. The mud content of these beds ranges from 5% to 60% by visual estimate and contributes to the overall mud content of each cycle.

Faunal Markers

Previously documented faunal markers were found in the core sections and the Maysville outcrop. These horizons contain unique fossil assemblages, in most cases having individual genera or assemblages combined with states of preservation that were not found elsewhere in the measured sections used here, despite centimeter-scale examination of thousands of bedding plane surfaces and multiple searches per core. The markers maintain their faunal composition and taphonomic character across several thousand square kilometers, as demonstrated by outcrop-based studies (Brett and Algeo, 2001). Additionally, in the framework of the Alexandria submember, these beds occur in consistent positions in the shales with respect to limestone beds and stand out from background fauna. These characteristics make them well suited as single-event correlation markers.

Four distinct markers at different stratigraphic levels within the Alexandria submember were used to aid correlation in this study (Fig. 4). Three of the markers are epiboles (*sensu* Brett and Baird, 1997)—distinctive horizons or intervals characterized by unusual abundance of a normally uncommon or absent taxon, in this case the graptolite *Geniculograptus pygmaeus* (at two separate levels) and the crinoid *Iocrinus subcrassus*. The fourth marker bed is an obrution (smothered) molt deposit of the trilobite *Cryptolithus tesselatus*, typified by skeletons that are partially articulated and well preserved. Skeletons are nearly always separated into thoracopygidia and cephala; this type of distribution in a trilobite skeletal deposit suggests that the fragments are exuviae (Speyer, 1987).

The markers identified in drill cores do not represent the true number that actually exist in the subsurface Alexandria submember at a given location; rather, they actually indicate a minimum number—that is, marker beds are almost certainly more widespread than observed here. Drill core samples are strongly biased against recognition of most markers because the obrutionary nature of certain markers means that rapid smothering preserved the original spatial patchiness of benthic assemblages (Seilacher et al., 1985; Taylor and Brett, 1996), and small-diameter cores (typically 5 cm in this study) have only a small chance of penetrating marker horizons at a point containing diagnostic specimens. It is believed that many marker horizons known from outcrop studies were not found in some or all cores simply because those cores happened to miss patches of diagnostic fossils at the appropriate horizon. Nonetheless, and all the more remarkably, several of the markers were identifiable in many of the drill cores.

The following markers are described in stratigraphic order from highest to lowest occurrence in the Alexandria submember (Fig. 5).

Upper Geniculograptus pygmaeus Epibole (Cycle 30).—This marker consists of dense concentrations of current-aligned, graptolite rhabdosomes, typically about 3 per cm^2. It is confined to bedding planes in a 1–3 cm interval in otherwise barren mudrock in the middle of cycle 30, ~30 cm below bed 30 and above bed 29. It has been found at every locality except New Paris and Middletown, making it the most ubiquitous of all the markers.

Cryptolithus tesselatus Interval (Cycle 29).—Abundant cephala and rarely articulated skeletons occur in a 20–30 cm interval between marker beds 28 and 29. This trilobite is otherwise exceptionally rare or absent in the upper middle Kope, and articulated specimens are known almost exclusively from this level, even though cephala are common in parts of the lower Kope. On average, this epibole occurs ~75 cm above bed 28 and 45 cm below bed 29. It is typically associated with silver white, crushed valves of *Zygospira modesta* and an unusually elongate morphotype of *Sowerbyella* and *Iocrinus subcrassus* pluricolumnals. Also found with this marker in some Cincinnati and northern Kentucky outcrops is the rare odontopleurid trilobite *Primaspis* (Kohrs, 2003). This marker has been located in the Dodsonville, Blanchester, Middletown, and Oxford cores.

Iocrinus subcrassus Epibole (Cycle 29).—This marker consists of the disparid crinoid *Iocrinus subcrassus*, with articulated stems and rare crowns in relatively sparse concentrations, typically without obvious current alignment. Partial disarticulation is common, with columnals imbricated against one another in linear fashion, mimicking the original articulated stem. These deposits are rapidly buried assemblages, as connecting tissue holding columnals together decomposes quickly and an articulated stem normally indicates burial either alive or very soon after death (Meyer and Meyer, 1986; Taylor and Brett, 1996; Brett and Ausich, 1999).

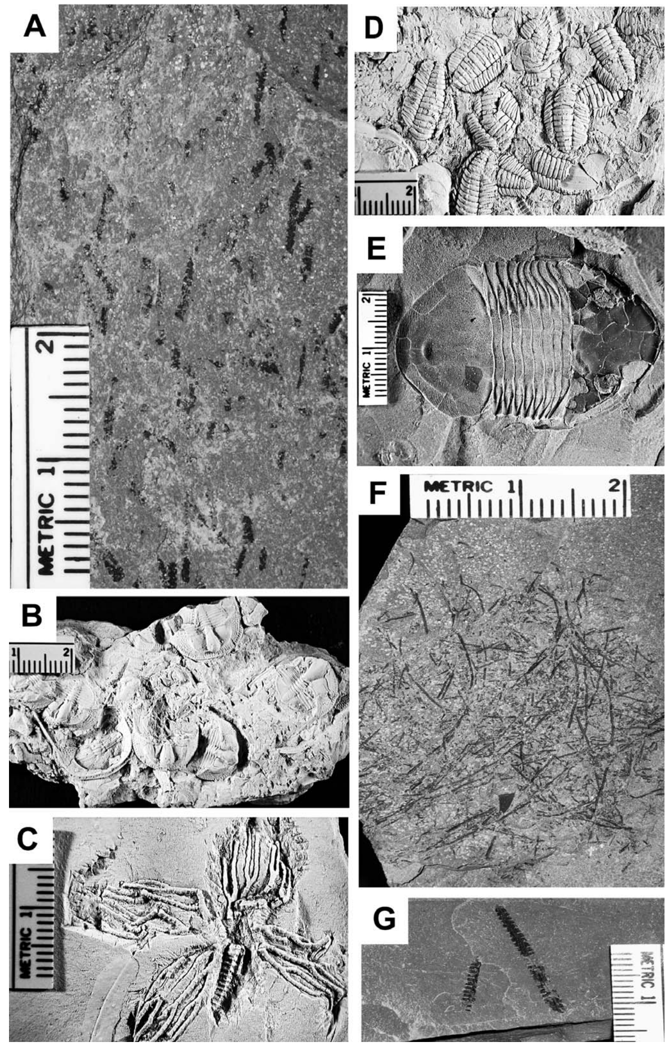

FIGURE 5—Fossil event beds in the Alexandria submember of Kope Formation. All specimens are from Sycamore Creek, along Loveland-Madeira Road, Indian Hill, Hamilton County, Ohio. Scales in millimeters. A–C = marker beds used in this study for correlation; D–G = other event beds found in the study sections. See Figure 4 for stratigraphic positions of marker beds. A) *Geniculograptus pygmaeus*, aligned fragmentary rhabdosomes; cycles 30 and 26. B) *Cryptolithus tesselatus*. This is the best individual specimen in the collection; cycle 29. C) *Iocrinus subcrassus* specimen buried with arms splayed and anal tube in center of view; cycle 29. D) Cluster of articulated molts (thoracopygidia missing cephala) of *Triarthrus eatoni* molt bed from cycle 28, preserved as both external molds and some original skeletal elements; oriented top upward. E) Articulated small specimen of *Isotelus* cf. *I. maximus*, preserved in inverted position; cycle 28. F) Intact fragile stolons of *Mastigograptus* sp.; cycle 27. G) *Cincinnatigraptus typicalis*; cycle 25.

This marker occurs on a single bedding plane ~30 cm above bed 28 and ~1.2 m below bed 29. It is present in the Dodsonville and Oxford cores; its absence in the Blanchester and Middletown cores may be a chance combination of marker-bed patchiness and drill-core siting.

Lower Geniculograptus pygmaeus Epibole (Cycle 26).—This marker is similar in fauna and taphonomy to the upper *G. pygmaeus* epibole. It is similar in stratigraphic occurrence as well, consisting of a series of bedding planes within a narrow 1–3 cm interval. This marker, however, occurs much lower in the Alexandria submember, about 15 cm above bed 25 and 30 cm below bed 26. It has been found at the Maysville, Winchester, Dodsonville, and Middletown localities.

Lithologic and Faunal Trends

An overall decrease in total limestone thickness of the entire Alexandria submember is evident from southeast to northwest along the study

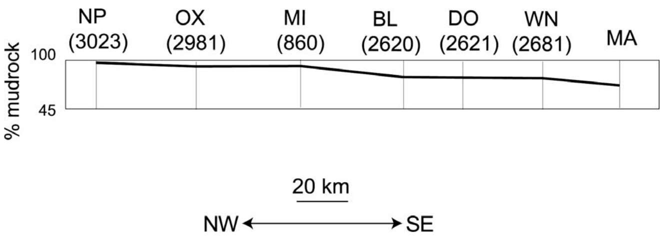

FIGURE 6—Average mudrock proportion for the Alexandria submember in each section along the correlation transect. Mudrock content (by visual estimate) of limestones with nodular fabrics (see Fig. 4) was included in all calculations of mud proportion. See Figure 3 for abbreviations. Lithologic data for the Maysville section from Kohrs (2003).

transect, along with a corresponding increase in mudrock proportion (Fig. 6). The most dramatic change in proportion occurs between Maysville and Winchester and between Blanchester and Middletown. In the former pair, the mudrock percentage of the whole submember increases by 14% (from 69% to 83%) over a distance of about 30 km; in the latter, mudrock content increases by 10% (from 86% to 96%) over 40 km. By comparison, the remaining adjacent pairs of sections average a mudrock percentage rise of just 1.33% in the distal direction.

Average faunal abundance data for the olenid trilobite *Triarthrus eatoni* and the inarticulate brachiopod *Leptobolus* sp. along the transect show two noteworthy patterns (Fig. 7). First, these taxa, both typical of dysoxic, organic-rich facies, are absent in all cycles of the four most proximal sections (Maysville, Winchester, Dodsonville, and Blanchester), appearing only in the Middletown section (*Triarthrus* only). For particular meter-scale cycles, *Triarthrus* abundance either increases or remains the same in the distal direction between the two most distal sites, represented by the Oxford and New Paris cores. There are some exceptions for *Leptobolus*; in cycles 25, 27, and 28, *Leptobolus* abundance decreases very slightly from Oxford to New Paris. Second, both *Triarthrus* and *Leptobolus* are absent from cycle 30 in the New Paris and Oxford cores. This is particularly interesting, as these taxa were found at numerous stratigraphic levels in other cycles in these two cores; the number of levels in which they occur reaches 14 (*Triarthrus*) and 17 (*Leptobolus*) in the basal cycle at these localities.

Rafinesquina abundances exhibit a pattern nearly opposite to that seen in the other two taxa (Fig. 7). It is absent in the New Paris, Oxford, and Middletown cores and sparsely present in the lower part of the submember at Blanchester and Dodsonville; its abundance rises significantly in the Winchester and Maysville sections.

DISCUSSION

Persistence of Lithologic Patterns and Implications for Cycle Genesis

An important finding of this study is that the basic patterns of thicker shale intervals and bundles of thin marker limestone intervals, used to delineate decameter-scale submembers in the Kope Formation, are regionally persistent. Moreover, within the Alexandria submember at least, individual marker limestone beds, used by Holland et al. (1997) to mark the tops of meter-scale cycles in the Cincinnati area, are recognizable throughout both the outcrop belt and in the subsurface of the entire study area, as this study shows (also see Brett and Algeo, 2001). The number and proportional spacing of these beds and, in fact, the thickness of the submember are similar throughout the study area. Furthermore, as noted, correlation of these beds based on pattern matching is corroborated by proximity to unique faunal markers. The persistence of the entire framework of thicker shales and thin limestones across a ramp-to-basin profile is significant in that it implicates a regionwide and probably allocyclic mechanism for the production of the alternations.

Furthermore, it is notable that limestone bundles thin and become more discrete in a basinward (northwestward) direction, rather than splaying

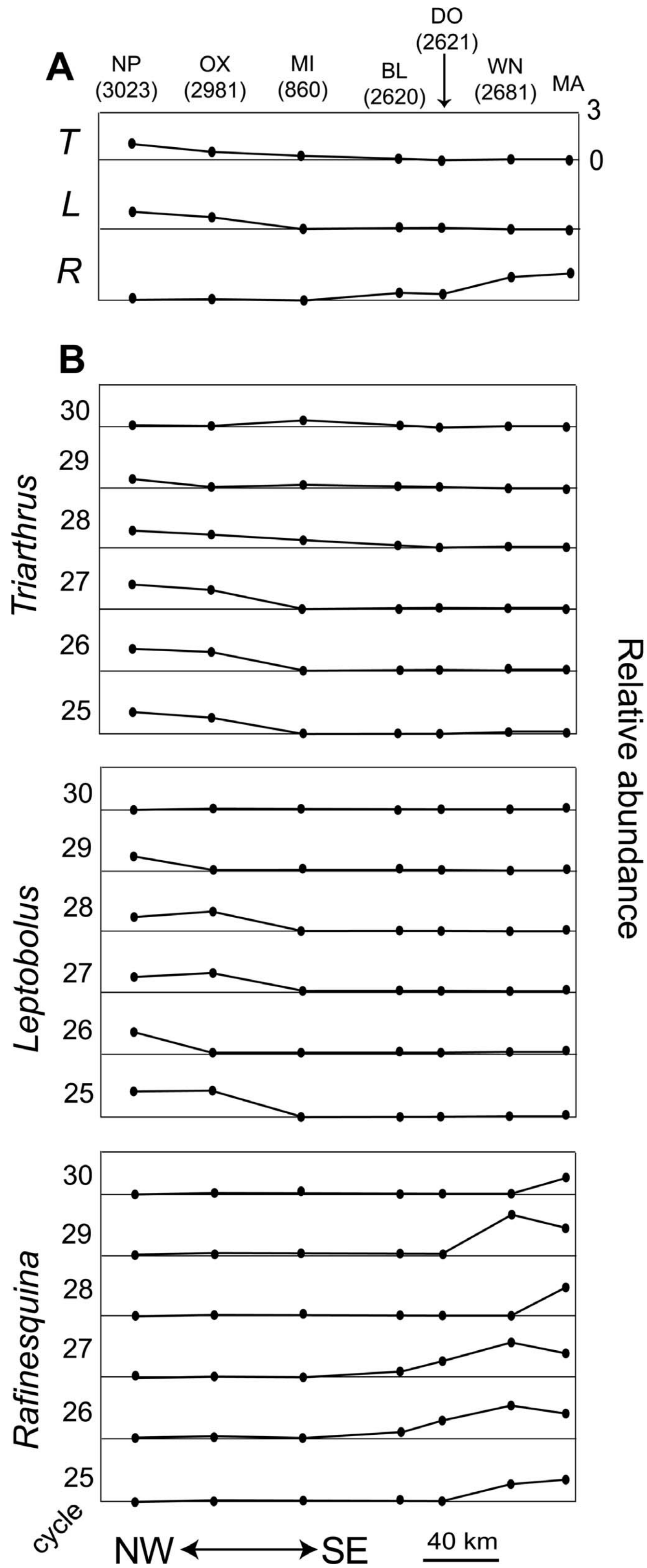

FIGURE 7—Trends in average abundance of *Triarthrus eatoni* (T), *Leptobolus insignis* (L), and *Rafinesquina* sp. (R), in the Alexandria submember along the study transect. Vertical scale for all plots is relative abundance by visual estimate, where 0 = absent, 1 = rare, 2 = common, and 3 = abundant. A) Average abundances for the entire Alexandria submember. B) Average abundances for each cycle. T: *Triarthrus eatoni*; L: *Leptobolus insignis*; R: *Rafinesquina* sp. See Figure 3 for explanation of abbreviations. Data for *Triarthrus* and *Leptobolus* at Maysville from C.E. Brett (personal communication, 2003). Data for *Rafinesquina* at Maysville from A.J. Webber (personal communication, 2003).

into a series of shell beds with alternating mudstones (Fig. 4). Despite their thinness, the basinal shell beds do not necessarily represent less time than thicker up-ramp equivalents. The highly comminuted, corroded nature of the skeletal debris in distal samples suggests long-term reworking, and the association with concretionary mudstone, including reworked concretions in distal core successions, suggests relative sediment starvation (Raiswell, 1988; but see Raiswell and Fisher, 2000) and possibly even minor seafloor erosion. The thinning of the limestones basinward probably reflects decreased production of skeletal grains. Shelly layers in distal dark shales consist mainly of small crinoid ossicles, dalmanellid brachiopods, and trilobite fragments. Conversely, thicker limestones up ramp contain a mixture of crinoids plus larger brachiopods and large ramose bryozoans.

The intervening shale-dominated intervals show a more complex pattern, thickening from Maysville, Kentucky, to the Middletown, Ohio, area and then thinning again to the north and northwest into dark, basinal shale facies. A combination of subsidence (accommodation) and sediment influx may account for this pattern. The thickening of the Alexandria submember northwest of Maysville may reflect input of muds from the northeast along the southeastern margin of the Sebree Trough, together with some fine-grained sediment bypassed from shallower-water areas to the southeast. Thinning of the section northwest of Middletown may reflect a reduction of sediment supply (especially from southeastern sources) toward the center of the Sebree trough.

Any model proposed to explain the limestone beds and, thus, the meter-scale cycles must account for their regional, facies-crosscutting relationship and their tendency to become more discrete and condensed in a down-ramp direction. These observations are inconsistent with hypotheses that invoke increased winnowing and bypass to explain skeletal limestones in shallow ramp areas (e.g., Holland et al., 2001), as such a mechanism implies bypass of substantial quantities of fine-grained sediment into deeper water. Such a process would seemingly result in a lower degree of condensation and splaying of thin shell beds alternating with muds in down-ramp positions, the opposite of the pattern seen. Rather, this pattern is more consistent with widespread sediment starvation, which allowed skeletal material to accumulate across a profile of shallow-to-deep-ramp environments. Cyclic alternation of shales and limestones may then reflect alternating periods of sediment starvation, such as those that occur during minor base level rise or climatic shifts, and periods of much more intense input of muds and silts to the ramp and basin. Although there is abundant evidence for storm deposition in both limestones and mudstones (Jennette and Pryor, 1993; Brett and Algeo, 2001; Brett et al., 2003), we conclude that storms did not provide the driving mechanism for generation of shell beds; rather their effects are superimposed upon a more pervasive regional process.

Faunal Patterns: Implications for Gradient Analysis and Paleogeography

A second result of this research is the better documentation of faunal gradients in proximal-to-distal ramp settings. Previous work by Holland et al. (2001), Miller et al. (2001), and Webber (2002) has established a basic gradient of Kope faunas based on detrended correspondence analysis, although this did not include the most distal faunal assemblages. The shallow end of this gradient is occupied by robust bryozoans and brachiopods such as *Rafinesquina* and *Platystrophia*; medial depths show an abundance of *Dalmanella* or *Sowerbyella*, or both, while deeper facies are typified by small crinoids, such as *Iocrinus*, *Ectenocrinus*, and *Cincinnaticrinus*, as well as graptolites. This study extends the gradient into still deeper biofacies typified by the trilobite *Triarthrus* and the small inarticulate brachiopod *Leptobolus*.

It is important to note that the overall faunal gradient is observable despite the occurrence of epiboles at particular levels. For example, although *Rafinesquina* occurs abundantly only in cycles 26 and 27 in Dodsonville and Blanchester, this brachiopod occurs at many levels (including cycle 28) at Winchester and Maysville (Fig. 7). Thus the utility of the epibole becomes blurred in this area because of the occurrence of the nominal species in many levels. Conversely, the trilobite *Triarthrus* is restricted to outcrops in the northwestern Cincinnati area where it may appear in dense clusters in an interval of ~10–20 cm of dark brown shale immediately overlying the *Rafinesquina* epibole (Kohrs, 2003). In the down-ramp drill cores at Oxford and New Paris, however, cranidia of this trilobite occur at many levels in all but one of the meter-scale cycles (Fig. 7).

The generally NE-SW trending subsurface transect roughly parallels the well-studied outcrop transect from Cincinnati to Maysville (Fig. 3) and shows strongly parallel trends. For example, the relative thicknesses of shale and limestone and the appearance of *Cryptolithus* in cycle 29 in the Dodsonville core are comparable to outcrops to the southwest along the AA Highway east of Alexandria, Kentucky. Likewise, the Blanchester core section of the Alexandria submember is most comparable in thickness, limestone proportions, and fauna to outcrop sections at the Cincinnati Nature Center, Route 445 in Fort Thomas, Kentucky, and the sections near the White Castle Distribution Center near Covington, Kentucky. These outcrop and core comparisons suggest a depositional strike oriented approximately NE-SW. They do not support the existence of a deeper Point Pleasant basin north of Mayville at this time, as has been postulated for Mohawkian–early Edenian time (Ettensohn, 1999; Brett et al., 2004).

Similarly, outcrop sections along a NE-SW line from Sycamore Creek to Rapid Run through the Cincinnati area show the most southeasterly occurrence of *Triarthrus* in cycle 28; this trilobite has not been recovered in any sections or cores to the southeast of this area, although it is known in all outcrop sections to the northwest (Kohrs, 2003). To the north-northeast of Cincinnati, in the Middletown area drill core, *Triarthrus* occurs at more than one level (Figs. 4, 7B). This trend is seen even more strongly in the Oxford core, which, although nearly due west of Middletown, shows an increased shale content (Fig. 6) and *Triarthrus* at multiple levels (Figs. 4, 7B). Finally, in the New Paris core, some 37 km north of Oxford, the Alexandria submember is barely recognizable, as the marker limestones are reduced to very thin skeletal debris horizons and intervening shales are dark gray with graptolites and *Triarthrus* at numerous levels. Together, this evidence indicates a NE-SW strike to facies belts and a ramp that is progressively deepening toward the northwest.

The deepening along this ramp may not have been entirely uniform, however. Based on significant increases in the average mudrock proportion of the Alexandria submember between Maysville and Winchester (Fig. 6) and changes in the distribution of dysoxic and shallow-water taxa in the same area (Fig. 7), a slight but significant deepening between Maysville and Winchester is suggested. Moreover, cycle-by-cycle comparisons of lithology and fauna indicate slight differences in the details of ramp configuration with minor reversals of trend (Figs. 6, 7B).

It is notable that the Alexandria submember, and the immediately overlying Grandview and Grand Avenue submembers, are the most similar and thus most readily identified portion of the Kope Formation in all drill cores and outcrops, suggesting that during deposition of this portion of strata, the ramp gradient overall may have indeed been subdued. Observations of many outcrop and core sections indicate much more abrupt lateral gradients in the lower Kope and underlying Point Pleasant and Lexington Limestone (McLaughlin and Brett, 2004), as well as in the overlying Fairview Formation (Hay, 1998; C.E. Brett, personal communication, 2004).

The Edenian seafloor in the study area has been characterized as a ramp in some previous work (Tobin and Pryor, 1983; Holland, 1993; Jennette and Pryor, 1993). The term ramp implies a paleoslope that is very gentle ($<1°$) but nevertheless detectable in the geologic record as lithofacies and biofacies changes and relatively uniform on a regional scale. The notion of a simple ramp has been challenged by results from faunal gradient analyses by Miller et al. (2001) and Webber (2002). They show that the overall paleoslope in part of northern Kentucky was either nonexistent or undetectably small, allowing local seafloor topographic variations to control the faunal record. The evidence from the present study confirms this hypothesis and expands it to include a large part of southwest Ohio.

These preliminary conclusions shed some light on an interesting question in Ordovician paleogeography of the Cincinnati, Ohio, region: What was the location and orientation of the transition zone between the Kope ramp and the Sebree Trough? Studies over the last decade (Mitchell and Bergström, 1991; Ettensohn et al., 2002) have usually agreed that this zone in southwest Ohio generally trended northeast-southwest, with the possibility of a southward-projecting embayment in south-central Ohio (Point Pleasant Embayment; see Ettensohn, 1999). Constraining the precise placement of this transition to true basinal facies of the Sebree Trough, however, has been challenging. The abrupt lithologic and faunal changes observed between Blanchester and Middletown, however, define the transition zone with greater precision and confidence than has been possible previously; these changes indicate the existence of a major topographic low to the northwest, the Sebree Trough. Moreover, data from the Dodsonville and Winchester cores near Maysville may provide subtle evidence for a remnant Point Pleasant embayment at the time of Alexandria deposition. Although these cores exhibit biofacies nearly as proximal as those at Maysville, the abrupt increase in proportion of mudstone in the Winchester core suggests increased subsidence and sedimentation north of Maysville. As noted above, however, there is no evidence for a deeper basin north of this area, and indeed facies trends appear roughly northeast-southwest through this region.

Epiboles and Obrution Deposits: Implications for Bioevents and Environmental Change

A third important result of this study is that paleontological event horizons of two distinct types appear to have broad-facies-crosscutting relationships. Although this fact makes such horizons particularly useful in stratigraphic correlation, it is not readily explained. Most of the paleontological event beds identified in this study are a type of proliferation epibole (terminology of Brett and Baird, 1997); that is, they represent brief proliferation of a normally rare or absent taxon over a large area. This phenomenon is perhaps easiest to explain in the case of the *Geniculograptus pygmaeus* epiboles, as changes in temperature, nutrient content, or other properties of the water mass may have favored geologically brief blooms of these planktonic organisms. The rhabdosomes of the graptolites could then settle out and be preserved in muds over a considerable tract of the shelf-to-basin profile. Indeed, these epiboles are the most widespread in the study area. More difficult to explain is the widespread proliferation of benthic species. For example, *Cryptolithus tesselatus*, a trilobite that is very rare in most of the upper Kope, occurs in large numbers in a few beds of cycle 29. Presumably some environmental factor, other than depth or sediment type, must have been altered to enable this species to flourish so abruptly.

The occurrence of *Rafinesquina* and absence of much more typical *Dalmanella* in bed 27 and adjacent shales of cycle 28 must record the alteration of conditions typical of the Alexandria submember. This appears to be a case of proliferation of a normally shallow-water taxon across a major portion of the ramp. Conversely, the occurrence of *Triarthrus*, also in a thin zone in cycle 28 near Cincinnati (although not in most proximal sections near Maysville), records the incursion of a taxon typical of basinal facies into up-ramp localities.

Cycle 28 thus presents a particularly interesting case because, as noted, it features a basinward excursion of a normally shallow-water taxon (*Rafinesquina*), immediately succeeded by the up-ramp excursion of a normally basinal taxon (*Triarthrus*). In some locations these two beds are also separated by a thin interval (typically one or two closely spaced bedding planes) covered with molluscan debris. This interval has the aspect of a condensed bed, and it is sharply overlain by dark shale, locally containing the *Triarthrus* remains. The net effect of these occurrences is to damp out the typical down-ramp faunal gradient within cycle 28, making it among the easiest intervals to correlate. At present, the cause for this is only speculative. Possibly this does record a time of minimal ramp gradient, although it is unclear what would cause the ramp to become less pronounced on a small time scale. As noted, the upper-middle portion of the Kope Formation appears to be the most uniform interval throughout the study area, suggesting possible leveling during this time. This could reflect equilibrium between subsidence and sedimentation. In addition, the abrupt juxtaposition of some of the deepest-water facies over shallow, *Rafinesquina*-bearing beds with a sharply defined discontinuity separating them suggests that cycle 28 may record a strong oscillation in relative sea level. Possibly some aspect of the forcing mechanism, such as ice buildup, could have amplified the signature of both sea level fall and rise. The rapidly changing conditions could have promoted opportunistic spread of particular taxa.

Perhaps more perplexing is the widespread distribution of certain single-event obrution beds, such as a bed of articulated *Isotelus*. Complete specimens of this trilobite are rare within the Kope, and thus it is notable that a single bed in cycle 28 carries abundant articulated specimens in several outcrops near Cincinnati. It is even more surprising that an articulated specimen was found at this level in a 2-inch-diameter drill core from Middletown some 50 km north of the outcrop belt. Likewise, a bed of articulated *Iocrinus* was found in several drill cores. These occurrences, while still incompletely documented, suggest the occurrence of obrution beds that persist over hundreds if not thousands of square kilometers. Details of clay microfabrics suggest that these widespread beds were buried rapidly by flocculated muds (Kohrs, 2003). Such muds may have formed plumes along density interfaces within the water mass and thus have been spread rather uniformly over large areas.

Implications for Layer-Cake Stratigraphy

The classic Upper Ordovician strata of the Cincinnati Arch region have long fascinated paleontologists because of the richness and quality of preservation of their fossils and the well-exposed and structurally simple strata. E.O. Ulrich, founder of the Cincinnati School (Hay, 1981), championed the concept of layer-cake stratigraphy, no doubt as a result of his extensive work in correlating the classic Cincinnatian strata. In its strictest sense (the Eo-Ulrichian paradigm; see Brett et al., 2004), layer-cake stratigraphy was a view of facies as laterally extensive, vertically stacked, and isochronous, and Ulrich has been rightly criticized as being overly zealous in application of this view (see, e.g., Prothero and Schwab, 1996, p. 345). Using actualism as a guide, geologists during much of the later 1900s reacted strongly against this view and interpreted most stratigraphic successions, including the famed Cincinnatian, as mosaics of facies with few if any beds or intervals traceable for any distance. As recently as the late 1990s, a synopsis of Cincinnatian strata (Davis and Cuffey, 1998) was titled *Sampling the Layer Cake That Isn't,* even though several papers in the same volume (e.g., Dattilo, 1998; Holland, 1998) presented data indicating marked lateral continuity of depositional sequences and marker beds.

In fact, Ulrich's view was undoubtedly at least partially correct, empirical, and based upon his detailed observations of the same Cincinnatian strata that were later considered facies mosaics. Moreover, it is quite clear that Ulrich did recognize lateral facies change as he notes (1914) that the Eden beds (Kope Formation) underwent a transition to black Utica Shale–type facies north of Cincinnati (Fig. 2), based upon drill cores that had been obtained from the area of Middletown, Ohio.

New outcrops and drill cores, such as those examined in the present study, not only vindicate many of Ulrich's earlier correlations but also indicate the existence of a high-resolution framework of regionally widespread marker beds. The facies are not continuous isochronous sheets, as individual correlated stratigraphic intervals do show lateral changes; a number of patterns and individual markers, however, crosscut this facies pattern. This framework of continuous layers pervades the overall regional facies change. Thus, while the extreme view of persistent facies sheets (commonly, though perhaps not credibly, ascribed to Ulrich) is not correct, a wealth of evidence supports a modified (neo-Ulrichian) view of layer-cake stratigraphy. Moreover, these sorts of phenomena are by no means unique to the Kope Formation or to the Ordovician. Very similar patterns of widely persistent limestone marker beds, epiboles, and obrution beds have been previously documented in similar mudrock successions of the Upper Ordovician Waynesville Formation (Frey, 1997; Schumacher and Shrake, 1997), the mid-Silurian Rochester shale (Taylor and Brett, 1996; Brett and Taylor, 1997), the Middle Devonian Hamilton Group (Brett et al., 1986; Miller et al., 1988; Parsons et al, 1988), and the Cretaceous Greenhorn cyclothem of the Western Interior (Hattin, 1985; Kauffman, 1988, Kauffman et al., 1991). These comparable observations suggest that a very detailed form of layer-cake stratigraphy can and does exist in these offshore muddy facies; indeed, we suspect that this pattern typifies many muddy offshore successions, at least during greenhouse supercycles. The nearly level, even character of epeiric seas and their gentle ramps also undoubtedly favored broad distribution of events.

Just why layer-cake patterns exist remains poorly understood. Brett (2000) identified two probable sources of persistence for thin intervals or frosting beds, both of which apply in the case of the Kope Formation: (1) the pervasive effects of certain very large scale phenomena, such as very large storms, and (2) basinwide responses to allocyclic effects such as sediment starvation and condensation. The first explanation pertains to widespread obrution beds and similar layers; the second, probably more important, explains the widespread framework of thin shell beds and limestones. The issue of epiboles remains less well defined, but these crosscutting faunal anomalies also probably reflect widespread changes in environmental parameters (e.g., temperature, geochemisty, nutrient level) that are not clearly reflected in lithofacies.

CONCLUSIONS

1. Geographically widespread faunal epiboles and mudrock-hosted taphonomic event deposits have been used successfully in conjunction with regionally extensive, thin (1–30 cm) skeletal limestone beds to correlate a portion of the Upper Ordovician Kope Formation in the subsurface on a regional scale in southern Ohio.

2. High-resolution ($<$1 m) correlation of subsurface Kope facies has revealed lithologic and faunal trends along a transect east and north of Cincinnati, Ohio, in areas not previously examined. The distribution of dysoxic and shallow-water taxa and the changes shown by mudrock-limestone proportions, based on subsurface and outcrop data, corroborate previous reconstructions of a northwestwardly dipping ramp between Maysville, Kentucky, and Oxford, Ohio, with an approximately NE-SW facies strike parallel to the narrow Sebree Trough.

3. Basinal facies to the northwest near the Ohio-Indiana border are dark gray shales with an abundance of graptolites, the inarticulate brachiopod *Leptobolus*, the olenid trilobite *Triarthrus*, and only minor shelly debris horizons correlative with skeletal limestones to the SE. The area between Middletown and New Paris, Ohio, shows a rather abrupt transition between typical Kope facies and the dark shales of the Sebree Trough basin during Alexandria submember time. This zone exhibits the faunal and lithologic changes expected for a transition from a shelflike to a basinal environment. Constraint of the boundary location to the area between these localities represents a higher spatial resolution than has previously been possible in Kope paleogeographic studies. This level of constraint also demonstrates the potential for high-resolution Edenian paleogeography in the Cincinnati area in general and for improved paleogeographic interpretation of similar mixed carbonate-siliciclastic units.

4. The persistence of thin marker-shell-rich limestone beds throughout the study area indicates their formation by regional, allocyclic processes, probably intervals of sediment starvation. Taphonomic event beds likewise have regional and event facies crosscutting distribution, probably because they record extraordinary burial events of large magnitude. Epiboles recording proliferation of particular taxa are presumed to represent widespread environmental changes that are not recognizable in the sediments. Similar units have proved useful in regional correlation in other units that possess them, including the Triassic Muschelkalk of Germany (Aigner, 1985), the Devonian Hamilton Group (Brett and Baird, 1986, 1997), and the Silurian Rochester Shale (Brett, 1983). The potential for detailed regional correlations, however, remains largely unexplored.

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