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Upper Ordovician Strata of Southern Ohio-Indiana: Shales, Shell Beds, Storms, Sediment Starvation, and Cycles

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IUGS UNESCO IGCP Project 591 The Early to Middle Paleozoic Revolution

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The Cincinnatian Series (ca. 450 to 442 Ma) of the Cincinnati Arch features some of the most spectacular Ordovician fossils in the world. The rich faunas of bryozoans, brachiopods, molluscs, echinoderms, and trilobites are preserved as discrete shell-rich limestones, cyclically interbedded with sparsely fossiliferous shales and mudstones that may yield exceptionally preserved trilobites and crinoids. Similar successions of shell beds interbedded with mudstones are common components of Paleozoic successions. In such successions, the genesis of the highly concentrated shell beds is often attributed to storm-winnowing, but is this the whole story? This trip will offer an overview of the classic Cincinnatian Series, with ample opportunity for examining and collecting the rich fossil assemblages throughout much of the succession. Discussions will focus on the origin of interbedded mudstone-limestone cycles. We will emphasize depositional processes, particularly the role of intermittent siliciclastic sediment supply, carbonate (shell) production, and winnowing by storms and other high-energy events in a critical discussion of the storm-winnowing model.

Introduction

The Upper Ordovician strata of the Cincinnati Arch region are world renown for their superbly preserved fossils and superbly exposed, undeformed strata (Meyer and Davis, 2009). These strata, totaling nearly 250 m of mudstones, shell-rich limestones and minor siltstones, span some 10 million years of the Late Ordovician, Cincinnatian Series (Katian Stage: formerly upper Caradoc and Ashgill Stages). Terrigenous muds and silts, derived from Taconic highlands to the east and southeast, alternate cyclically with intrabasinal ("homegrown") skeletal carbonates. These sediments accumulated along a northwest dipping ramp that sloped gently into an intracratonic basin, the Sebree Trough (Fig.1; see also Figure 22). Both the Sebree trough and the adjacent Lexington platform to the south of Cincinnati may have been produced by far-field tectonic forces from the Taconic orogeny (Ettensohn, 1992; Ettensohn *et al*., 2002). The shallow subtropical seafloor intermittently hosted diverse faunas of ramose and massive bryozoans, brachiopods, molluscs, crinoids, trilobites, and other invertebrates. The exceptionally preserved faunas have been documented in the book "Sea without Fish" by Meyer and Davis (2009). Yet, for all their fame, there is still much to be learned from the Cincinnatian strata.

A "renaissance" or renewed interest in the classic Cincinnatian strata (McLaughlin *et al*., 2008) is manifest in several ways including: a) the development of high-resolution stratigraphic frameworks, correlated at the scale of meters to decimeters (Tobin and Pryor, 1981; Jennette and Pryor, 1993; Dattilo, 1996; 1998; Miller *et al*., 2001; Holland *et al*., 2001; Brett and Algeo, 2001; Brett *et al*., 2008a, b; Meyer and Davis, 2009); b) an attempt to synonymize identical units that have been differentially assigned to a plethora of terms across the state lines of the Tristates area (Ohio, Indiana, Kentucky; see Fig. 1) (Tobin, 1982; Holland, 1993; Brett and Algeo, 2001; Schramm, 2011); c) integration of magnetostratigraphic, chemostratigraphic, and sequence stratigraphic concepts in the interpretation of this lithostratigraphic framework (Ellwood *et al*., 2007; in press; Schramm, 2011; Marshall, 2011); d) reconsideration of the classical models for deposition in the Cincinnatian mixed siliciclastic carbonate successions (Brett *et al*., 2003; Brett *et al*., 2008a; Dattilo *et al*., 2008; Schramm, 2011; Dattilo *et al*., in press); e) recognition of patterns of stasis and change in the well preserved faunas and their relation to stratigraphic patterns (Brett and Baird, 1995; Patzkowsky and Holland, 1997; Holland and Patzkowsky, 2004).

The purposes of this field trip and guidebook are to provide an overview of the refined stratigraphic framework of the Cincinnatian with a focus on the Edenian and Maysvillian Stage strata (Fig. 2). A major focus is on the patterns and interpretation of key marker units, including distinctive condensed intervals, concretion horizons, unusual event beds, and faunal epiboles that permit high-resolution correlations. In addition, we discuss new evidence for correlation and interpretation of the temporal scale of stratigraphic units, including magnetic susceptibility and stable isotope chemostratigraphy. Beyond these tools we consider the meaning of apparent cyclicity in the Cincinnatian. Specifically, we focus on the causes of cyclic alternation between shell-rich pack- and grainstones and mudstones.

Of particular interest are many counterintuitive patterns that emerge when these rocks are examined in detail. The following is a summary of the most important observations.

a) Thin, shell-rich units show evidence of representing long intervals of time, while thicker mudstones record stacks of events recording little net depositional time.

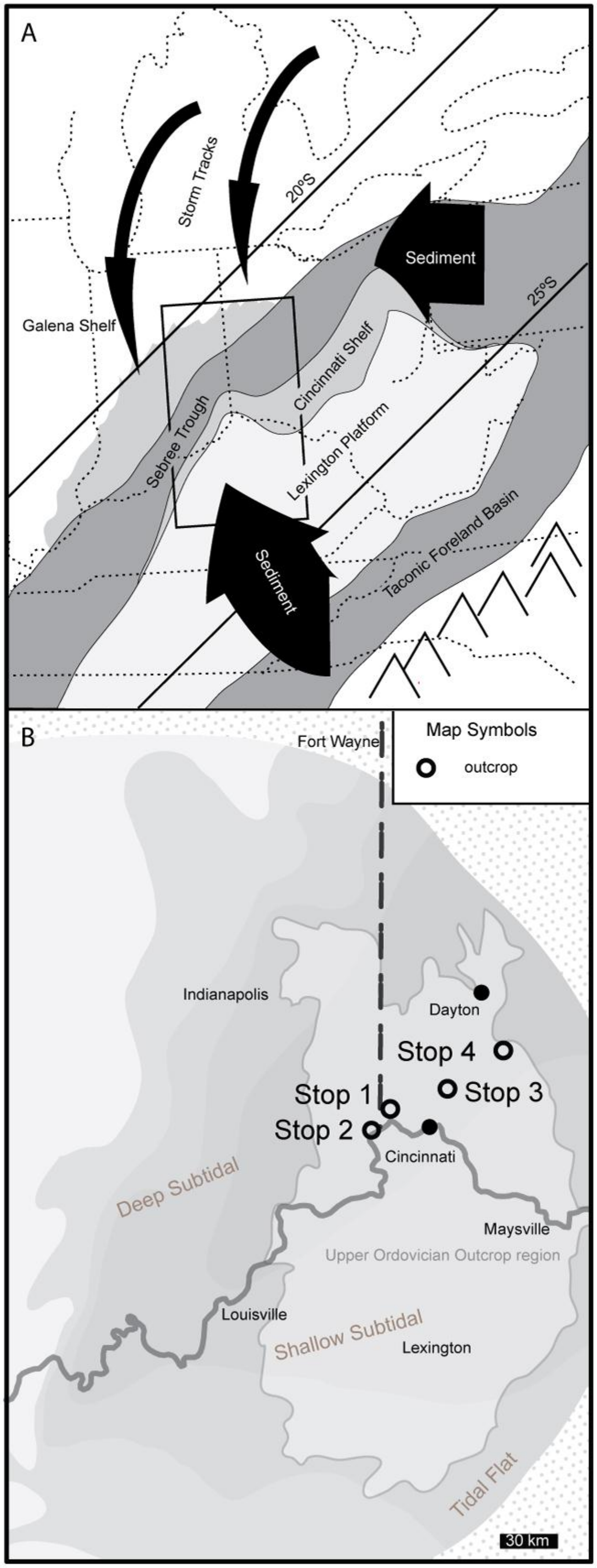

Figure 1

Study area maps. A) Regional paleogeographic map showing the region in context. Thin arrows are inferred storm tracks. Thick arrows represent possible sediment transport routes from the Taconic Hinterland. B) Location map showing field trip stops, depositional thickness of the lower Cincinnatian sediments (shaded: modified from Hohman 1998), paleoenvironments (gray lettering), and the Ordovician outcrop region. Field trip stops include: Stop 1: Rivers Edge Commercial Park, fitness club, Cleves, Ohio (39°11'42"N 84°37'15"W) Stop 2: Rte. 48 Roadcut, Lawrenceburg, Indiana 39°05'32"N 84°51'21"W, Stop 3: Trammel Fossil Park, Sharonville, Ohio 39°17'47"N 84°24' 15 "W, and Stop 4: Caesar Creek Spillway Access and roadcut on Clarksville Road (39° 28'49" N, 84° 3'25" W).

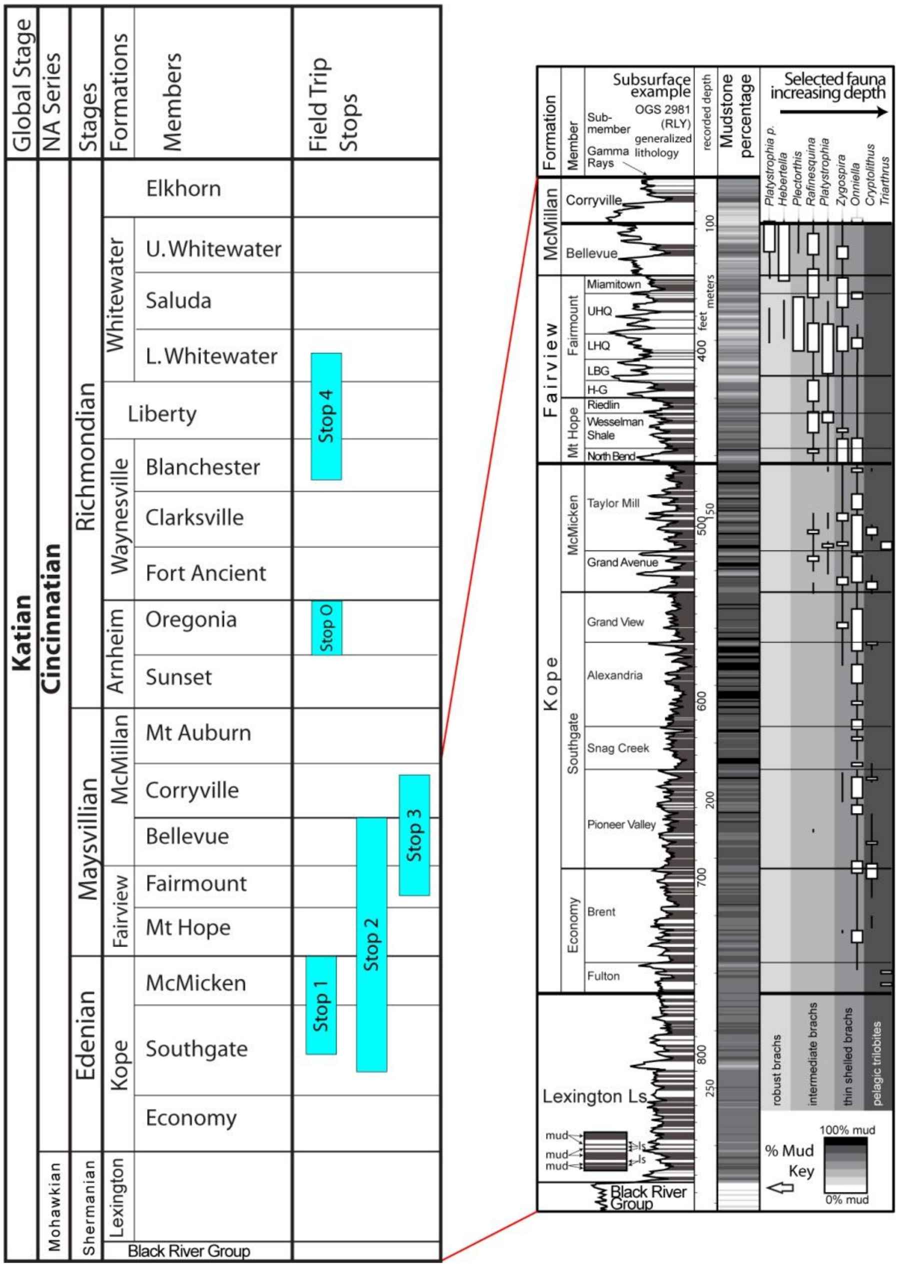

Figure 2

A) Stratigraphic column of the study interval. On the left is Overview of Cincinnatian stratigraphy showing the approximate stratigraphic interval of each of the fieldtrip stops; modified from Caster *et al*., (1961). On the right is a more detailed Stratigraphic column of the Mohawkian, Edenian, Maysvillian strata of the Cincinnati Arch. This is based on a borehole gamma ray log illustrated with increasing radioactivity to the right. Also shown is a generalized lithology column showing intervals dominated with white representing intervals dominated by limestone and dark gray representing intervals dominated by mudstone; a gray scale mudstone percentage column showing averaged lithology interpreted from log with white representing uninterrupted limestone, black representing uninterrupted mudstone, and different grays representing different proportions of interbedded limestone and mudstone; and a chart showing the occurrences of selected fossils with robust shallow-water forms on the left (light background), progressing to delicate deep-water forms on the right (dark background), boxes represent intervals of particular abundance, lines represent presence.

b) Fine-grained intervals do not simply represent quiet "background" conditions, but actually comprise stacks of event beds, some of them recording substantial erosion (Tobin and Pryor, 1981; Brett *et al*., 2008a; Dattilo *et al*., 2008).

c) Conversely, some rippled grainstones, traditionally viewed as "high energy" deposits, are composed of variably preserved remains of fragile shells and "snowshoe" brachiopods adapted to low energy soft bottom regimes (Brett *et al*., 2008a). They are clearly not simple storm beds but highly time-averaged accumulations of shells derived from normally "low energy" settings.

d) Many packstones have matrix between the grains composed of micrite and cannot have been formed by winnowing of mixed muds and shells (Dattilo *et al*., 2008).

e) Packstones thin and pass into grainstones in downramp sections (Brett *et al*., 2008a; Dattilo *et al*., in press).

It is particularly the consideration of these paradoxical aspects that has led us to an unorthodox view of these strata.

Event Horizons: Marker Beds

Continuity of limestone beds/bed bundles, "big shales" and siltstones:

Big Shales: Among the most important markers in the Cincinnatian, especially in the more distal Kope, Fairview, Corryville and Waynesville intervals (Fig. 2), are thick and relatively limestone-free intervals of mudstone, typically with interbedded thin (1-10 cm) siltstones (Fig. 3). Close examination of these intervals in fresh stream cuts and cores shows that they are composed of stacked often sharply based beds of mudstone and siltstone with subtle graded bedding (Tobin and Pryor, 1981; Kohrs *et al*., 2008). Certain of these beds show evidence of rapid, single-event deposition, such as obrution deposits, discussed below.

Indurated, typically laminated, silt-sized, fossil-poor, calcareous beds in the Cincinnatian have long been referred to as calcisiltites and some of them perhaps fit this category. However, analysis of many such beds in the Kope Formation indicates that they are actually dominated by silt- and even fine sand-sized quartz grains with calcitic cement (Marshall, 2011). Hence, they are dominantly of extrabasinal origin.

This of course, raises the question as to the source of these silts. In the upper Kope Formation the thin siltstones common in the Cincinnati region appear to be distal fingers of the much thicker Garrard Siltstone (Marshall, 2011), which thickens up to 30 m to the southeast. However, other siltstone packages are not known to correlate with thicker silt bodies. Trace element geochemistry studies suggest that the siltstones had the same source as interbedded mudstone and reflect a source of roughly rhyodacite composition (Marshall, 2011).

Shell-rich limestones: The second major component of Cincinnatian successions consists of thin (5 to 40 cm) lenticular to tabular beds or bundles of beds of skeletal pack- to grainstone. These beds contain variably preserved shells, especially of brachiopods, bryozoans, and crinoids.

In most cases, time-averaging is indicated by multi-generational debris ranging from corroded and abraded shell fragments to complete valves and even articulated multi-element skeletons. Recently, Kolbe *et al*., (2011) demonstrated that shell coloration may relate to the extent of exposure time; nearly all pinkish colored brachiopod shell material is fresh and taphonomically unaltered, whereas blackened shells correlate strongly with fragmentation, abrasion, and edge-rounding. Most of the thicker more persistent shell beds contain multi-colored shells, again suggesting time-averaging.

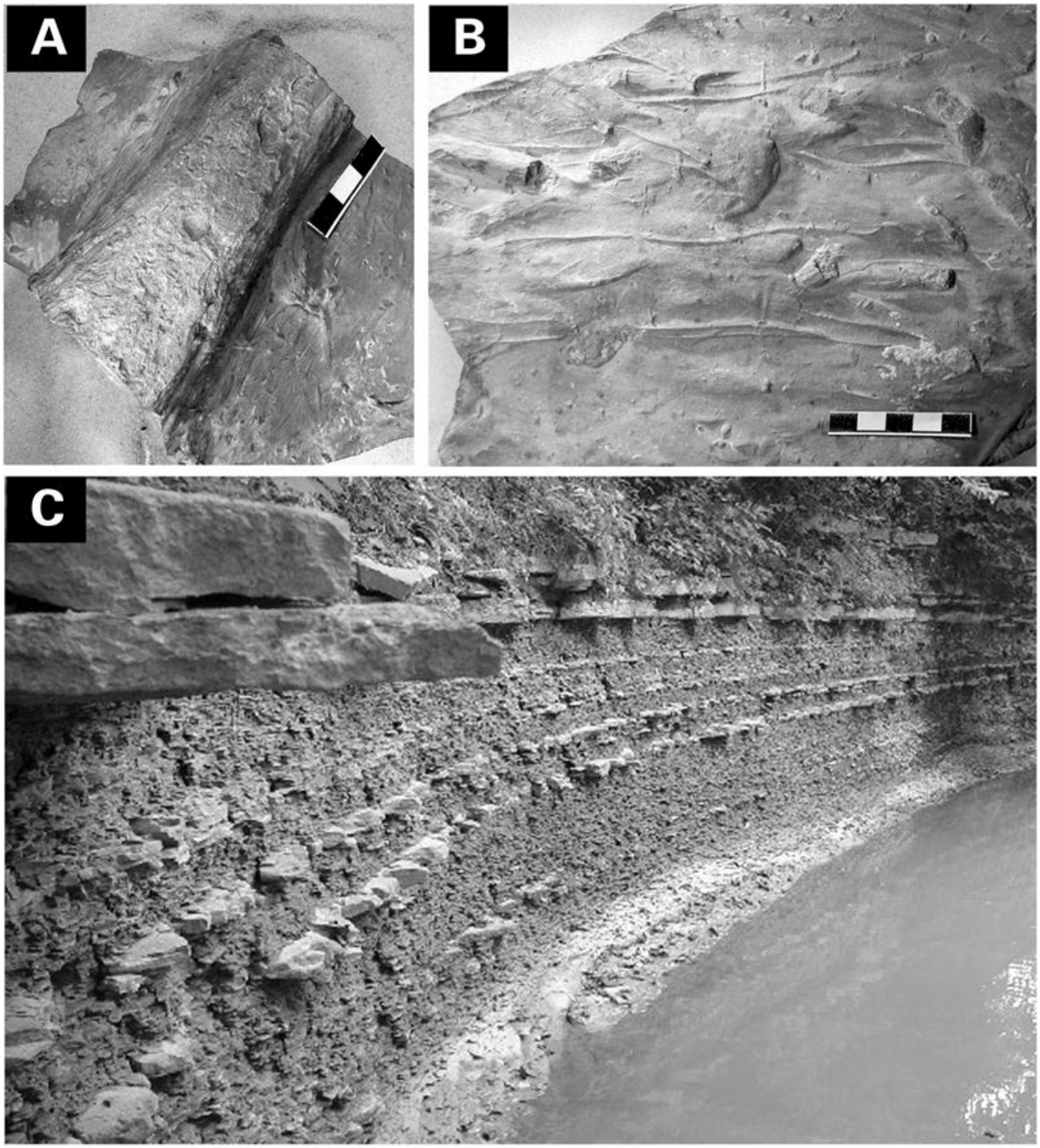

Figure 3
A) Cluster of siltstone beds in upper portion of "Big Shale 4" Alexandria submember. Note grouping of silt beds closely below bed 25. B) gutter cast of base of Kope siltstones. Sole features of siltstones in the Kope Formation. A) gutter cast; note tool marks along sides of 5 cm deep gutter. B) subparallel tool marks. Adapted from Brett *et al*., (2008a).

Figure 4
Meter scale cycles beds 29, 30) in upper Alexandria submember, Southgate Member of Kope Formation at Rapid Run, Delhi Township, Ohio. Note symmetrical ripples on the top of bed 30 at the base of “Big Shale 5”. Note concretionary siltstones at base of section below bed 29.Tammie Gerke and Meghan Welsh for scale.

Many of these beds show sharp nearly planar bases indicating erosion (Fig. 4); these include sharply incised trace fossil molds and minor gutter-like scours. Certain skeletal beds contain sub-angular to rounded mudstone clasts up to several centimeters across. These evidently have been torn up from underlying mudstones (Brett *et al*., 2008a; Dattilo *et al*., 2008).

Upper surfaces of these beds may be strongly rippled, typically with sub-symmetrical, straight-crested to slightly sinuous ripples with wavelengths of 30 to 100 cm and amplitudes up 2 to 10 cm (Jennette and Pryor, 1993).

Shell-hash limestone beds, or more precisely, bundles of shelly limestone are demonstrably persistent across large outcrops up to 1 km long and, more importantly, can be traced over tens of kilometers from one outcrop to the next (Fig. 5) (Brett and Algeo 2001; Brett *et al*., 2003).

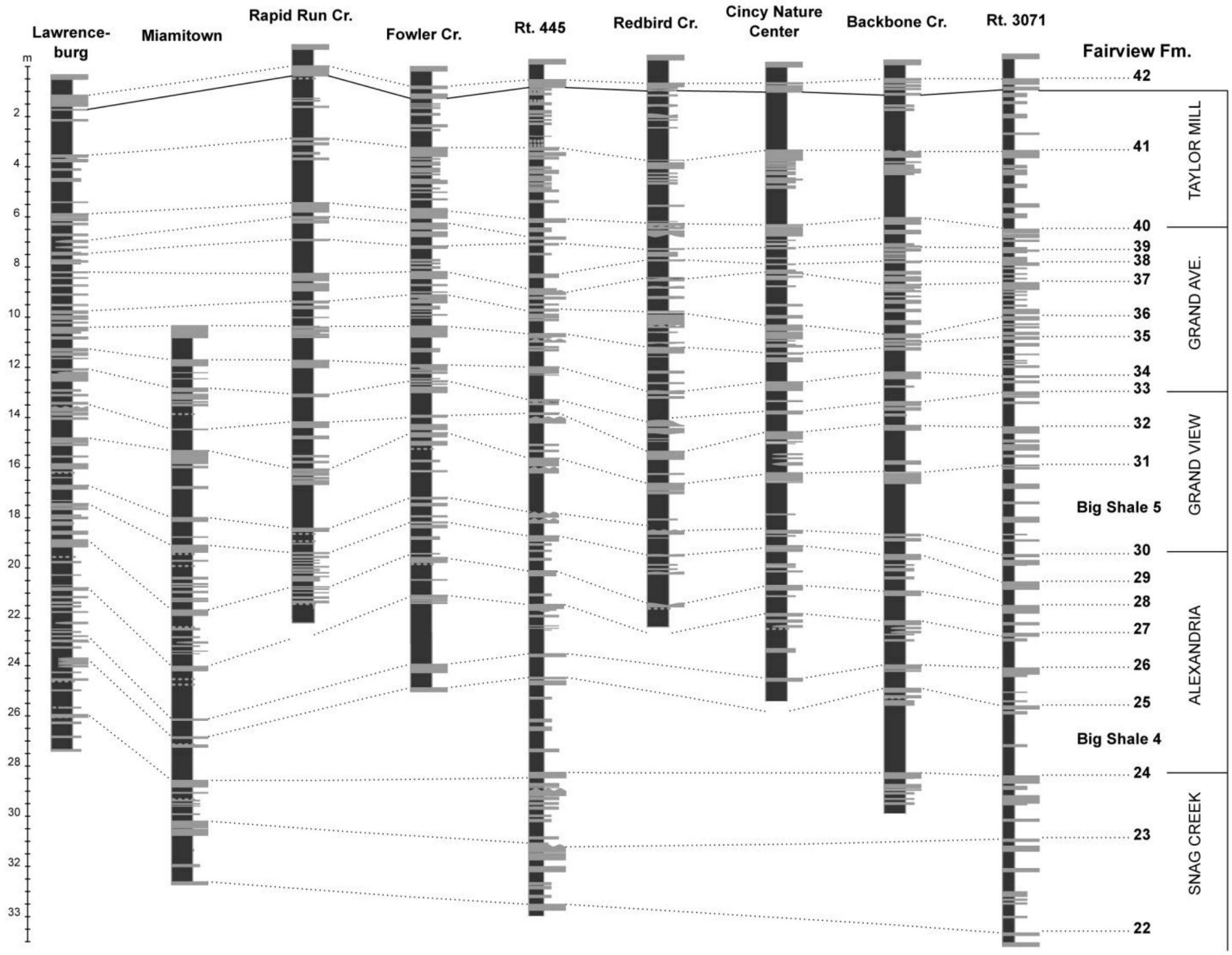

Figure 5

Stratigraphic sections of the upper Kope Formation from Lawrenceburg, Indiana to Maysville, Kentucky (approximately 100 km west to east) showing detailed correlation of submembers and cycles. Dark gray represents shale and light gray represents limestone, which is the most "weather resistant" on the profile, and the siltstones, which are more inset. The cycles were correlated using limestone bed thickness, bed spacing and specific sedimentological and/or fossil indicators not necessarily shown on this diagram.

Storm Depositional Events: Mudstone Obrution Beds

As noted, most mudstone intervals show evidence of deposition as multiple events, such as silt laminae and muds of different colors and textures with sharp, scoured bed bases. Some mudstone beds show abundant articulated fossils such as trilobites and crinoids indicating that they represent obrution beds or smothered bottom conditions. Brett *et al.*, (2008b) documented a series of distinctive obrution beds, including molt ensembles of the rare, deep-water trilobite *Triarthrus*, beds of articulated *Cryptolithus* trilobites, and crinoids in the Kope Formation of the Cincinnati region (Fig. 6). Certain of these beds are found in every outcrop throughout areas exceeding 2500 km^2 (Brett *et al*., 2008b). Another excellent example of this phenomenon is the

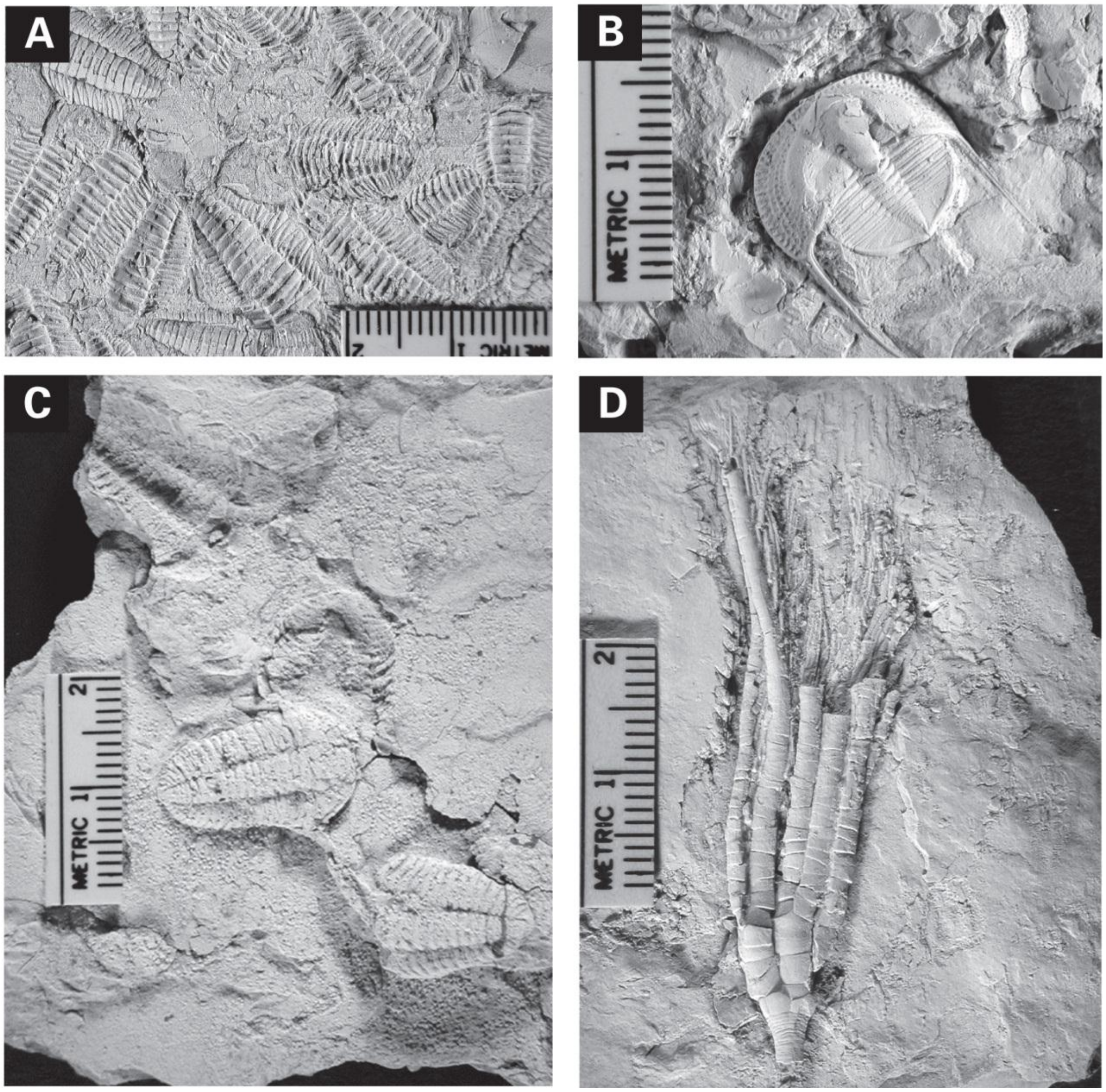

Figure 6
Evidence for rapid burial of multi-element skeletons in the Kope Formation; scales in centimeters. All specimens except C from Alexandria submember of Kope Formation at Sycamore Creek, along Loveland-Madeira Road, Indian Hill, Hamilton County, Ohio. Scales in millimeters. (A) Cluster of articulated molts (thracopygidia missing cephala) of *Triarthrus becki* molt bed from Cycle 28. Specimens are preserved as both external molds with some original skeletal elements. This sample is oriented top upward.(B) Eceptionally preserved specimen of *Cryptolithus bellulus* from the "upper *Cryptolithus* bed"; cycle 29. (C) Several *Flexicalymene* sp. from mudstone just below bed 28 at the I-74, Miamitown, OH site. Specimens are preserved as internal molds in a concave down position. (D) *Ectenocrinus simplex* from Cycle 29. Specimens reposited in the collections of the Cincinnati Museum Center.

Flexicalymene retrorsa "minuens" bed of the uppermost Waynesville Formation (Schumacher and Shrake, 1997; Hunda and Hughes, 1997; D. Copper, pers com. 2011). This thin shale contains abundant enrolled specimens of entirely diminutive *Flexicalymene*, generally just a few millimeters in diameter, as well as very large articulated *Isotelus* in outcrops between St. Leon, Indiana and Waynesville, Ohio, over 120 km (75 miles). Similar enrolled trilobite beds have been traced within the Waynesville Fm. (Fig. 7) (Schumacher and Shrake, 1997). A siltstone interval in the "Hill Quarry" beds of the Fairview Formation has yielded articulated *Glyptocrinus* crinoids in sections between Lawrenceburg, Indiana and Maysville, Kentucky (Brett, Deline, and

McLaughlin, 2008; D. Meyer pers. com., 2011) well over 130 km (80 miles) even slightly across depositional strike. These paleontological event beds appear to represent mass mortalities associated with extraordinary burial events.

Figure 7
Enrolled specimens of *Flexicalymene meeki*. Waynesville Formation. Figure courtesy of Brenda Hunda.

At present, the mechanisms permitting such widespread burial events are poorly understood. Kohrs *et al*., (2008) and Brett *et al*., (in press) suggest that these record events of hypopycnal flows of muds and silts along water mass boundaries resulting from mass inundate (flood outwash) events when an extraordinary volume of sediment was transported long distances offshore dispersed along water surfaces. Possibly clays remained suspended in fresh waters long enough that they did not flocculate until they were carried far offshore and then underwent mass flocculation and deposition during mixing. Regardless, these horizons, like ash beds provide very precise time lines for correlation.

Siltstones

Siltstones within these intervals show classic tempestite features including: sharp, erosive soles with tool marks, including bi-polar prod marks, scoured burrows, minor grading, and larger gutter casts (Fig. 3). Silts also show small-scale hummocky cross lamination (HCS), rippled/hummocky tops and top-down post-event burrowing (lam-scram fabrics). That these beds may reflect single events is indicated not only by HCS extending through their thickness but also occasional escape structures and incorporation of well-preserved fragile fossils such as crinoid stems extending through their full thickness (up to 8 cm). Individual particularly thick siltstones can be traced from outcrop to outcrop over considerable distances (up to 50 km along depositional strike) in outcrop. These may thus reflect extraordinary events in which large volumes of silt were abruptly input into the local depositional basin.

A few siltstones have distinctive features that make them usable regional maker beds. In particular, a few beds show labyrinthine patterns of circular pits on their upper surfaces referred to as rill marks or Kinneyia. These are thought to be the result of expulsion of gas bubbles under constraining blanket soft mud possibly stabilized by microbial mats (Pfleuger, 1999). Another distinctive feature, termed "millimeter ripples" is found in a particular lithology of thinly interlaminated silt and clay layers. Although these structures resemble very small scale straight crested ripples these are certainly not true ripples. They are repeated on all successive bedding planes through thicknesses of up to 10 cm. We suggest that they are the result of shearing during seismic events.

Gutter cast beds are relatively uncommon and confined to a few widespread horizons (Jeannette and Pryor, 1993). These are often sinuous scour fills, up to 10 cm deep with parallel tool marks. These scours evidently reflect rare very strong storm surge events associated with massive influx of silts. Their form may have been partially derived from pre-existing burrows (Fig. 3).

Freshly deposited silts appear to have been preferentially colonized by deposit feeding and certain filter feeding invertebrates. In particular nearly all siltstone beds are riddled by small to medium sized *Chondrites*, typically with open tops. Another trace that is particular well represented in thicker siltstones throughout the Fairview and Kope formations is *Diplocraterion*. These U-shape, burrows, frequently flaring at the lower corners are very common in silt beds greater than 5 cm. Moreover, they are typically found in deeper gutter casts where they appear to "fit" the profile of the gutter (Fig. 8).

Figure 8
Trace fossils in siltstones are common in the Kope Fm. Pictures A is an excellent examples of a siltstone horizon riddled with trace fossil *Diplocrateri*on. Boot for scale. B) Close-up view of *Diplocraterion* showing typical dumb-bell form; also note circular holes at tops of *Chondrites* tunnels. Finger for scale. *Diplocraterio*n are U shaped dwelling burrows". *Chondrites* is a branching "min -ing" burrow and although they are sometimes associated with dysoxia, that need not be the case for the Kope.
Such burrows reflect post-event colonization of storm silt layers.
Certain *Diplocraterion*-bearing siltstones can be traced between outcrops over considerable distnaces, recording ichnological event beds. The pervasiveness of trace fossils in siltstones indicates preferences for silty substrates and food contained in event deposits.

Storm depositional features in limestones include minor grading, amalgamation and cross-cutting of scour surfaces, presence of mud rip-up clasts and rippled tops. Different limestone beds have different ripple crest orientations but individual beds may show rather consistent orientations over several outcrops indicating the idiosyncratic signature of an individual widespread storm event. Hence, ripple orientation might provide a local correlation tool (Fig. 4).

Another distinctive feature of some importance in correlation is the occurrence of coquinas of edgewise shells of flattened or concavo-convex brachiopods, especially *Rafinesquina*. These brachiopod shell beds are thought to reflect the interfering effects of storm currents and waves (Seilacher and Meischner, 1965).

Concretion Horizons

One of the intriguing aspects of Cincinnatian sedimentology, well displayed in the Edenian Kope Formation, is the frequent occurrence of horizons of small ellipsoidal concretions, typically in the upper quarter of the mudstone intervals and most frequently within 10 to 20 cm below the thicker shelly limestone beds (Fig. 9). These are calcite-cemented nodules, commonly nucleated on small, cylindrical, pyritic burrows. The concretions are generally flattened in the bedding plane direction and frequently elongated ovoid shapes with long axes of 10-20 cm and lesser dimensions of 5 to 15 cm. They appear to nucleate preferentially on silty beds. Other than the pyritic burrows the concretions are generally unfossiliferous, although a few possess uncompressed fossils, including molluscan shells, trilobites, and in one notable horizon, masses of current aligned rhabdosomes of the graptolite *Geniculograptus typicalis.* The alignment of the concretion long axes parallel to clumps of perfectly aligned graptolites suggests that these concretions reflect cementation of gutter fills.

Figure 9

Concretionary sub-beds beneath Kope Formation; Brent submember limestone 6 at two localities near White Castle Distribution Center, Covington, KY

The association of the concretions with pyrite and moderately negative $\delta^{13}C$ values of the carbonate cements suggest formation in the zone of sulfate reduction, perhaps in the transition to an underlying methanogenic zone (Marshall, 2011). An absence of compaction of burrows and body fossils contained within the concretions indicates cementation prior to compaction.

A majority of the concretions lie beneath skeletal limestone beds and more than half of the skeletal limestones in the Kope Formation show “mirroring” concretionary layers a short distance below their bases in at least one locality near Cincinnati, although certain beds invariably show concretions beneath them (e.g., Beds 25, 28).

That these concretions were penecontemporaneous with development of the skeletal limestones is indicated not only by their close spatial association but by the occurrence in at least five instances of reworked concretions within or just beneath the limestone beds (Figure of reworked concretions). In these instances the concretion surfaces are smooth and may show borings, as well as encrusting bryozoans, crinoid holdfasts, and/or edrioasteroids (Wilson, 1985; Fig. 10)

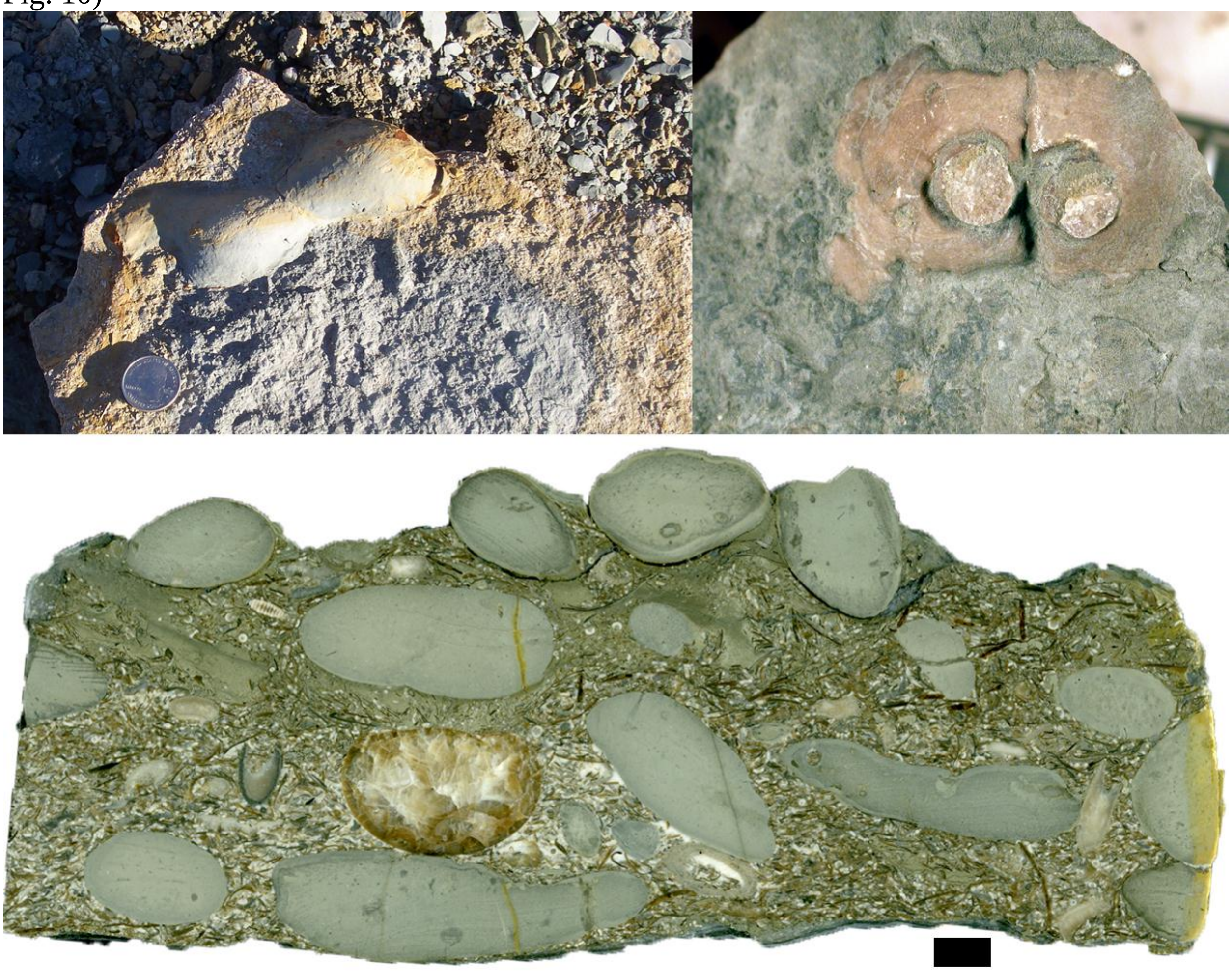

Figure 10

Reworked concretions in Kope Formation limestones. A) Reworked concretion in grainstone, quarter for scale. B) crinoid holdfasts encrusting reworked concretion in Pioneer Valley submember; Corporex site, Covington, KY. c) reworked concretions conglomerate, Fulton submember; Rte. 127, Monterey, KY. Black scale bar represents one centimeter

Brett *et al*., (2003; 2008a) contend that these concretionary layers are a reflection of sediment starvation at the sediment-water interface and that pauses of sedimentation and stable location of the sulfate reduction zone, up to several millennia in duration were required for the buildup of cements around nucleation centers in a zone of carbonate supersaturation (Fig. 11).

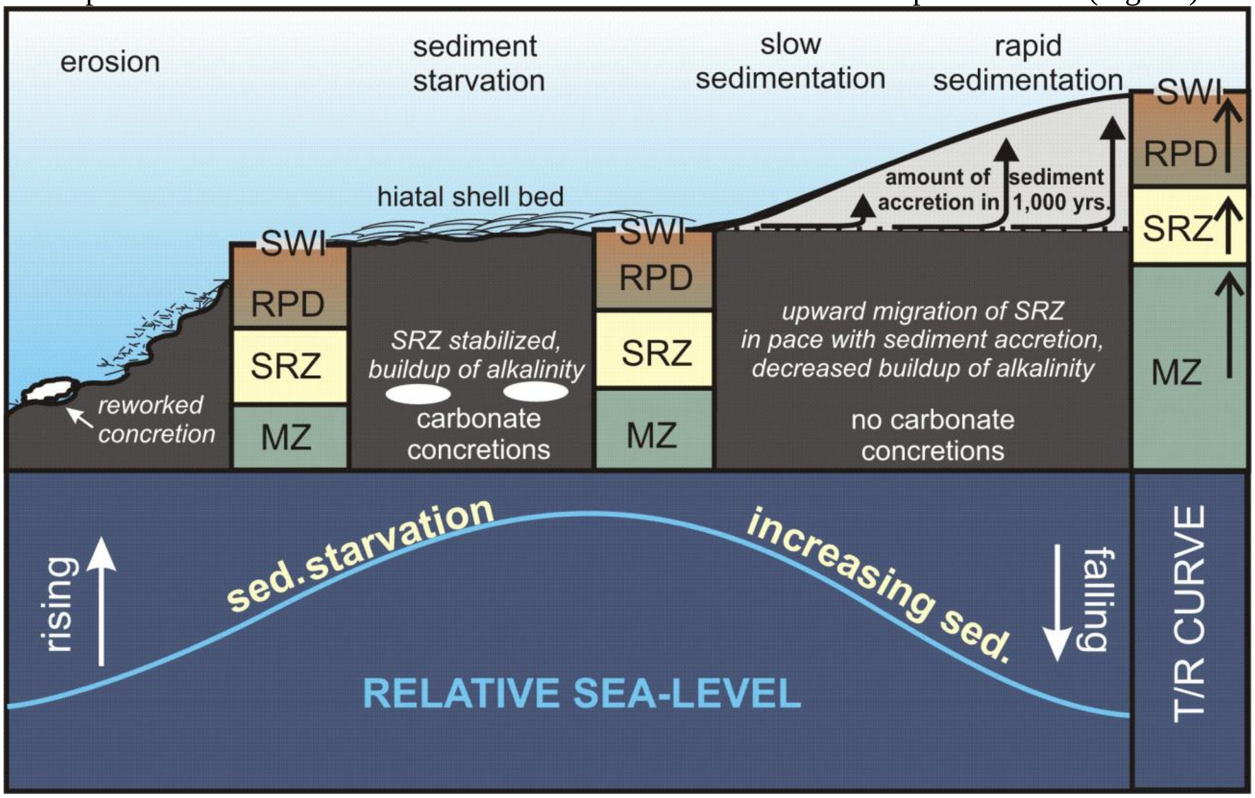

Figure 11

Relationship of sediment accumulation rates to formation/exhumation of concretions. Bar on right shows position of SRZ (sulfate reduction zone), RPD (redox potential discontinuity) and SWI (sediment-water interface) at outset of interval. Note that these zones remain static during period of sediment starvation but migrate upward to varying extents as sediments accrete to differing extents. Carbonate concretions will nucleate and accrete during conditions of sediment starvation in the stable SRZ; however, under conditions of sediment buildup; these zones will migrate upward in the sediment and no concretions will form; during sediment starved periods extreme storm erosion may erode down to the SRZ, exhuming concretions. Bar at the bottom shows possible relationship to sea-level oscillations, with starvation/erosion and concretion formation during rising base level (sediment sequestering in source areas) and increasing rates of sediment aggradation during falling sea level. Modified from Brett *et al*., (2008a).

The presence of reworked concretions in some skeletal limestones further proves significant erosion at the bases of these deposits presumably by storm waves/current winnowing in the absence of renewed sedimentation, after a period of skeletal accumulation on the seafloor. We infer that, both the skeletal accumulations and the concretionary sub-beds, were responses to periodic sediment starvation on the seafloor.

Distinctive concretion horizons, such as the afore mentioned graptolite concretions, as well as reworked concretionary horizons make useful stratigraphic markers and the reworked concretions may also signify erosional periods associated with related to stratigraphically important surfaces, such as forced regression surfaces.

Faunal events: Epiboles

Epiboles are widespread, thin intervals, which frequently cross depositional facies characterized by an exceptional abundance of a normally rare or absent taxon (Brett and Baird, 1997). These horizons are of uncertain origin but evidently record widespread ecologically altered conditions. They can be divided into various types including proliferation epiboles in which a rare species abruptly becomes extremely abundant for a brief interval and incursion epiboles, which reflect a temporary immigration of a taxon from outside the local depositional basin.

The Cincinnatian rocks host numerous examples of epiboles. Excellent examples include the *Strophomena*-rich interval near the base of the Fairview Formation (North Bend submember) and Mt. Hope-Fairmount Members boundary of the Fairview Formation, the *Heterorthina* beds of the upper Fairview Formation and the *Retrosirostra carleyi* "Zone" of the Sunset Member, Arnheim Formation (Caster *et al*., 1961). Each of these epiboles occurs in an interval, up to several meters thick, which has been traced very widely in the Cincinnati Arch. An epibole of *Orthorhynchula* in the upper Fairview Formation may be traceable into the Martinsburg Formation of the Appalachian Basin (Bassler, 1919; Felton pers. comm. 2010; Schramm, 2011).

Examples of highly specific epiboles include several widespread layers in the Kope Formation discussed in detail by Kohrs *et al*., (2008). For example, a thin interval, typically <10 cm thick in the lower part of the shale between beds 27 and 28 of the Alexandria submember which contains abundant remains of the trilobite *Triarthrus eatoni* (Fig. 6). This species only occurs at two levels within the Kope in the outcrop belt, though much more widely in the dark shales of the subsurface in the Sebree Trough. This epibole represents the local incursion of a taxon normally absent from the upper ramp environments near Cincinnati. This may represent a minor deepening and/or incursion of dysoxic water mass similar to that of the basin center.

A second very useful and widespread epibole is the occurrence of very abundant *Cryptolithus* and an unusual morph of *Sowerbyella* in the shales of cycle 28-29 (Fig. 6). These taxa, though very abundant in the lower Kope are virtually absent in the upper half of the formation except at this level and very rare occurrences in the upper Taylor Mill submember. The occurrence of extremely rare, articulated *Cryptolithus* in one or two beds within this level might also be termed a taphonomic epibole. These and many other distinctive levels have great utility in correlation (Fig. 6).

Magnetic Susceptibility

One of the tools that is presently being applied to Cincinnatian Strata is Magnetic Susceptibility. This technique provides a rapid and relatively inexpensive way of generating datasets useable for high-resolution stratigraphic correlations and for time-series analysis. New data are yielding important insights into cyclicity in the Cincinnatian rocks and the relative timing of those cycles.

Low-field bulk Magnetic Susceptibility (MS) measurements indicate the strength of a materials transient magnetism when the material is in the presence of an external magnetic field, and the material becomes "susceptible" to magnetization (Ellwood *et al*., 2000). This transient, or susceptible magnetism is much different than remnant magnetism, which relies on the intrinsic magnetism of a material, and these two measurements can be very different for the same samples (Ellwood *et al*., 2006). Susceptibility in marine strata/settings is dominantly controlled by detrital iron-containing paramagnetic and ferromagnetic grains, composed of clays, and eolian grains (dust). Diamagnetic materials (-MS) such as calcite and quartz are the dominant mineral components of marine sediments, but due to their very low magnetic susceptibility values they have little effect on total MS (Ellwood *et al*., 2000). This small percentage of detrital and eolian components controlling susceptibility values is used as an independent proxy of weathering and climate (Weedon and Jenkyns, 1999). Single beds traced over long distances have demonstrated non-varying MS values and provide a powerful tool for correlation (Ellwood *et al*., 1999). Used in a vertical succession this allows an independent dataset to adjust and evaluate stratigraphic position of sequences to improve correlation, and can be used to establish MS zones to correlate stratigraphic sections with high precision, even when biostratigraphic enigmas or small unconformities are known to occur (Ellwood *et al*., 2007). Additionally, the use of abiotic methods used in conjunction with conventional biostratigraphy is being stressed by the ICS for boundary correlation.

Used in vertical stratigraphic successions MS provides a powerful tool for the regional and global correlation of strata (Crick *et al*., 1997; Ellwood *et al*., 1999, etc.). Consequently, use of MS has increased in areas of stratigraphic and paleontological significance, such as the Cincinnatian and the Devonian Hamilton Group of New York (Ellwood *et al*., 2007; Ellwood *et al*., 2011; Schramm, 2011; Ellwood *et al*., in press). Ellwood *et al*., (2007) demonstrated the ability to correlate MS cycles in the Cincinnatian, Kope Formation where known correlations had been independently established. MS in the Kope Formation is controlled by the amount of clay in the sample (Ellwood *et al*., 2007). Ellwood *et al*., (in press) later quantified the duration of MS and visually identified lithologic cycles based upon composite Cincinnatian (Kope) sections. They recognized a series of significant Milankovitch cycles within the composite data set and outcrop, including precession, obliquity, and eccentricity cycles to represent dominant sub-meter, meter, and decameter scale cycles apparent within Cincinnatian outcrops. Based upon the number and duration of these cycles (eccentricity, obliquity, and precession), a length of ~ 2 myr has been assigned to the Kope composite section.

Building stratigraphically upwards from a wide base of knowledge within the Edenian Stage, Kope Formation, Schramm (2011) applied MS in vertical successions of the Maysvillian Stage. Recognition of regionally persistent MS cycles facilitates correlation at higher resolution than conventional biostratigraphy, offering a powerful tool in Cincinnatian strata lacking high resolution biostratigraphic control, and where facies changes exist. While providing such correlation, large single point shifts in MS have been used to corroborate previously unidentified unconformities within the Cincinnatian: Schramm (2011) recognizes a widespread unconformity beneath the base of the Bellevue Member based on field evidence and an abrupt shift in MS values (Figure 12). These new findings have greatly improved existing interpretations of Cincinnatian basin architecture and timing.

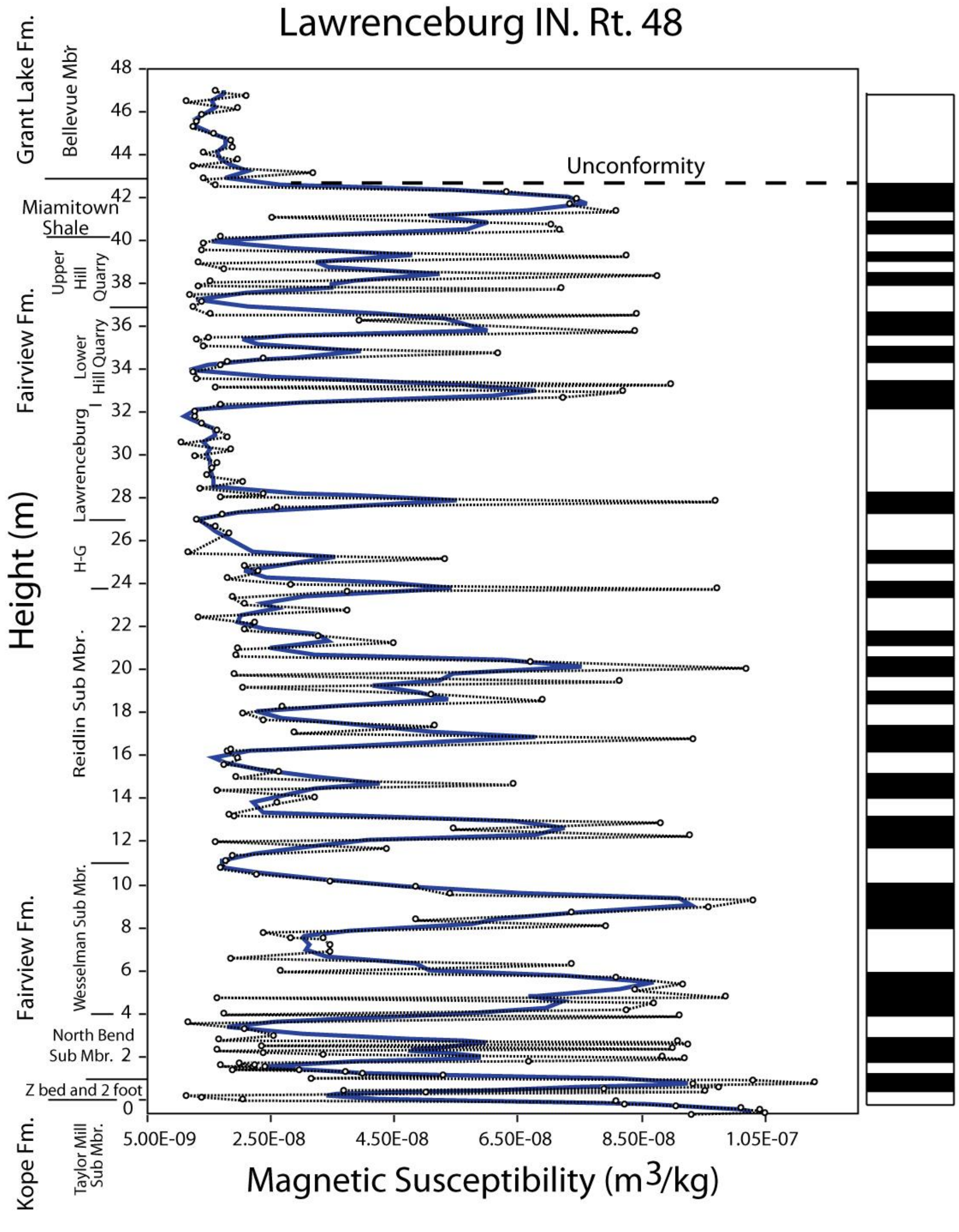

Figure 12

Low field bulk Magnetic Susceptibility (MS) has been measured through an approximately 47 meter stratigraphic interval ranging from the uppermost Kope, Fairview, Miamitown, and Bellevue formations. High resolutions MS measurements were conducted from samples taken at a regularly spaced, 30 cm interval. Fine dashed black lines with white dots represent measured data points, which were later smoothed using splines, indicated by the thick blue line. Bar logs of splined MS half cycles were created to aid in correlation of MS cycles, indicated by alternating black-white bars on the left side of the diagram. A total of forty MS half cycles have been observed in the Fairview Fm., with a sharp offset to low values occurring at the base of the Bellevue Mbr. of the McMillan Fm. This single data point shift in measure MS values is indicative of an unconformity at the base of the Bellevue Mbr. Modified from Schramm (2011).

Models for Limestone Formation and the Development of Meter and Decameter Scale Cycles

The most striking feature of the Cincinnati Ordovician rocks is the seemingly monotonous interbedding of shelly limestone and mudstone. On closer inspection, alternation between limestone-dominated and mudstone dominated hemicycles is apparent. Over the last 30 years the beds and cycles have come to be known as "tempestites" and "storm cycles", suggesting that storms were responsible for generating shell beds from undifferentiated shelly muds, and cycles have been explained by modulation of storm intensity or frequency of storm-scouring of the sea-bottom.

Our view is unorthodox; we suggest that, despite the ubiquity of storms during the Late Ordovician, storms did not generate shell beds, but that shells grew in place to generate condensed deposits during periods or siliciclastic sediment starvation. Here we discuss the tempestite model, the "episodic starvation model," and evidence supporting them.

Storm Winnowing and Tempestite proximality

The tempestite model for shell bed and cycle generation is really two separate models, the first of which is integrated into the second: 1) the storm-winnowing model (Kreisa, 1981a), wherein storms winnow the subtidal seafloor to make shell beds, and 2) the tempestite proximality model (Aigner, 1985) in which fluctuations in sea-level modulate storm winnowing to make sedimentary cycles (Fig. 13).

Kreisa (Kreisa, 1981a; Kreisa and Bambach, 1982) first suggested that storm winnowing was responsible for creating the limestone-mudstone interbeds in the Ordovician of eastern and midwestern North America, including Cincinnati specifically (Kreisa, 1981b). Tobin (1982) adopted this model as well. Jennette and Pryor (1993) applied the tempestite proximality model (Aigner, 1985) to the Cincinnatian, documented details of the cyclic succession, and established long-distance correlation of meter-scale cycles and beds. Subsequent workers (Miller *et al*., 1997; Holland *et al*., 1997; Miller *et al*., 2001; Drummond and Sheets, 2001) expanded cycle descriptions and correlations, citing the tempestite proximality model until Holland *et al*., (2001; also Webber 2002) were unable to find significant depth-related ecological differences between the faunal assemblages of the muddy and shelly cycle phases of the Kope Formation. Holland *et al*., (2001; also Holland, 2008) postulated that storm winnowing was modulated by climatic changes, rather than eustatic changes.

The process of storm winnowing is key. Dattilo *et al*., (2008; in press) argued that if storm winnowing is the principal agent in generating shell-mud interbeds (Kreisa, 1981a, Kreisa and Bambach, 1982), then it must concentrate originally undifferentiated sediments: an unsorted mixture of allochthonous siliciclastic mud transported into the basin and autochthonous shells (Fig. 13A). As a storm passes, storm waves resuspend this fair-weather sediment, and sort it as they redeposit it. Shells settle first, followed by shell fragments, siliciclastic silt and then clay-sized mud.

During a particular storm event, shallower portions of the seafloor suffer more intense winnowing than deeper seabeds, and winnowing diminishes to zero as depth approaches storm wave base (Kreisa, 1981a; Kreisa and Bambach, 1982; Aigner, 1985). On a sloping seafloor, the waxing-phase storm waves are refracted into shallow water where wave setup leads to a buildup of water—part of the storm surge. This excess water returns down-ramp as waning-phase

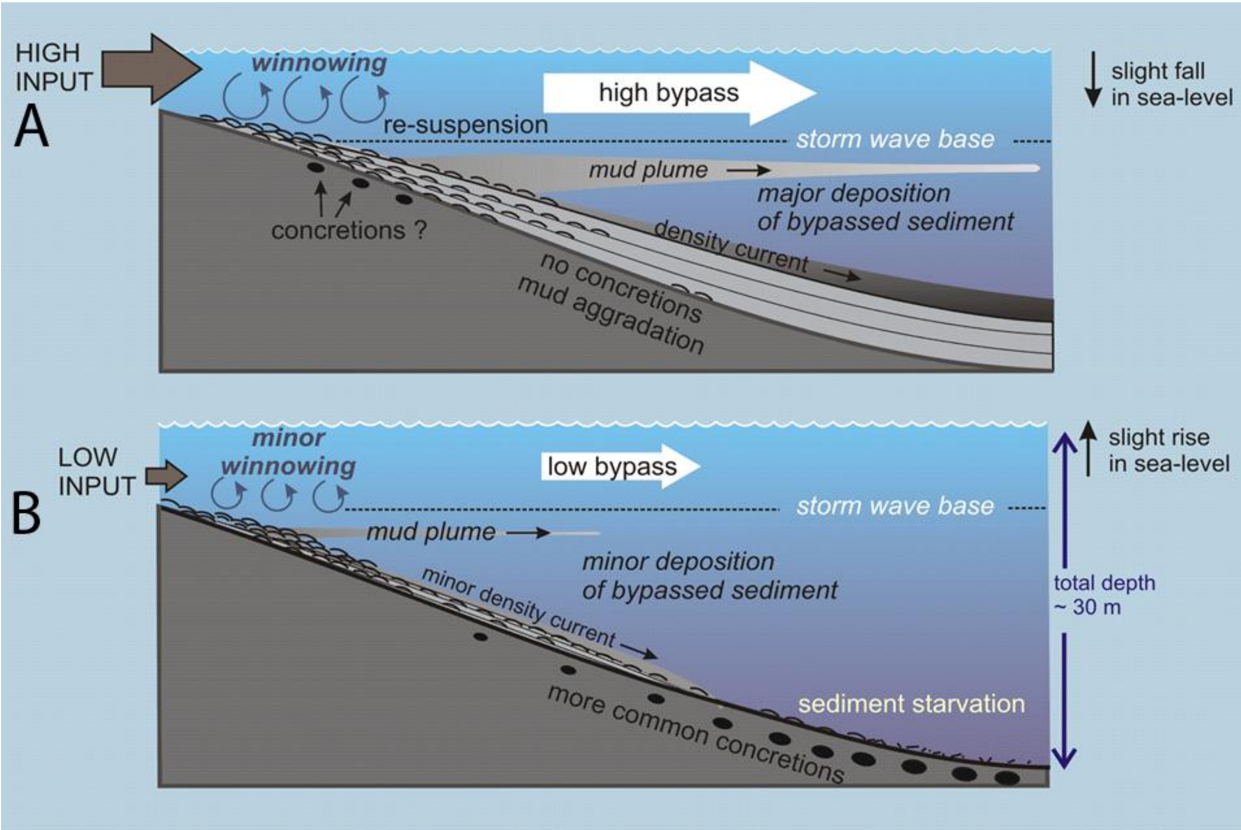

Figure 13

Two models of formation of shell-rich limestone in Kope Formation mudrocks. (A) Formation of shell limestones by intensification of storm wave winnowing; in this model a constant to increased sediment input; this implies high rates of sediment bypass as a result of winnowing and in turn the fallout of abundant muds in downramp positions. (B) Formation of shell-rich beds as a result of sediment starvation and winnowing; in this model low input of sediment is matched by low bypass; shells are exposed to repeated storm disturbances; minimal sediment accumulates downramp and sediment starved conditions may prevail in the basin; note that low rates of sediment aggradation may favor increased concretion formation downslope. Modified from Brett *et al*., (2008a).

gradient currents. These currents transport the finer sediments into deeper water, where storm winnowing is weak or absent (Aigner, 1985). The effect is that the proximal storm deposit is enriched in shells by removal of the fine fraction to deeper water and the distal storm deposit is enriched in mud by the addition of the resuspended fine fraction (Fig. 13A).

Episodic starvation and the role of growth during periods of condensation

Kidwell (1985; 1986; 1991; 1998), as well as Baird (1981), Brett and Baird (1986; 1996), and Parsons *et al*., (1988) had earlier argued that sediment supply was a principal controlling factor in the development of shell beds with or without winnowing. In the Cincinnatian, Brett and Algeo (2001), Brett *et al*., (2003; 2008b) and Dattilo *et al*., (2008) reviewed the available evidence and concluded that, despite the evidence for winnowing, sediment supply was principally responsible for generating Cincinnatian beds and cycles (Fig. 14B). Dattilo *et al*., (2008) suggested two possible mechanisms for delivering sediment to the region in 20-40 ka pulses: (i) wet-dry climate fluctuations that result in varying rates of erosion and therefore sediment supply from the source area.; or (ii) sediment trapping in the nearshore areas during minor relative sea-level rise and sediment flushing during relative sea-level fall (also Brett *et al*., 2008b).

How well do the depositional models fit reality?

Evidence cited in support the role of storm winnowing model is a suite of sedimentary structures found in a repeated bedding scale lithologic succession (Kreisa, 1981a; Kreisa and Bambach, 1982). Evidence cited for the tempestite proximality includes the alternation between muddy and shelly phases of meter-scale hemicycles, and the long-distance continuity of meter-scale cycles (Aigner, 1985; Jennette and Pryor, 1993). Does evidence for winnowing imply that winnowing or sediment transport is the principal factor in the formation of a shell bed, or are winnowing events a subsidiary part of the process of shell gravel accumulation?

Evidence that there was no fair-weather sediment from which to winnow shell beds.

Brett *et al*., (2008b) and Dattilo *et al*., (2008) concentrated on the storm-winnowing model and Kreisa's (1981a) claim that storm processes were responsible for winnowing sediments in situ to form shell beds where none had existed previously. This implies an undifferentiated fair-weather "precursor" sediment (Dattilo *et al*., 2008), but such sediment does not exist:

a) Most mudstone units consist of discrete, shell-poor, thin- to medium-bedded intervals interpreted as event deposits possibly related to storms (Tobin and Pryor, 1981; Jennette and Pryor, 1993; Potter *et al*., 2005; Kohrs *et al*., 2008; Brett *et al*., 2008b; Dattilo *et al*., 2008).

b) Those mixed shelly muds that do exist are either already concentrated into grain-supported shell beds (Dattilo *et al*., 2008), or consist of bedding-plane shell pavements within barren mudstone intervals. Neither deposit meets the criteria of a precursor deposit (Dattilo *et al*., 2008).

c) Kreisa (1981a) suggested that fossiliferous mudstones should be more common where there were fewer winnowing events to consume them, and claimed that field observations confirmed this prediction. Dattilo *et al*., (2008) tested this hypothesis and demonstrated the opposite pattern: shell-rich muds are associated with shell-bed limestones and are less abundant in thick mudstone intervals.

d) Dattilo *et al*., (2008) estimated that shell beds contain, on average, 60 times as much shell material as typical mudstone units. This suggests that winnowing up to six meters of mudstone would only generate a ten-centimeter shell bed (Dattilo *et al*., 2008), not accounting for compaction; typical muds undergo at least three-fold compaction; thus, a decimeter scale shell bed might require removal of more than 18 meters of sediment. No more than about 50 cm of erosion has been documented below any Cincinnatian shell bed (Brett *et al*., 2008b). Thus, storm winnowing alone would have been ineffective at concentrating shells from typical mudstone-dominated intervals.

Evidence that winnowing was not the most important factor in generating shell beds

Conversely, Brett *et al*., (2008b) and Dattilo *et al*., (2008) argued that shell beds formed by growing in place over long time periods, with only minimal concentration by winnowing, and that shell bed growth was halted by sudden influxes of blanketing mud:

a) The bedding-plane shell pavements commonly show unique fauna and may preserve multi-element skeletons (e.g. Hughes and Cooper, 1999; Hunda *et al*., 2006). Some of these unique obrution deposits have been traced for tens to hundreds of kilometers by paleontologists and amateur collectors, indicating large-scale blanketing by mud deposits (Brett *et al*., 2008b; c).

Rapid burial of the seafloor also explains the preservation of undisturbed complex bryozoan colonies scattered in patches across large bedding-plane exposures (Dattilo *et al*., 2008). These thin, discontinuous biostromes, recording patchy communities at the time of burial, were not concentrated by winnowing of previously undifferentiated shelly mud.

b) Un-winnowed shell-beds are common in certain intervals. Some beds are not winnowed at the base, but are winnowed at the top. These demonstrate that shell beds initially accumulated without storm influence (Dattilo *et al*., 2008).

c) Evidence of obrution of live organisms at the tops of fragmented shell beds is common and includes edrioasteroid-encrusted shell pavements (Meyer 1990) and live-burial and escape response of brachiopods (Dattilo 2004; Dattilo *et al*., 2009). Most shells in these beds display a range of breakage, abrasion, and discoloration states (Brett *et al*., 2008b; Kolbe 2011). This suggests that such beds were exposed to multiple winnowing-recolonization-exposure cycles, with the last generation of colonizers preserved by blanketing mud deposits that ended shell bed growth (Brett *et al*., 2008b; Dattilo *et al*., 2008).

d) Concretions found in mudstone intervals, centimeters below thicker, comminuted shell concentrations would have required thousands of years to form at shallow depth (Pratt, 2001; Brett *et al*., 2008b; 2011). At certain levels, concretions are reworked, and bored or encrusted by epibionts (Wilson, 1985; Brett *et al*., 2003; 2008b; 2011). Reworked concretions suggest that associated shell beds were generated by accumulation and submarine erosion during prolonged periods of slow or no siliciclastic deposition at the sea bottom, which subjected them to numerous storms and other high-energy winnowing events (Brett *et al*., 2003; 2008b).

Tempestite proximality does not predict facies distributions.

Brett *et al*., (2008a) and Dattilo *et al*., (in press) also examined regional facies patterns and found three characteristics that argue against the tempestite proximality model and support the episodic starvation model.

a) Evidence for significant bypass mud deposition is lacking. Isopachs of thick subsections of the Kope Formation (Gray, 1972; Hohman, 1998) suggest that sediments thicken toward source, and in the distal direction they thicken only slightly in the Sebree Trough, before continuing to thin. Kirchner and Brett (2008) and Dattilo *et al*., (in press) traced Kope and Miamitown cycles, respectively from Cincinnati into the subsurface and observed that individually they thin distally to the northwest, even if some cycles thicken slightly in the Sebree Trough. Furthermore, it is the mudstone hemicycle that thickens, while the limestone hemicycle continues to thin. This suggests that shell beds, especially shell beds in Cincinnati at the southeast flank of the Sebree trough itself, could not have formed by winnowing and distal bypass of fine sediment. Episodic starvation does not depend on winnowing and explains why thickening is restricted to the mudstone hemicycles, which would have formed during a high-sediment input phase.

b) Kirchner and Brett (2008), Schramm (2011), and Dattilo *et al*., (2012 in press) observed that limestone hemicycles contain more grainstones when traced to deeper-water facies, and that they contain more packstones when traced into shallow-water facies. If shell beds formed by winnowing, the opposite pattern would be expected and grainstones should be more prevelant in shallower water. Many of the grainstones are dominated by thin-shelled brachiopods and deep-water crinoids (Meyer *et al*., 2002; Brett *et al*., 2008a). Episodic starvation suggests that shell beds should be increasingly starved in more distal settings away from the sediment source, and lime mud is less likely to be generated in deeper water than in shallow water.

Grainstones, though traditionally interpreted as evidence of high-energy (Folk, 1959; Dunham, 1962), can form in quiet water if there is simply no mud to be deposited.

c) Kirchner and Brett (2008) and Brett *et al*., (2008a) also made the observation that Kope Formation limestone packages tend to become thinner and more compact even as individual shell beds within these bundles became amalgamated. Dattilo *et al*., (in press) traced limestone hemicycles in the Miamitown Shale of the Cincinnati region from the shallow-water facies in outcrop to the deep-water facies in the subsurface and demonstrated that the thin bedded limestones in thick bundles nearshore merged into amalgamated medium bedded limestones distally. This is opposite of the expectations of the tempestite proximality model which predicts distal "splaying" of shell beds- that thick, repeatedly-winnowed amalgamated shell bed accumulations in nearshore settings should split into component single-event storm-winnowed beds separated by bypassed muds in offshore settings, grading into fine grain distal storm deposits in deep-water settings (Figs. 13, 14). Proximal splaying is consistent with the episodic starvation model because more mud-depositional events reach proximal settings than distal settings, and shell production is more rapid to match.

This is not to say that storm processes were unimportant agents of deposition and erosion in the Cincinnatian. Storm-generated erosion and deposition is evident in many cases by the sharp bases of limestone beds, rip-up clasts, graded bedding, and rippled bedforms on upper surfaces. However, as noted above, there is also abundant evidence for storm erosion and deposition within the shale rich portions of the cycles, as emphasized by Brett *et al*., (2008a). Most mudstone intervals consist of stacked packages with sharp, scoured bases slightly differing color or texture and in some instances evidence of micrograding. Moreover, interbedded siltstones show scours up to 10 cm deep, gutter casts, tool marks, bipolar prod marks, as well as graded bedding small scale hummocky to climbing ripple cross lamination. All of this evidence points to episodes of erosion and high-energy deposition during deposition of the thicker mudstone intervals, as during shell bed dominated intervals.

Hence, a comprehensive model for Cincinnatian small-scale cycles must consider both the effects of intermittent sediment starvation and ongoing storm action. Figure 14 attempts to illustrate this interplay in a time series that compares the effects of storm winnowing and deposition during an interval of substantial siliciclastic influx versus a time of relative clastic starvation. Storm wave and currents produce scouring in both instances, but in cases of high net siliciclastic influx mud scouring produces only minor or no skeletal lags and rapid infilling of scours leads to subtle mud-on-mud erosion surfaces. Recolonization of newly deposited muds favors opportunistic communities of mobile epifauna and infauna and sediment-resting, snowshoe brachiopods such as *Rafinesquina* and *Strophomena* (Fig. 14, left column).

In contrast, during times of low net siliciclastic input this has the effect of removing only thin veneers of sediment and amalgamating skeletal remains and in some instances concretionary diaclasts derived from subjacent muds (Fig. 14, right column). Recolonization involved taphonomic feedback in which cleaned skeletal pavements and/or reworked concretions provided hard substrate for cemented organisms including crinoids and bryozoans, resulting in a more complex community.

Figure 14. (caption on next page)

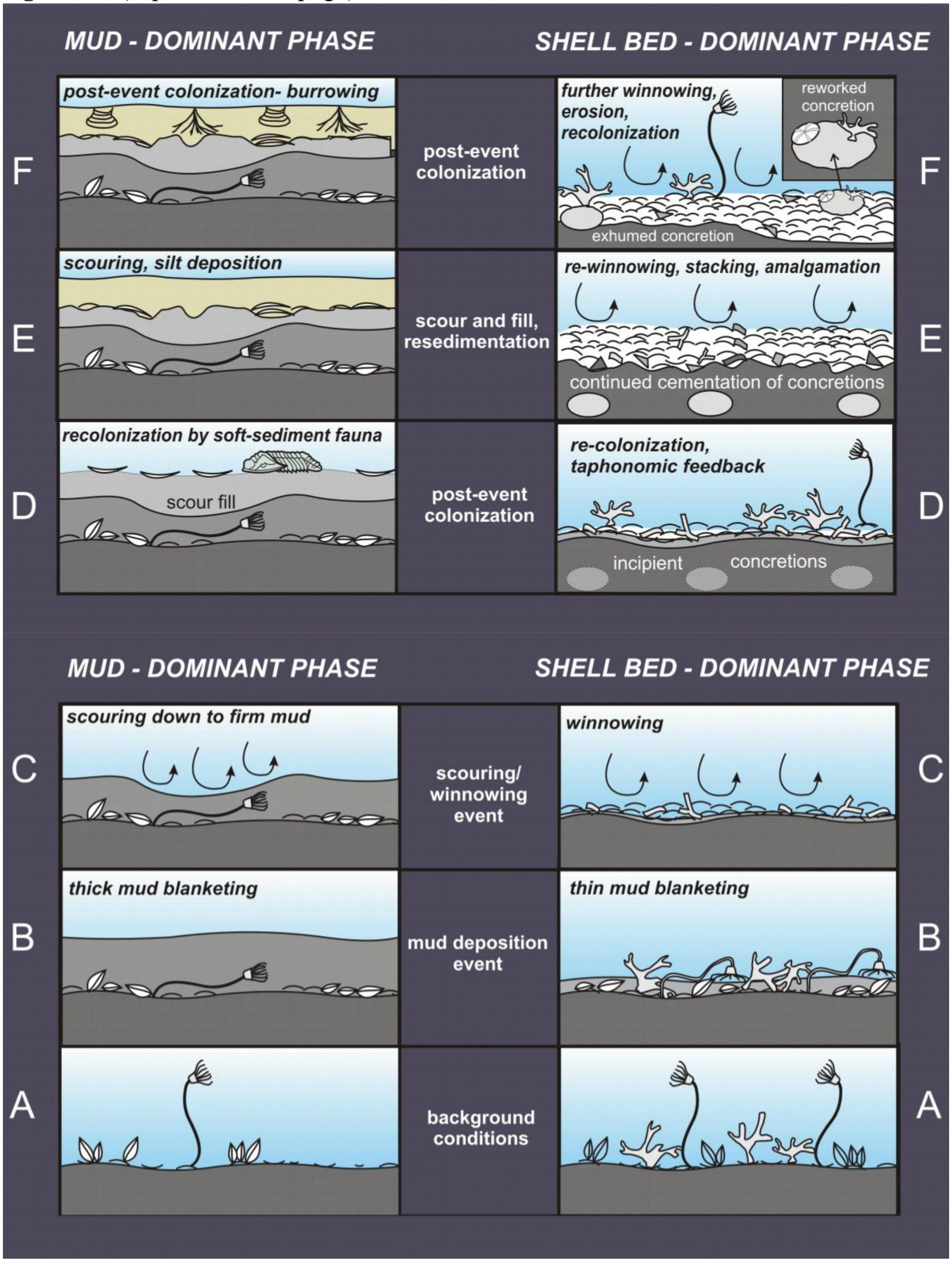

Figure 14 (previous page)
Analogous seafloor processes during mudstone dominant phase (MDP; left column), and shell-bed dominant phase (SDP; right column). Note that both sediment accumulation and erosion may occur in either phase, but to different effect. A) Background conditions at outset of interval; note general accumulation of skeletal debris during pause in sedimentation. B) Mud-blanketing; thick layer in the MDP, note obrution deposit with buried intact crinoid; thin mud layer in SDP. C) Seafloor erosion by storm currents; in MDP: scouring is effective in cutting down to firm muds, but does not erode through relatively thick mud blanket; little or no shell lag formed; in SDP: winnowing removes thin mud blankets aggregating shelly debris buried by several previous events. D) Post-event re-deposition and colonization; in MDP relatively thick silt/mud buries scoured surface, muds colonized by "snowshoe strategist" brachiopods and vagrant trilobites; in SDP: minimal mud accumulation; re-colonization involves taphonomic feedback with exposed shell-ground. E) Scour and re-sedimentation; in MDP storm erosion produces irregular scoured surface with gutters buried by silt layer; in SDP scouring creates irregular erosion surface and firm mud clasts may be torn up; muds are removed and shell debris is further stacked and concentrated; a thin silt layer may accumulate on top of shell hash. F) Recolonization; in.MDP :opportunistic burrowers colonize storm silts producing *Diplocraterion*, *Chondrites*, and other traces; in SDP: recolonization of hard substrate adapted taxa, including bryozoans and crinoids; exhumed concretions may be encrusted or bored with *Trypanites*. Modified from Brett *et al*., (2008a).

Cycle and Sequence Stratigraphy of the Cincinnatian

Recent fieldwork combined with time series of magnetic susceptibility datasets (Ellwood *et al*., in press) in the Late Ordovician of the classic Cincinnati Arch region has elucidated a hierarchy of meter- to decameter-scale cycles (Fig. 15). This section serves as a general overview of the delineation and definition of several orders of cycles within these rocks. These include small-scale (low order-high frequency) 6^{th} and 5^{th} order meter scale cycles, which may span 20 to 100 kya, 4^{th} order cycles with an idealized 405,000 year duration (Vail *et al*., 1991; Brett *et al*., 2011), and larger scale (high order-low frequency) 3^{rd} order depositional cycles. These various scales/orders of cycles occur as a nested hierarchy observable within Cincinnatian strata representing multiple magnitudes of environmental change and sedimentological processes on the Cincinnati Arch (Fig. 15). The present sequence stratigraphic interpretation builds on the previous discussion of meter- and decameter-scale cycles, in that bedsets of relatively clean skeletal limestones are associated with intervals of reduced siliciclastic sedimentation owing to sequestration during base level rise, and/or periods of climatic aridity that promoted shelly carbonate production, while more mud-rich intervals are inferred to represent times of increased siliciclastic influx associated with stable to falling base level.

Fifth and Sixth Order Cycles

The smallest scale of cycles manifest within the Cincinnatian rock record represent the shortest temporal durations and may reflect Milankovitch orbital forcing of climate and/or sea level. High frequency cycles appear in the form of sub-meter to meter-scale alternations of sparsely fossiliferous, medium to dark gray siliciclastic mudstones/siltstones and compact shell-rich limestone, the so-called "meter-scale" scales (Fig. 16).

Detailed field studies indicate that these successions show considerable variation (Holland *et al*., 1997; Figs. 3, 4); for example, while many cycles show a sharp contact between the shale and the next overlying limestone, others show a gradational contact; others show sharp upper contacts of the limestones and still others are gradational both above and below. However, despite these variations, recent studies also indicate some important commonalities of motif that and the basin-wide distribution of the cycles (Fig. 5) suggests a consistent, allocyclic process

Figure 15
Large cut on access road to River's Edge Indoor Sports Club; 5255 Rte. 128, Cleves, Ohio (Stop 1) showing beds 31 (thick cluster at base), 32, 33, (Grand View submember) and beds 34-37 (Grand Avenue submember near top). Such beds define bases of meter scale cycles; decimeter limestone-shale alternations, defined by clusters of meter-scale cycles overlain by a thicker "Big Shale" interval. Jim Thomka and Alex Borrell for scale.

related to climate and/or minor sea-level oscillations that produced alternating periods of elevated and reduced siliciclastic influx.

Time-series analyses based on magnetic susceptibility values at 5 cm intervals of the entire Kope indicate that these small-scale successions may represent periodic variations of sedimentation related to Milankovitch band precessional (~19 Kyr) and/or obliquity (30 and 37 Kyr) cycles (Ellwood *et al*., 2008; in press). These estimates are in line with estimates of the time durations required for formation of concretionary under layers, on the order of 10,000 years of

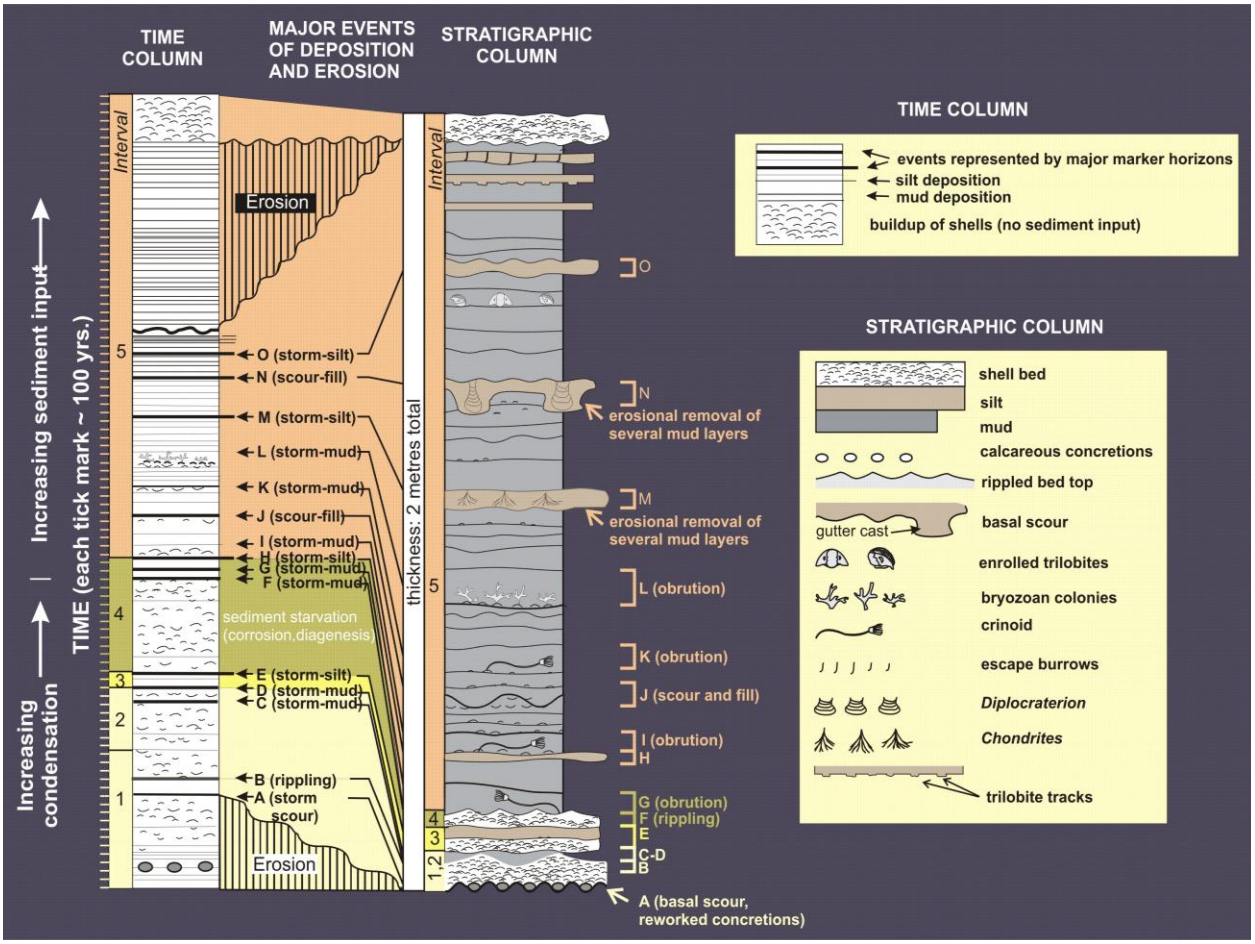

Figure 16

Idealized stratigraphic profile of Kope meter-scale cycle of alternating shell-bed accumulation and mudstone depositional phases at center; shows typical features of basal, rippled shell beds (pack- to grainstone), overlain by mudstone interval, thin skeletal bedding planes and siltstones. Column to the left of the stratigraphic profile is scaled to time rather than thickness with scale in 100-year increments. Horizontal lines indicate events of deposition; short lines mud depositional events, longer lines: silts or calcarenite deposits (each event is essentially instantaneous so line thickness is constant and actually exaggerated with respect to time); note that specific events are lettered and shown on the stratigraphic column with interpretation of process given to the right. Time intervals 1and 2 represent intervals of generally low sediment input; interval 3 and 4 more extreme sediment starvation; note that these intervals have relatively few mud or silt accumulation events; skeletal debris builds up in "background" times. These intervals, comprising about a third of the total time, are represented by thin complex of shell beds. Time interval 5 encompasses a time of increasing sediment aggradation; note deposition of a series of mud and silt layers (including obrution deposits); also note that many upper layers are subsequently removed in erosional interval, preceding and contemporaneous with, next shell hash accumulation. Portion of preserved mudstone interval comprising about a third of the time occupies the great majority of thickness of the preserved cycle. From Brett *et al*., 2008a.

stable sulfate reduction zone (Canfield and Raiswell, 1991; Brett *et al*., 2008). The sedimentary dynamics of these cycles are discussed in the previous section. Thus, we term the smallest scale of cycles as 5th and 6th order cycles following the estimated time-scales of cycle orders outlined by Vail *et al*., (1991).

As discussed previously, shell-rich limestones show abundant evidence of low rates of deposition and prolonged reworking and amalgamation of skeletal debris. First, the limestone bands are extremely widespread, being present as thin grainstones even in basinal dark shale facies, suggesting a basin-wide response to an allocyclic process. Second, many of the limestones are not fully winnowed and, in fact, may show micritic matrix rather than siliciclastic mud, suggestive of local, *in situ* generation of both shelly sediment and lime muds. Third, many limestones show sharp firmgrounds or hardgrounds at their tops and associated concretionary beds beneath, indicative of sediment starvation. Fourth, many limestones become more compact, thin skeletal grainstones and/or concretionary carbonates in a down ramp direction rather than splaying into a package of interbedded thin, graded layers and muds, as might be predicted if normal rates of sediment input were balanced by winnowing and bypass during limestone deposition (Kirchner and Brett, 2008; Dattilo *et al*., 2008). Thus, these limestones show a pattern similar to larger scale transgressive systems tract in which rates of terrigenous sedimentation are decreased in offshore areas. The sharply erosional bases of many of the limestones (Figures 3, 4) also appear analogous to sequence boundaries, although they are thought to record multiple episodes of submarine storm erosion during periods of sharply lowered sedimentation, not subaerial unconformities.

Conversely, the mudstone-dominated portions of cycles show features analogous to those in larger scale highstands. Studies of silt distribution incorporating data from all cycles in the Kope Formation indicate that, as a whole, siltstones tend to be concentrated in the upper half of meter-thick shale intervals (Marshall, 2011; Fig. 17). This suggests a process of sediment progradation as might be at work in deposition in the mudstone intervals.

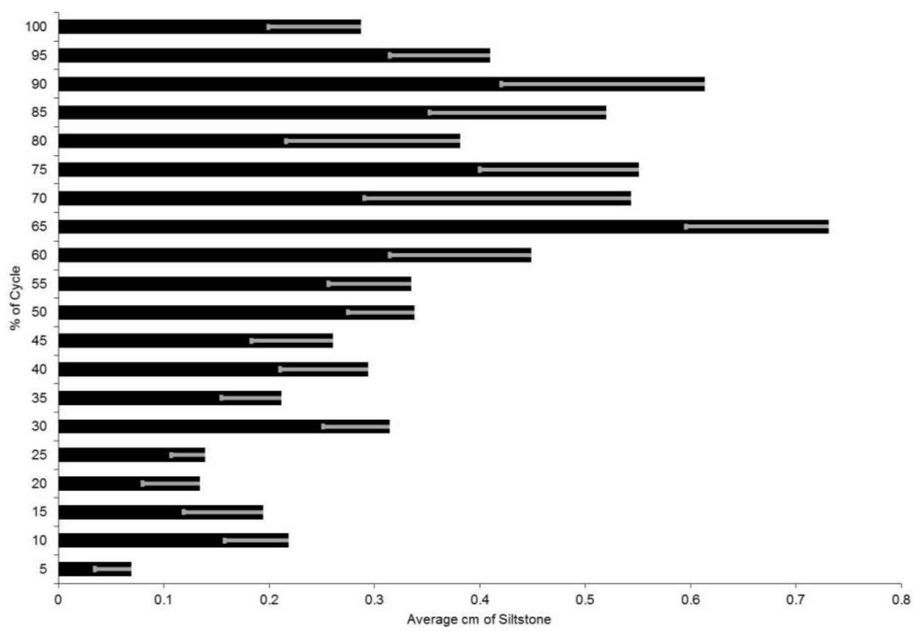

Figure 17
Averaged siltstone distribution of an Kope meter-scale cycle. 286 cycles we measured across the complete thickness of the Kope, with an average of 7 locations for an individual cycle. Each cycle was normalized into 100% and an average number of cm of siltstone was calculated for each 5% interval. Error bars give the lower standard error because it is far more likely that the siltstone thicknesses were over estimated. Note tendency for upward increase in silt thickness in the lower 75% of cycle and slight decrease in upper quarter. Adapted from Marshall (2011).
See text for discussion.

Moreover, using sulfur isotopes as a proxy for depositional rate, Marshall (2011) identified a consistent pattern of very negative $\delta^{34}S$ values, corresponding to low rates of net sedimentation, both within and immediately below and above the shell-rich limestones (Fig. 18). From these values most studied cycles show an upward increase in $\delta^{34}S$ values through most of the shale succession, interpreted to indicate an increase in relative sedimentation rates through the time interval represented by the succession. Hence, the mudstone portions of cycles show evidence of upward increase in sediment influx followed by an abrupt decrease approaching overlying limestones. The interval around the major shell rich limestones, including both the shell beds themselves and synjacent mudstones, shows evidence of lowered siliciclastic sediment input.

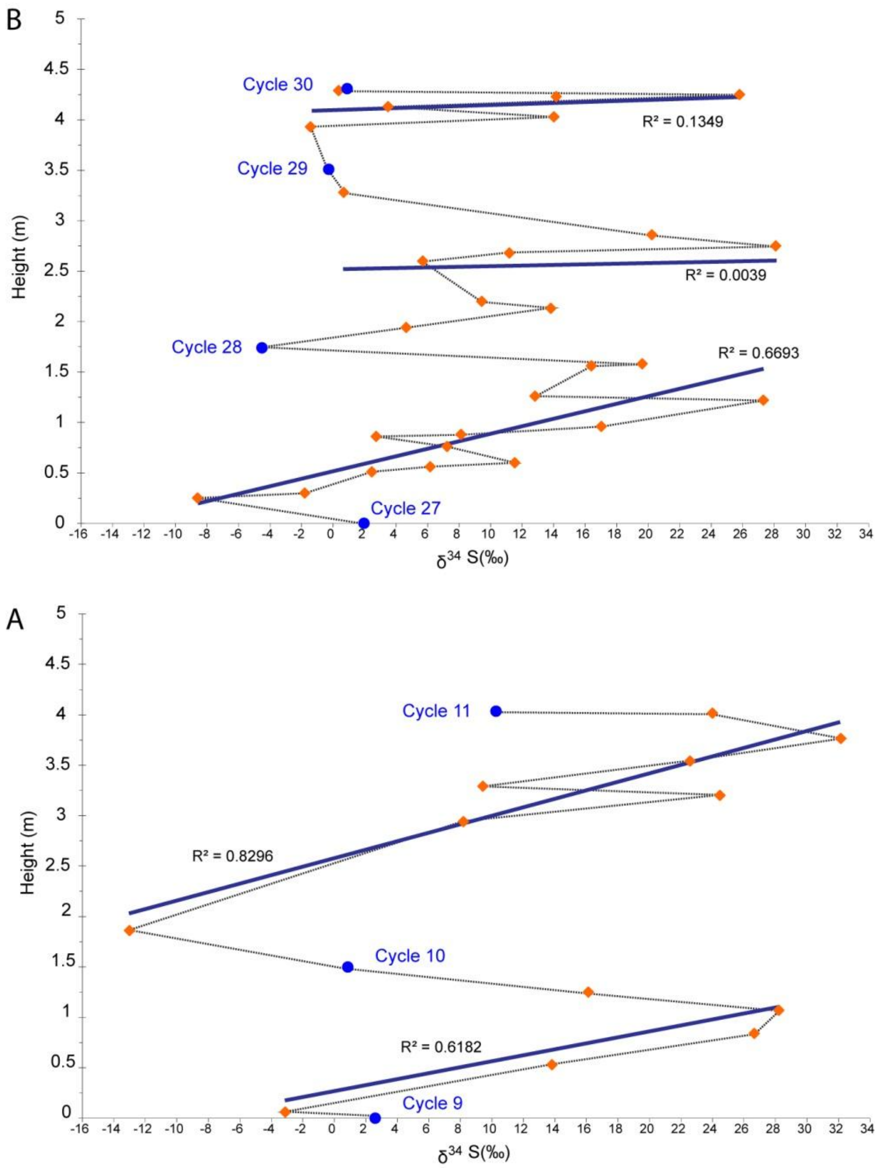

Figure 18
Plot of $\delta^{34}S$ values as a proxy for sedimentation rate in successive meter-scale cycles. Note that lowest values occur slightly above the major limestone bundles, followed by steadily increasing values up to a few centimeters below the limestones. This suggests a pattern of increasing sediment starvation associated with the onset of carbonate deposition and increasing rates above a thin condensed zone just above the limestones. A) Cycles 9-11 the Pioneer Valley submember, Rapid Run, Delhi Township. Ohio. B) Cycles 27-30, Alexandria submember; Fowler Creek, near Independence, Kentucky.

In summary, meter-scale cycles show a number of features analogous with larger scale depositional sequences. These features may be interpreted as the response to small-scale oscillations in sea level that caused sequestration of sediment during base level rise and increased sediment supply during stable to slightly falling sea level. Alternatively, these small cycles may record climatic oscillations such as alternating periods of arid and more humid conditions in source areas that led to fluctuations in sediment runoff.

On the basis of the time series analyses, we suggest that most of the previously recognized 40+ meter- to sub-meter cycles in the Kope Formation record ~30-37 Kyr obliquity cycles (Ellwood *et al*., in press). Moreover, the common occurrence of two closely spaced (0.2 to 0.5m) limestone ledges may reflect the siliciclastic sediment-starved portions of two precessional cycles that are bundled into a single cycle of sub-meter scale. In some cases the limestone bundles are divided into approximately three to five individual limestone ledges (themselves lateral-vertical amalgams of minor lenticular bands), separated by thin, sparsely fossiliferous shales. These clusters could be interpreted as a stacking of precessional cycles and representing the majority of a 100 Kyr (5^{th} order) eccentricity cycle condensed by thin or truncated intervening mudstone intervals. Examples of this type of stacking are seen in Beds 34 and 36 of the Grand Avenue submember. The thicker shales that lie between these clusters reflect accentuated single 6^{th} order cycles.

Fourth Order Cycles

Fourth order cycles, may have a stratigraphic thickness of approximately 3-10 meters. The cycles, are each composed of transgressive, highstand, and falling stage systems tracts, and represent easily distinguishable cycles in outcrop. 4^{th} order cycles often compose systems tracts of broader 3^{rd} order cycles 4^{th} order cycles display the same general components as do larger scale depositional sequences and are composed of a series systems tracts which parallel those of the latter.

For practical purposes, Brett and Algeo (2001) subdivided the Kope Formation, into eight submembers, 3 to 13 meters thick, each defined as decameter-scale cycles commencing with a particularly thick shale ("Big Shale") interval and culminating in a series four to five increasingly tightly stacked limestone-shale cycles (Fig. 15). This definition used a parasequence motif definition of these intervals; i.e. the shales were viewed as maximum highstands and the more tightly stacked 1-2 m-scale limestone-shale cycles as the regressive, shallowing-upward portion of the cycle, with no representation of the transgression. However, even at that time it was acknowledged that the cycles could and perhaps should be defined in the opposite way; i.e. with the thicker limestone beds at the base (see also discussion in Brett *et al*., 2003). In such an arrangement the more tightly spaced limestone-shale 5^{th} order cycles, are viewed as an expanded transgressive to early highstand systems tract. This would make the thick and often silty "Big Shales" the later highstand and/or falling stage. This is our present interpretation of fourth order cycles and it makes the big shales effectively the tops of small-scale depositional sequences rather than the bases of shallowing upward parasequences.

The curves of siltstone occurrence (Marshall, 2011) provide further insight into the dynamics of decameter-scale cycles (Fig. 19). Siltstones show distinct patterns of abundance with four peaks (excluding the lowest Kope Fulton submember): (A) cycles 2-4, (B) cycles 9-12, (C) cycles 20-25, and D) cycles 39-41. Sharp spikes of silt frequency in cycles 2, 10, 19, and 39/40, are associated approximately with "Big Shales" 1, 2, 3, and 7, formerly used to subdivide submembers; lesser peaks occur in cycles 6, 16, 28, and 33/34. The bases of each of these intervals are interpreted as maximum flooding surfaces and the intervals themselves as fourth-order highstands.

Distinct lows in silt frequency in cycles 5-7, 11, 13, 17-19, 25, 28 and 32 coincide some of the major fossil-rich limestone intervals of the Kope. They clearly mark the limestone bundles of the decameter cycles previously identified as submembers by Brett and Algeo (2001).

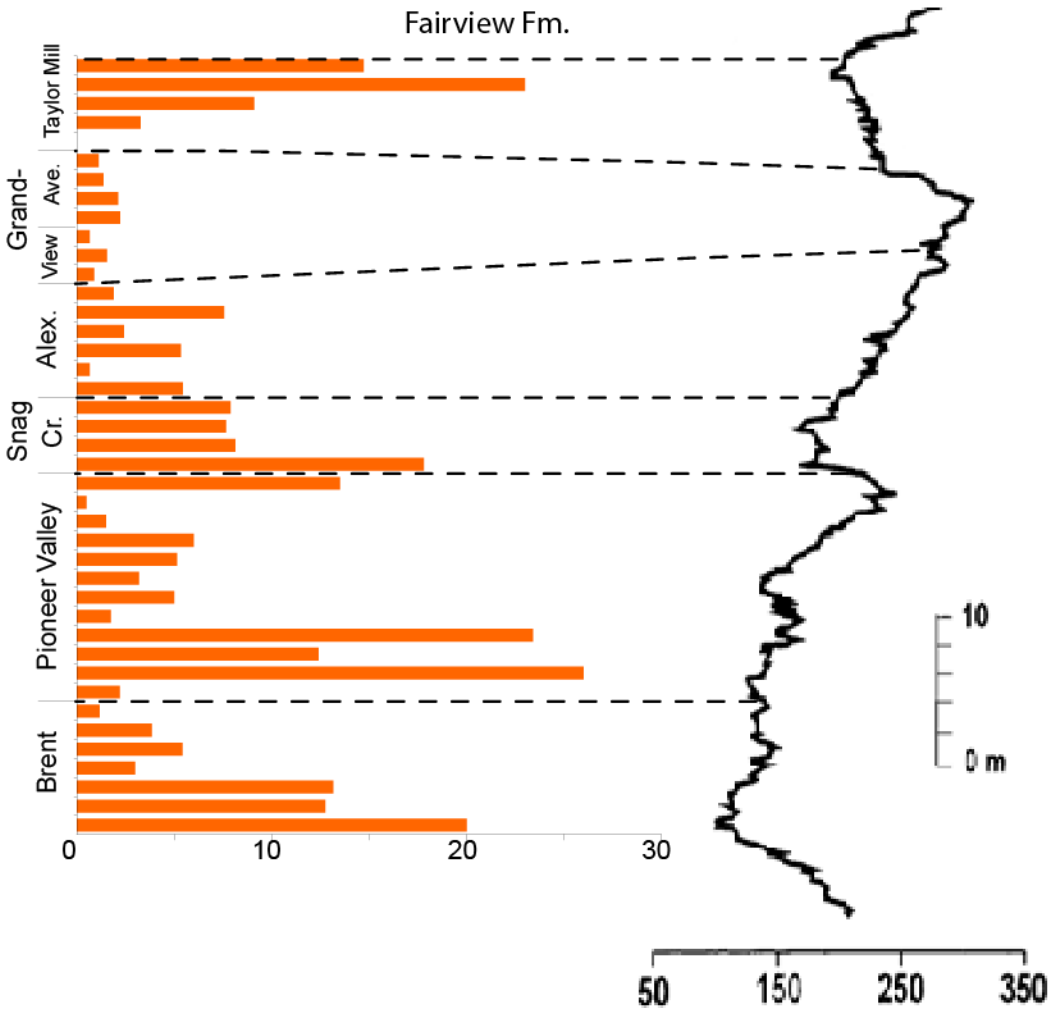

Figure 19
Total thickness of siltstone per meter-scale cycle averaged for all localities at which that cycle is exposed (generally >5). Note peaks in the lower Brent, lower Pioneer Valley, at the Snag Creek/Pioneer Valley boundary, and upper Taylor Miller. These appear to correspond to falling stages or regressive portions of fourth-order cycles. Curves to right show DCA ordination scores for fossil assemblages from Miller *et al*., (2001). Figure adapted from Marshall (2011).

Siltstone frequency does not parallel shallowing trends as interpreted from faunal gradient analyses of Miller *et al*., (2001). Rather peaks of silt frequency are associated with relatively low DCA scores interpreted as deeper water biofacies (Fig. 19, Marshall, 2011). Alternatively, the low DCA scores may, in some cases, record increased rates of sedimentation associated with the input of more silts, whereas higher DCA scores may indicate low sedimentation rates associated with initial transgressions, which promoted a higher diversity of suspension feeding organisms.

In some cases thick, persistent siltstones occur the bases of "Big Shales, very slightly above the inferred fourth order maximum flooding surfaces. Why this is so remains enigmatic.

We suggest that, during the early highstand, silts sequestered during rising base level may be flushed from nearshore clastic traps during the first very large storms occurring after onset of highstand conditions. (Fig. 19)

To summarize, decameter-scale cycles, the "submembers" of Brett and Algeo (2001) and herein recognized to be approximately the scale of the as fourth-order sequences, are inferred to consist of two major parts, a lowstand to transgressive systems tract, comprising a series of meter-scale limestone-shale cycles that show a general pattern of upward decrease in thickness and a highstand comprising a relatively thick, typically silty shale. The inferred lowstand/transgressive systems tract cluster commences with a thick limestone bundle that shows evidence of minor erosion at the base and condensation of two or more high-frequency cycles; stacking of two closely spaced limestones is typical. This distinctive bed is overlain by a rather thick shale interval, which may be nearly as thick as the underlying shale, though generally less silty. This initial shale might be interpreted as a lowstand or early transgressive deposit, formed when sea level rise was still occurring at a low rate such that mud progradation into the basin continued during smaller-scale cycle highstands. This first thick shale is followed by several more discrete limestones alternating with shales, which thin upward; the proportion of siltstone appears also to decrease upward and faunal patterns may also suggest upward deepening at least to a point. The highest limestones in the bundle may show a "microhash", including phosphatic steinkerns as well as reworked concretions. This interval is interpreted as a maximum flooding zone.

This upper limestone is abruptly overlain by a thick shale, typically with siltstone beds. Marshall (2011) has demonstrated that the siltstone beds typically increase in frequency and thickness upward and concretions occur near the tops of many of the Big Shales. We interpret these packages as particularly thick 5th order cycles that reflect highstand to falling stage conditions in the 4th order cycle with correspondingly increased rates of siliciclastic sedimentation. This package is sharply overlain by the next thick basal limestone, with the contact interpreted as a fourth-order sequence boundary.

Third-Order cycles

Ranging from 10 to 40+ meters in thickness, 3rd order cycles represent increased magnitude base level changes, composed of multiple systems tracts, and lower order (smaller-scale) cycles. Third order cycles are defined based upon the physical attributes of bounding unconformities (Embry, 1995), and may vary in cycle duration from 0.5 to 3 million years (Vail *et al*., 1991). Idealized third order depositional cycles may represent a 1.25 to 1.3 million year cycle duration, concurrent with long eccentricity cycle durations implying an orbital control of cycle genesis (Berger, 1977; Shackleton *et al*., 1999). Additionally, some 3rd order cycles may be of a non-eustatic or tectonic origin: for additional discussion of distinguishing tectonic vs. eustatic effects on base level in Maysvillian strata see Schramm (2011).

Brett *et al*., (2004) and McLaughlin recognized three systems tracts within these large-scale sequences: a) Basal lowstand to early transgressive systems tract that sharply overlies subjacent silty to sandy beds. These TST deposits comprise stacked skeletal carbonates, typically a single fourth-order sequence with pack and grainstones that are capped by thinner condensed, commonly phosphatic skeletal packstone, commonly with hardgrounds and interbedded shales. b) Thicker successions of shales and thin nodular to tabular packstones interpreted as highstands; these intervals are generally composed of two or more fourth order sequences. c) in some instances a single 4th order sequence with a strongly upward-coarsening succession of silty shale with abundant gutter and channel fills of siltstone, commonly showing soft sediment deformation. These are interpreted as falling stage systems tracts. We have applied this same set of divisions to the Cincinnatian.

The Cincinnatian succession was initially subdivided into five depositional sequences by Holland (1993) who designated these successions as C1-C5. He recognized very thin TSTs, typically showing evidence of condensation, overlain by thick successions of mudstones and increasingly shelly limestones interpreted as, progradational highstands. The Kope Formation as a whole was originally considered to represent a part of major depositional sequence that also included the overlying Fairview and Bellevue formations (Holland, 1993). Subsequently, Holland and Patzkowsky (1996) assigned the Kope Formation to sequence C1 and the Fairview Formation through Bellevue Member of McMillan (or Grant Lake) Formation to a separate third-order depositional sequence, a redefined C2. This then changed the number of Cincinnatian sequences from five to six: Sequence C3, as redefined, comprised the Corryville and Mount Auburn (members of McMillan Formation), Sequence C4 the Arnheim Formation, C5 the Waynesville, Liberty and Whitewater Formations, and C6 the Elkhorn and upper Whitewater formations (Fig. 2).

Extensive recent field investigations provide the basis for new sequence stratigraphic interpretations of the Kope, Fairview, and McMillan (Grant Lake) formations. These units collectively are now interpreted to represent more than a dozen 4th order cycles perhaps as many as five 3rd order depositional cycles. The development of this 3rd order framework is based upon new data, including previously undocumented unconformities, and does not precisely reflect the 3rd order sequence stratigraphic model of previous Cincinnatian workers, although it also has many common features. The 3rd order sequences and revised stratigraphic framework described briefly in this article (Fig. 20) are discussed in further in Brett *et al*., (2004) and Schramm (2011).

Brett *et al*., (2003; 2004) argued that the Point Pleasant (as redefined therein) and Kope, should be considered, collectively, as parts of the same depositional sequence, with the Point Pleasant representing the early transgressive systems tract (Fig. 2). The Point Pleasant overlies deformed calcarenites and shales with sharp unconformity and shows some tendency toward upward shallowing and then deepening through a series of five to seven meter-scale cycles and with a strong middle (fifth-order?) highstand shale. Overlying beds locally include trough cross-stratified crinoidal grainstones, but these beds pass upward into thinner ledges of brachiopod pack and grainstone and faunal gradient analysis of the Point Pleasant suggests upward deepening trends (McLaughlin and Brett, 2007).

The hardground/corrosion surface at the upper contact of the Point Pleasant with the Fulton submember of the Kope Formation was interpreted as a maximum starvation surface (Brett, 1995). The Fulton submember, with several hardgrounds and reworked concretionary conglomerates was regarded as the third order late transgressive systems tract (McLaughlin and Brett, 2007) with a possible maximum flooding surface near its top marked by a thin phosphatic, pyritic lag bed. The overlying thick package of sparsely fossiliferous shales and calcisiltites/siltstones (“Big Shale 1”) was interpreted as a “highstand systems tract”. However, newer studies suggest that this interval should perhaps be subdivided into two third order sequences. The very silty upper Kope Taylor Milll submember and its southeastern equivalent, the heavily deformed Garrard Siltstone are interpreted to record a falling stage (regressive) systems tract at which a large influx of silt resulted from lowering of base level (Fig. 20).

The sequence boundary of Holland's C2 sequence is now interpreted to occur at the base of the so-called "Z-bed" (Brett and Algeo, 2001), a thick brachiopod-rich limestone, which appears to overstep truncated deformed beds in the upper Garrard Siltstone. The limestone-rich succession of the North Bend submember of the Mount Hope Member (Fairview Formation) is interpreted as the TST and overlying mixed silty shales and lenticular packstones as a highstand. The Hooke-Gillespie submember (presently assigned to the Fairmount Member), an interval of thicker, locally deformed siltstones resembling the Garrard, provides an excellent candidate for the falling stage of this 3rd order sequence. In this interpretation, the upper Fairmount Member, including the informally named Lawrenceburg, upper and lower"Hill Quarry", and Miamitown Shale submembers, represent the transgressive, highstand and falling stages of another sequence.

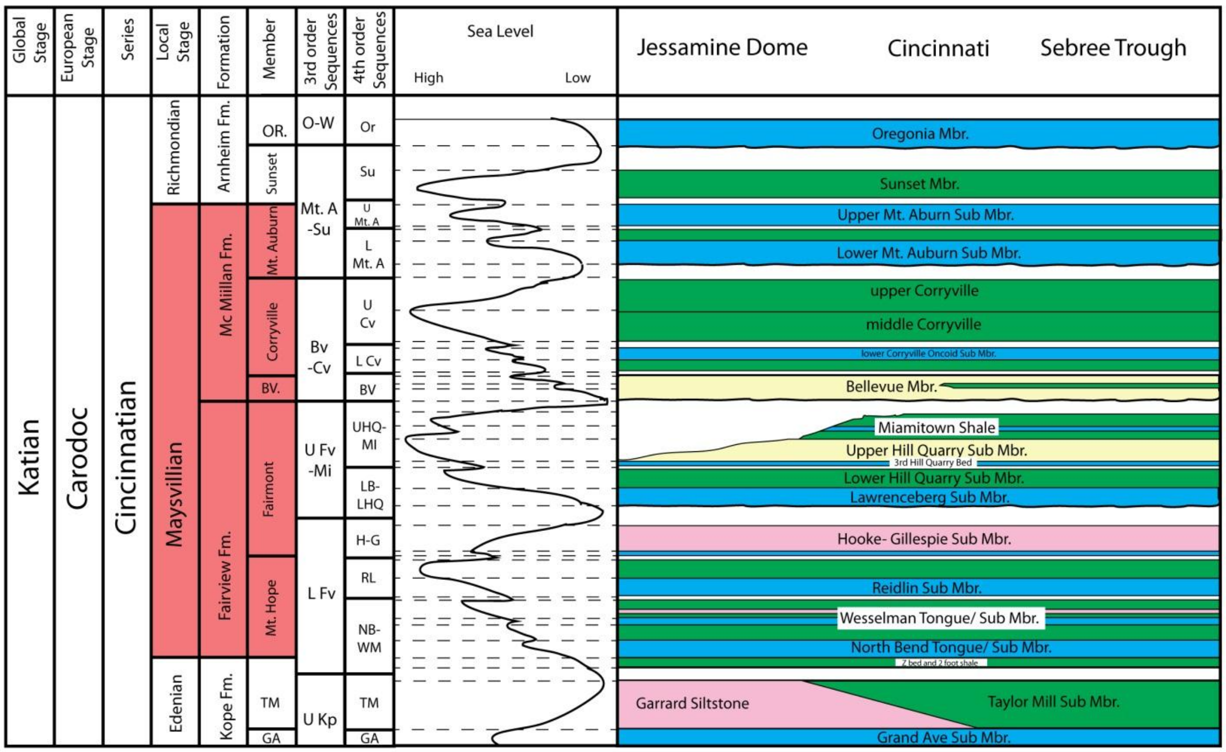

Figure 20

Diagram showing sequence stratigraphic interpretations of Maysvillian Stage, and surrounding strata on the Cincinnati Arch USA, modified from Schramm (2011). Colors represent dominant lithologies of associated units, however, this color scheme does not account for facies variations across the Cincinnati Arch. Blue represents dominantly carbonate pack to grainstone intervals, Pink represents deformed siltstone horizons, green represents mudstone-rich intervals, and yellow (lemon) represent argillaceous rubbly bioclastic packstone intervals. The black curve illustrates variations from high sea level on the left to low sea level on the right. A series of 3rd order sequences are shown, U Kp (Upper Kope); L Fv (Lower Fairview), composed of the North Bend, Wesselman, Reidlin, and Hooke-Gillespie submembers; U Fv-Mi (Upper Fairview-Miamitown) composed of the Lawrenceburg, Lower Hill Quarry, Upper Hill Quarry, and Miamitown submembers; Bv-Cv (Bellevue-Corryville), composed of the Bellevue and Corryville Mbrs. of the McMillan/Grant Lake Fm.; and Mt. A-Su (Mt. Auburn-Sunset), composed of the Mt. Auburn Mbr. of the McMillan/Grant Lake Fm. and Sunset Mbr.; O-W (Oregonia Waynesville). Changes from the Jessamine Dome to Sebree Trough represent an approximate paleo-ramp from Southeast to Northwest. Missing strata below the Bellevue Mbr. in the Jessamine Dome region indicate the presence of an unconformity. 4th order sequences include the GA (Grand Avenue), TM (Taylor Mill), NB-WM (North Bend-Wesselman), RL (Reidlin), H-G (Hooke-Gillespie), LB-LHQ (Lawrenceburg-Lower Hill Quarry), UHQ-MI (Upper Hill Quarry-

Miamitown), BV (Bellevue), L Cv (Lower Corryville), U Cv (Upper Corryville), L Mt. A (Lower Mt. Auburn), U Mt. A (Upper Mt. Auburn), and S (Sunset).

The sharp base of the Bellevue Member (McMillan Formation), which appears to regionally overstep the truncated Miamitown Shale may represent a third major sequence boundary. In this interpretation the Bellevue and Corryville represent the transgressive and highstand to falling stage systems tract of a previously unrecognized large-scale sequence (Fig. 20); for details of this interpretation see Schramm (2011). Finally, the Mount Auburn Member and overlying Sunset Member Shale, formerly considered to be separated by a sequence boundary may actually constitute parts of another sequence separated by a major flooding surface.

Second Order Cycles

Finally, strata from the Black River (Tyrone) Limestone to the basal Silurian unconformity represent one 2^{nd} order orogenic scale cycle, bounded by major unconformities. This is effectively synonymous with the Creek division of Sloss's (1963) Tippecanoe Megasequence. This succession is, in part, tectonically driven and associated with the Taconic Orogeny which produced driving subsidence that produced a foreland basin in eastern North America as the eastern edge of Laurentia was partially subducted beneath an accretionary wedge-island arc complex. Shallow water carbonate banks (Black River-Trenton groups, Figure 2) abruptly and perhaps diachronously deepened into an underfilled foredeep. The foreland basin was then gradually and episodically infilled with dark shales (Utica-Kope formations), flysch (Martinsburg), and siliciclastic molasse including the Juniata-Queenston redbeds (Ettensohn, 1992). To the west, in the area of the Cincinnati Arch flysch facies are absent and in their place are typical Cincinnatian successions of fossiliferous mudstones and thin pack to grainstones. These pass upward into silty dolomitic mudstones including reddish shales in the uppermost Drakes Formation, and desiccation-cracked, laminated thin bedded argillaceous dolomicrites.

Tectonic and climatic overprints on cycle development during the Kope and Fairview Formations

The same processes that control cycle development and sedimentology during deposition of the Edenian Stage, Kope Formation were active and the dominant control during deposition of the Maysvillian Stage Fairview Formation, and to a large degree the Bellevue and Corryville Members of the McMillan Formation as well. The major difference between these units is the amount (thickness) of mudstone occurring in between limestone beds. This difference in percent mudstone is obvious just by glancing at outcrops: Kope carbonate-shale cycles typically exhibit 1-5 m thick shale-mudstones units, while analogous mudstones are much thinner in the Fairview Formation (Fig. 21). The dominant sedimentological processes occurring during for the vast majority of both of these times is still the same: shelly-carbonate development. The only difference is the amount of time-poor, storm deposited mudstone tempestite horizons. The current study suggests the Episodic Starvation Model (Brett *et al*., 2008a, Dattilo *et al*., 2008; in press) as the driver for carbonate development during the Edenian and Maysvillian Stages, occurring during small-scale sea level transgressions. The carbonate rich deposits of the Fairview Formation essentially preserve a series of stacked minor transgressive deposits with limited, rather thin highstand deposits. Under this paradigm sediment starvation, resulting in limestone development on the Cincinnati Arch is essentially the norm, and offshore mudstone rich intervals are small-scale highstand-falling stage deposits representing episodic deposition that occurred during periods of increased erosion and sedimentation from high relief areas.

Figure 21
Outcrop photograph of the Kope and Fairview formations contact at Bald Knob, Cincinnati, OH. Note thicker mud- stone intervals in the Kope Formation cycles than those of the overlying Fairview Formation. Stacked carbonate beds inter-bedded with thinner shales being more common in the Fairview Fm. Photo by J. Zambito.

Mudstone-dominated intervals can be attributed to increased relief of source areas, weathering of source areas (mud development), and transport and deposition of mud into the basin where mud is preserved. Tectonically active areas, exhibiting high relief, in moist humid environments, with no intermediate basins to sequester clay deposits provide ideal conditions for the development of muddy basinal deposits (Potter *et al*., 2005).

Clay development during the Late Ordovician took place in the Taconic hinterland-orogenic belts of eastern Laurentia. These were located approximately 20-25 degrees south of the equator in the semi-arid subtropics (Holland, 2009; Blakey 2012; Fig. 22). Conditions of high relief and relatively low or intermittent humidity might not favor high rates of production of clay; but it should be noted that much of the source terrane consisted of older shales and weakly metamorphosed mudrocks which eroded to produce prolific quantities of clay. Also, climatically driven shifts of the intertropical convergence zone may have produced fluctuations in rainfall from more arid to humid conditions, which, in turn, could translate into strong variations in the supply of muddy sediment into the foreland basin. These factors appear to be the control of shale-mudstone development during the Taconic Orogeny with thick mudstone deposits occurring in the Martinsburg (Ramseyburg Member), Utica, and to a lesser extent, equivalent Kope Formation. These mudstone intervals, associated with the height of orogenic activity, were deposited during the highest production, and deposition of muds. Mudstones of the Kope Formation were not simply the result of increased mud production, however. Mud and silt had to be transported a minimum of 600 kilometers from the orogenic center to reach the area of the modern Cincinnati Arch. These muds had to be deposited in the Martinsburg or Utica basins, and periodically re-suspended and transported to the Cincinnati Arch region by large storms, turbidity currents, and sediment plumes producing the tempesite and obrution mudstone deposits of the Kope Formation.

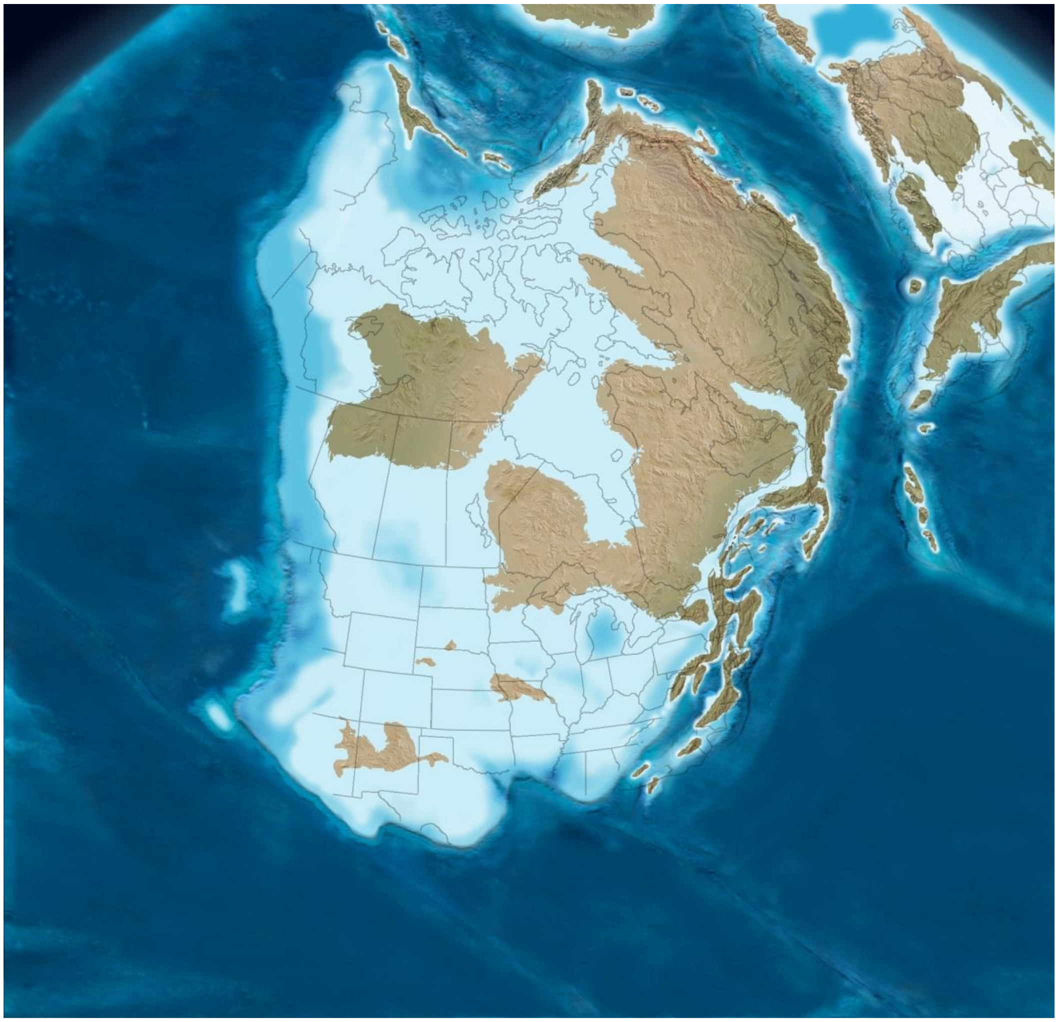

Figure 22
Paleogeographic map of Laurentia for Late Ordovician. From Blakey, 2012 http://cpgeosystems.com/nam.html

Carbonate shell bed development within the Fairview Formation is attributed to the same factors as carbonate development in the Kope Formation, and likewise mud storm beds within the Fairview Formation are associated with the developmental factors as those within the Kope Formation. The only difference is the thickness of mudstone deposits occurring in between carbonate pack-grainstone beds, with the Fairview Formation displaying stratigraphically thinner mudstone horizons. Laurentia did not suddenly relocate out of the nearby vicinity 2 million years earlier occurring during the Kope Formation, so geographically (continental drift) induced climate change is not plausible at this timescale (see Holland, 2009; Schramm, 2011). One possible solution to the production of thinner mudstone horizons within the Fairview Formation is decreased orogenic activity occurring at this time; or a winding down of the Taconic Orogeny (Ettensohn, 1992). A lower rate of tectonic upland development associated with decreased orogenic activity, or less land relief in the orogenic hinterland and mountain belt regions, would theoretically result in less mud production and deposition. Stratigraphic intervals equivalent to the Fairview Formation in the Appalachian-Taconic foreland basin, the Pulaski Fm. of New York State, and Penn Argyl Member of the Martinsburg Formation exhibit increased silt content relative to the underlying units equivalent to the Kope Formation. These tectonic factors may be attributed to decreased mud formation and deposition during the Fairview Formation time. No intermediate basin that might have served to trap muddy sediments between the orogenic hinterland and the Cincinnati Arch is known, eliminating the possibility of mud sequestration.

A second viable mechanism for decreased mudstone thickness associated with small-scale cycles of the Fairview Fm. is climate change occurring during this time. Saltzman and Young (2005) conclude based upon carbon isotope records from stratigraphic sections in Nevada that glacial icehouse conditions existed approximately 10 million years before widespread Hirnantian glaciation. This coincides with the timing of the Cincinnatian Series and may indicate changes in global climate and weathering rates occurring at this time. High relief areas of the Taconic highlands may have provided favorable environments for the development of glaciers. Additionally, changes in climate in source areas may have decreased weathering rates and associated mudstone deposition in adjacent basins.

We conclude that the Kope, Fairview and other Cincinnatian formations record essentially similar processes within the Late Ordovician. Even though these two formations are divided by a sequence boundary (Holland and Patzkowsky, 1996; Schramm, 2011) their depositional mechanisms and unit morphology are essentially the same. Small-scale cycles, prominent within these two formations, record variations in siliciclastic sediment supply. Sediment starvation occurred during small-scale sea level transgressions, during which siliciclastic sediments were sequestered in coastal areas and carbonates grew, while mudstone intervals reflect increased, episodic influx of fine-grained siliciclastics. The major lithologic differences between these two units units are attributed to variations in mud production from source areas associated with decreased tectonic activity or decreased siliciclastic erosion and transport.

Summary

Recent research on the Cincinnatian rocks has provided important new insights that are leading to a somewhat modified view of the timing and depositional dynamics of these classic strata. Key aspects of this revised view of the Cincinnatian include the following points.

A) Cincinnatian strata are subdivisible into a number of distinctive marker beds, intervals, and faunal epiboles that permit high resolution, bed-scale correlations over much or all of the outcrop belt in northern Kentucky, southeastern Indiana, and southern Ohio. Certain of these markers have also been recognized in the subsurface basinal facies to the north of Cincinnati.

B) These correlations and detailed studies of sedimentology, faunas, magnetic susceptibility, isotope geochemistry and other techniques have led to recognition of sedimentary cycles, primarily manifest as alternations in the amount of mudstone, siltstone, and shelly limestones, that vary from sub-meter to decameter-scale. These cycles are also recognizable regionally.

C) Effects of storm erosion (e.g., scoured bases, gutter casts, tool marks) and deposition (graded bedding, small-scale hummocky cross stratification, wave rippling) are ubiquitous throughout the Cincinnatian in both mudstone and shelly carbonate-dominated deposits. Hence, much of the seafloor in the Cincinnati region was within the reach of at least deep storm waves. This corroborates independent evidence for shallow water deposition such as microendoliths that indicate photic zone position for much of the strata (Vogel and Brett, 2009). Actual depth variations evident in the beds range through a few tens of meters from near fair weather wave base to slightly below storm wave base.

D) Previous models have emphasized changes in storm-wave winnowing, produced by sea level fluctuation or variations in storm intensity/frequency, as the primary mechanism generating limestone-shale cycles. However, recent investigations of the limestone-shale/siltstone cycles reveal a number of features not predicted by a storm-winnowing model. These include: a) broad lateral persistence of individual limestone bedsets, b) patterns of basinward condensation and upramp splaying in these sets, c) evidence for sediment starvation, including concretionary sub-beds, hardgrounds, and miciritic matrix in many packstones, and d) sulfur isotope proxies for systematic changes in net silicilcastic sedimentation rate from lows associated with limestone-dominated intervals to upward increasing rates in mudstone-dominated portions.

E) Together, these lines of evidence indicate that a major control, on their formation was variation in siliciclastic sediment supply from Taconic source areas and not simply variations in storm winnowing intensity. We suggest a new model of episodic starvation regulated by either minor oscillations in sea level or climatic changes. Periodic siliciclastic sediment starvation, leading to offshore skeletal limestone accumulation, could be the result of base level rise and nearshore sediment sequestration or periods of more arid climate and lower fluvial runoff.

F) Stacking patterns and time-series analysis of Cincinnatian cycles, suggest that they form a hierarchy of time scales, including large third-order sequences exceeding a million years in duration, decameter-scale fourth order cycles, of perhaps 0.4-0.5 million year durations and smaller, meter-scale cycles of a few tens of thousands of years duration. These cycles may be driven by Milankovitch-band climatic oscillations.

G) Casting the Cincinnatian cycles in terms of sequence stratigraphy, we argue for fractal patterns in which sharp bases of shelly limestone bedsets or tightly spaced limestone bundles, record small scale sequence boundaries, sharpened by submarine storm erosion, skeletal limestones reflect siliciclastic-starved analogs of transgressive systems tracts, and mudstones with thin packstones and siltstones represent highstands. At least in the larger, third and fourth-order sequences, clusters of thicker, commonly deformed siltstones record rapid progradation during falling stages.

H) Finally, although the basic processes of episodic starvation applied throughout the Cincinnatian in forming cycles and sequences, the pattern of these cycles was modified by long-term changes in the supply of terrigenous sediments to the foreland basin system. These changes may reflect tectonic pulses associated with the active uplift and denudation of the Taconic orogenic belt.

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Field Guide to the Upper Ordovician, Cincinnatian Series

Road Log

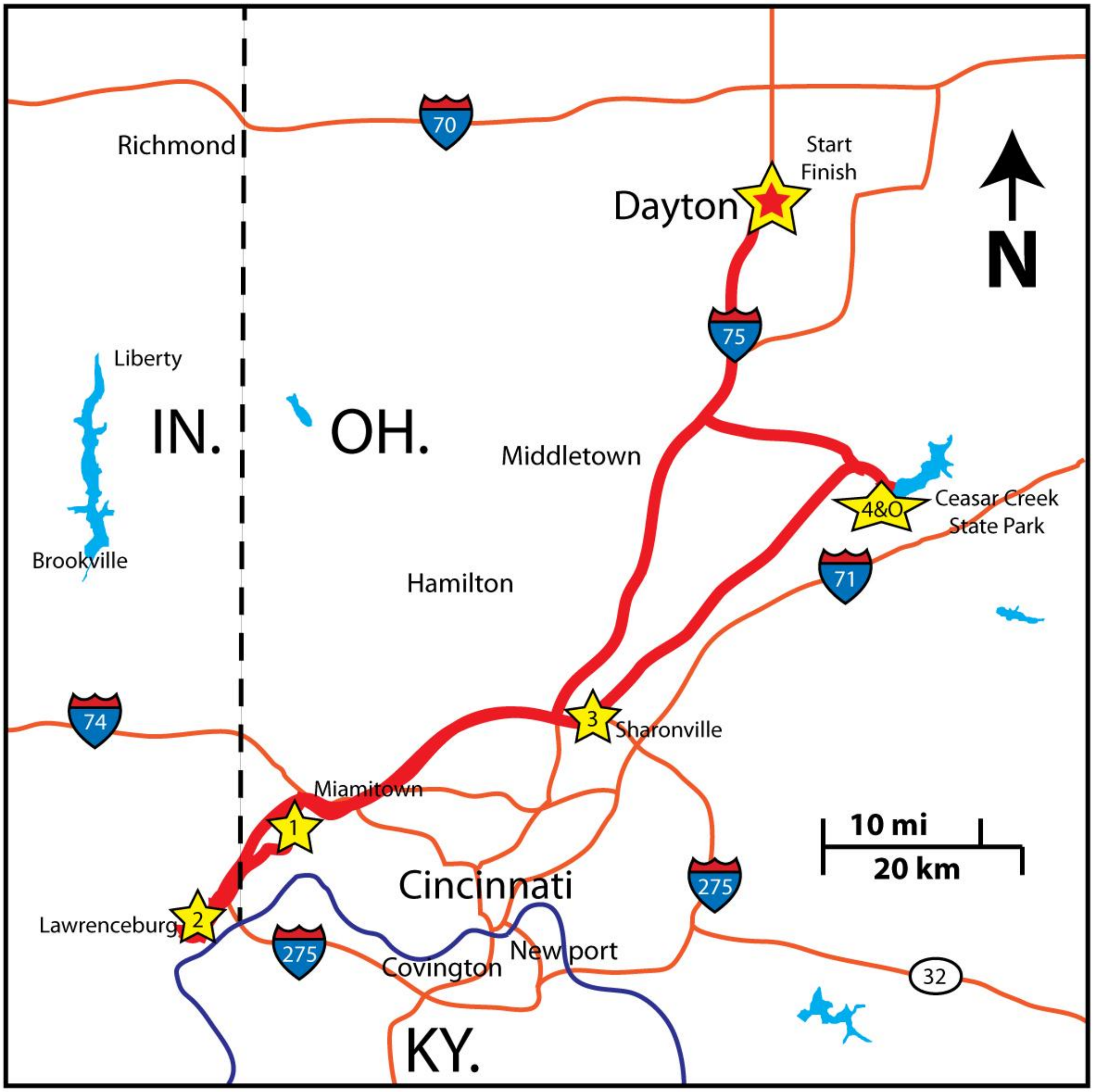

Figure 23
Map of field trip route with stops identified.

Mileage

0.0 22 E 5th St, Dayton, OH 45402, Convention Center
Head east on E 5th St towards S Jefferson St

0.5 Turn right onto Wayne Ave

0.7 Slight right to merge onto US-35W toward Eaton

1.9 Take the exit onto I-75 S toward Cincinnati

37.6 Take exit 16 to merge onto I-275 W toward I-74/Indianapolis

54.5 Take exit 7 for OH-128 S/Hamilton Cleves Pike Rd

57.9 Turn right onto driveway for "Rivers Edge Commercial Park Fitness Club"

58.2 Park in Fitness Club Parking Lot

STOP 1. Rivers Edge Indoor Sports Club cut: Kope Fm., Alexandria-Taylor Mill submembers

58.2 Exit Parking Lot

58.5 Turn right onto OH-128/Hamilton Cleves Pike Rd

60.2 Turn right onto US-50 W/Cincinnati Louisville Pike

61.7 Crossing Whitewater River

63.9 Entering Indiana

69.5 Crossing Tanner Creek (Note Seagrams Distillery on Right)

71.3 Turn right onto IN-48 W/Bielby Rd

71.9 Pull over locality on Right

STOP 2. Rte. 48 Lawrenceburg, Indiana: Kope, Fairview, Miamitown, Bellevue Fms.

71.9 Exit Rte. 48 Lawrenceburg Locality
Turn Left (make U-turn) onto IN-48 E/Bielby Rd

72.4 Turn left onto US-50 E

73.1 Crossing Tanner Creek

75.9 Turn right onto Belleview Dr. Signs for I-275

76.4 Keep left following signs for I-275N/Ohio, and merge onto I-275N

78.3 Entering Ohio

82.4 Crossing Whitewater River

84.5 Keep right to stay on 275N

85.6 Outcrop of Miamitown Shale at Type Locality

86.9 Outcrop of the Kope and Fairview Fm.

87.9 Crossing Great Miami River

88.2 Kope Exposure on right

88.7 Keep left toward Dayton Exit 9

89.5 Outcrop of the Kope and Fairview Fm.

93.2 Weathered Outcrop

106.1 Take exit 46 for US-42 toward Mason/Sharonville

106.4 Turn left onto Lebanon Rd

106.6 Turn left onto Hauck Rd

107.2 Turn right onto Tramway Dr

107. 6 Turn into parking lot for Trammel Fossil Park

STOP 3: Trammel Fossil Park Sharonville, Ohio: Fairview, Miamitown, Bellevue and Corryville Fms.

107.6 Leave Trammel Fossil Park
Head Southeast on Tramway Dr

108.0 Turn left onto Hauck Rd

108.6 Take second right onto Lebanon Rd

108.8 Turn left to merge onto I-275E toward I-71/Columbus

111.3 Take exit 49 to merge onto I-71N toward Columbus

122.8 Take exit 28 to merge onto OH-48N/US-42 Bypass W toward Burt Ave/Forge Dr

128.7 Turn right onto US-42N

135.7 Turn right onto OH-73E

136.8 Turn right onto N Clarksville Rd/Co Rd 37

139.3 Turn left onto Caesar Creek Gorge Access Road

140.8 Caesar Creek Gorge Parking Area (Park Here)
Follow path upstream along northwest side of Caesar Creek
Outcrop is directly before Dam.

OPTIONAL STOP 4A: Caesar Creek Gorge: Oregonia Mbr. of Arnheim Fm.

140.8 Exit Caesar Creek Gorge Parking Area, Continue along Caesar Creek Gorge Access to N Clarksville Rd

141.7 Turn right onto N. Clarksville Rd/Co Rd 37

142.4 Park at Caesar Creek Spillway Parking

STOP 4: Caesar Creek Spillway and N Clarksville Rd Roadcut: Waynesville, Liberty, and lower Whitewater Fms.

142.4 Exit Caesar Creek Spillway Parking
Head northwest on N Clarksville Rd

145.6 Turn left onto OH-73 W

151.3 Turn right onto OH-48 N

166.3 Turn right onto E 5th St Destination will be on right.

22 E 5th St, Dayton, OH 45402, Convention Center. END OF TRIP

Stop Descriptions

Stop 1: Rivers Edge Commercial Park, fitness club, Cleves, Ohio (39°11’42”N 84°37’15”W)

Figure 24
Panoramic view of outcrop at Stop 1; person for scale. A represents lower exposures, B represents exposurs in the driveway,

The fresh exposures in the cut along the access road leading uphill to the River’s Edge Sports Club, Rte. 128, Cleves, Ohio (Fig. 24), provide an excellent section of the middle and upper Kope Formation (Cincinnatian: Edenian) in a relatively distal section that will be compared to the section at Lawrenceburg, Indiana.

The Kope Formation, formerly termed Eden or Latonia beds, was formally defined by Weiss and Sweet (1964), with a reference section at Kope Hollow, Levanna, Ohio, near Maysville, Kentucky. The Kope interval is approximately synonymous with the Edenian Stage of the Cincinnatian Series. Ulrich and Bassler (1914) divided the Eden Shales into three members, the Economy, Southgate, and McMicken, largely on biostratigraphic grounds that have been preserved slightly redefined lithologically by Brett and Algeo (2001).

This section actually has three outcrops: the main roadcut on the road leading uphill to the athletics club (Fig. 24B), a large cut on the hillside parallel to Highway 128 (Fig. 24A), and a lower small cut in a storm water treatment facility. The section on the main road commences with bed of the Alexandria submember (Southgate Member; see Brett and Algeo, 2001 for definitions of Kope divisions), although cuts above the main road expose upper layers (including beds 23-24) of the Snag Creek submember.

Alexandria submember

The lowest interval exposed in a small gully at the lower end of the roadcut is a 132 cm shale with thin siltstones (Big Shale 4) marking the base of the Alexandria submember of Brett and Algeo (2001); beds of distinctive concretions occur in the upper shale, about 100 cm and 20 cm below Bed 25. The latter is here is unusually thin 4-6 cm mixed crinoidal-brachiopod

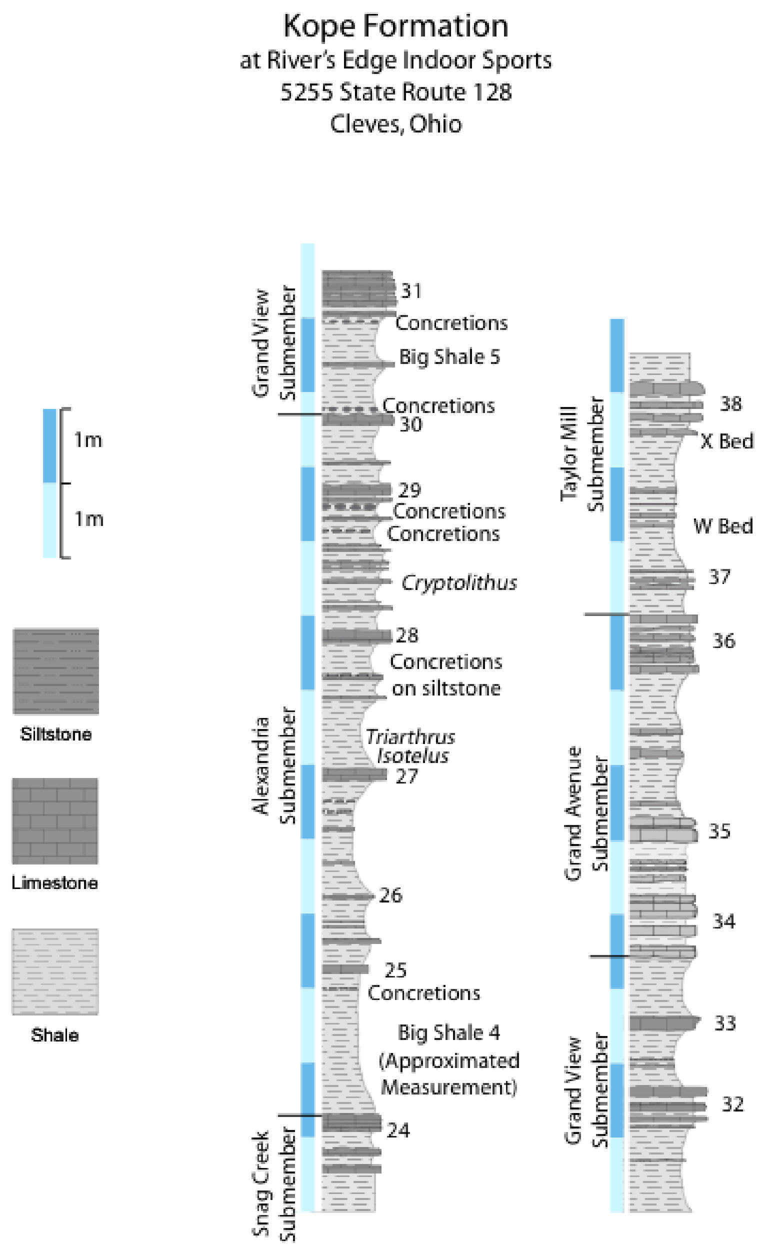

Figure 25
Stratigraphic section of upper Kope Formation at ASAP River's Edge Sports Club, Cleves, Hamilton Co., Ohio. Major beds are numbered. Figure by D. Haneberg-Diggs.

(*Dalmanella*) packstones. About 55 cm of shale separates beds 25 and 26, the latter here a 23 cm thick interval with three 4 to 5 cm crinoidal packstones (Fig. 25).

Bed 26 is overlain by a thick shale, totaling 160 cm that shows two horizons of small, ellipsoidal concretions at 180 and 197 cm above the base (46 and 23 cm, respectively, below bed 27). Bed 27, a 4-15 cm-thick brachiopod-crinoid packstone is distinctive in showing abundant crinoid ossicles and *Rafinesquina* shells; the basal surface of this bed shows distinctive firmground burrows (*Planolites*) it shows a somewhat gradational passage upward through a series of thin lenticular packstones interbedded with shale. The total 27-28 shale is 152 cm, shows a few thin, interbedded siltstones and a prominent concretion bed 39 cm below Bed 28. Medium, dark gray mudstone about 30-40 cm above bed 27 is mostly barren, but contains a few cranidia of the trilobite *Triarthrus* at this locality. This epibole has been identified at several other localities in northern Hamilton County, Ohio (Kohrs *et al*., 2008) and appears to mark the incursion of a normally deep water, dysoxic adapted trilobite; it provides an excellent stratigraphic marker (Fig. 25).

Bed 28 comprises 18-20 cm of crinoidal, *Dalmanella*-rich packstone in two main beds; the base shows distinct hypichnial casts of firmground burrows (*Planolites*). The overlying 164 cm shale contains six or seven thin (2-5 cm), crinoidal-brachiopod packstones; certain of these beds commencing at 23 cm above Bed 28 contain very abundant cephala of the pitted, eyeless trilobite *Cryptolithus*, a taxon abundant in the Economy Member of the lower Kope but in the upper half of the Kope exposed in this roadcut, entirely restricted to the Bed 28-29 interval; these trilobites are further joined by an unusually wide morphotype of *Sowerbyella*, a brachiopod also normally found only the Economy Member (Brett *et al*., 2008b). These markers serve to illustrate the types of paleontological event horizons that permit high-resolution correlations within the Kope. They also serve to demonstrate the dynamic aspects of habitat tracking by benthic species and the notion of epiboles (Brett et al., 2007).

Bed 29 is a strongly lenticular limestone 15 to 23 cm in thickness with; the basal bed displays a sharp slightly channeled base with distinctive hypichnial burrows as on the base of bed 28. A zone of ellipsoidal concretions lies slightly (~6 cm) below this bed base. About 90-92 cm of shale with very thin limestone stringers separate beds 29 and 30. Here, as elsewhere, this shale carries thin flattened *Zygospira* brachiopods and may show partings covered with the minute graptolite *Geniculograptus pygmaeus* the nominal species of the *pygmaeus* Zone (Mitchell and Bergström 1991, Brett *et al*., 2008b). Bed 30 is about 13 cm of crinoidal packstone with prominent ripples on its top; small concretions also lie immediately above the bed; these latter do not appear to be reworked, although in several other localities reworked concretions, encrusted with bryozoans are found within bed 30.

McMicken Member: Grand View, Grand Avenue and Taylor Mill submembers

An ~1.5 m thick relatively silt-free shale, with a single 7 cm un-numbered packstone (Bed 30B) about midway in the interval, “Big Shale 5”, above Bed 30, represents the base of the Grand View submember, as defined by Brett and Algeo (2001); this submember is distinctive in possessing two thick shales with almost no siltstones and a great abundance of ramose bryozoans in both limestones and shales and brachiopods dominated by a large form of *Zygospira*. Bed 31 forms another prominent marker in the section, which is readily identified in all localities in the Tristates area and in drill cores. At 42 cm thick this complex bundle, here comprising at least nine 1 to 7 cm thick bryozoan-crinoidal packstones separated by cm-scale shales, is everywhere the thickest individual limestone bundle within the upper Kope. This clearly represents a complex amalgamation of up to three small, sub-meter cycles.

The 178 cm-thick 31 to 32 interval is a second rather pure shale interval as at nearly every other locality, but here shows several thin, lenticular bryozoan packstones and a single set of concretions in the upper half meter, suggesting a transition upward to the two-part, 18-20 cm Bed 32. About 1 m of shale separates Beds 32 and 33. The limestones and shales in this part of the section are increasingly rich in ramose bryozoans and bed 32 is a ~20 cm bryozoan packstone. The meter-scale, pure shale overlying Bed 33, here about 73-75 cm thick, was used by Brett and Algeo (2001) to define the basal “Big Shale 6) of their redefined Grand Avenue submember. The latter forms a series of ledges, typically four to five major limestone beds (Beds 34-36) and interbedded, fossiliferous shales packed with bryozoans at the bend in the road (Fig. 25).

Shales with abundant siltstones and limestones (Beds 38 A and B; also termed W and X beds) of the Taylor Mill submember are exposed in the upper portion of the roadcut, which stops short of the contact with the overlying Fairview Formation. These beds will be examined in greater detail at Stop 2.

STOP 2. Rte. 48 Roadcut, Lawrenceburg, Indiana 39°05'32"N 84°51'21"W

Figure 26
View of the east side of the Rte. 48 Roadcut, Lawrenceburg, Indiana. This shows nearly the entire interval from Kope bed 24 in the background on the right, to the Bellevue at the top of the cut.

Excellent large roadcut exposures along Rte. 48 in Lawrenceburg, Indiana commence in the middle Kope Formation and extend with essentially complete exposure upward through the Bellevue Member (Figs. 26, 27, 28). These fresh new exposures provide excellent reference sections of the lower Cincinnatian strata, now poorly exposed in the type area, and offer a glimpse into depositional environments approaching the Sebree Trough. Ongoing research at this outcrop includes, geophysical, geochemical, magnetic susceptibility, paleoecological, and sequence stratigraphic studies, providing a multifaceted approach to study of Late Ordovician strata in the Cincinnati region.

Kope Formation

The lower ~0.4 km exposes the middle and upper Kope Formation The lowest portion, lower Southgate Member of the Kope, is exposed on the southwest side of the road starting directly west of the junction of Rtes 48 and 50. This lower roadcut is very shaly but exposes prominent limestone beds 20-25 of the uppermost Pioneer Valley and Snag Creek submembers, overlain by a 2.3 m prominently shaly interval (Fig. 27A).

Southgate Member: Snag Creek submember

The lowest marker horizon, bed 20 at the top of the Pioneer Valley submember, exposed at the base of the extreme southeastern portion of the roadcut, is a thick (up to 30 cm) shell-rich pack to grainstone, rich in the brachiopod *Sowerbyella rugosa*. This brachiopod, common in the lower Kope Formation, abruptly declines in abundance above this level. Bed 20 is overlain by a thick, ~3 meter, interval of sparsely fossiliferous shale, and thin siltstones, termed "Big Shale 3" by Brett and Algeo (2001) and used by them to define the base of the Southgate Member. It includes two horizons of concretions. This interval is capped by a 6 to 12cm, bryozoan-rich conglomeratic packstone unit (Bed 21) containing abundant yellow-weathering reworked and encrusted concretions at its base, informally termed the "Aurora bed" for excellent exposures behind a small plaza on the west side of Rte. 50, about 3.2 km (2 mi) to the south at Aurora, Indiana.

About 1.3 m of shale and siltstone with two distinct concretion beds, the lower, associated with distinct pyritic burrow fills, developed on a siltstone about 40 cm below Bed 22, and the upper immediately below the base of this bed to partially incorporated into the grainstone. Bed 23, about 1 m higher is actually a cluster of orange-weathering bryozoan-rich grainstones and siltstones. About 1.5m higher near the break in slope, Bed 24, a series of two or three crinoidal pack-to grainstones composed mainly of *Cincinnaticrinus* columnals with blackened, slender ramose bryozoans forms the top of the Snag Creek submember (Fig. 27A).

Alexandria submember

The overlying thick shale, Big Shale 4, formerly used to define the base of the Alexandria submember (Brett and Algeo, 2001), contains only a single thin packstone bed but shows a bundle of 4 to 5 thin, burrowed siltstones about 55 cm below bed 25 and a prominent 10-15 cm long, ellipsoidal concretion beds occur within this interval. The weathered ledge of Bed 25 occurs at the top of this south exposure, but outcrop above becomes poor; the section continues on the north side of the highway.

The Alexandria submember is well exposed on the north side of the road where the series of limestone Beds 25 to 28 is seen to best advantage in a small gully behind a light pole. (Ditch is lined with concrete with large irregular cobbles making walking slightly difficult in this stretch; use caution). Bed 25 is about 15 cm-thick compact crinoidal grainstone; Bed 26 occurs about a meter higher and an unnamed limestone occurs 65 cm higher. Bed 27 shows a distinctive lower splay nearly 28 cm below the main 10-15 cm limestone which yields mainly crinoids, including the distinctive pentangular stems of *Iocrinus*, many of them encrusted with bryozoans and small *Rafinesquina* brachiopods and is overlain locally by shale and graded packstone-siltstone bed. Excavation of dark brownish gray shale above yielded very rare remains of *Triarthrus*. Siltstones and a prominent concretion bed occur about 47 cm below Bed 28, a 25-30 cm cluster of packstones.

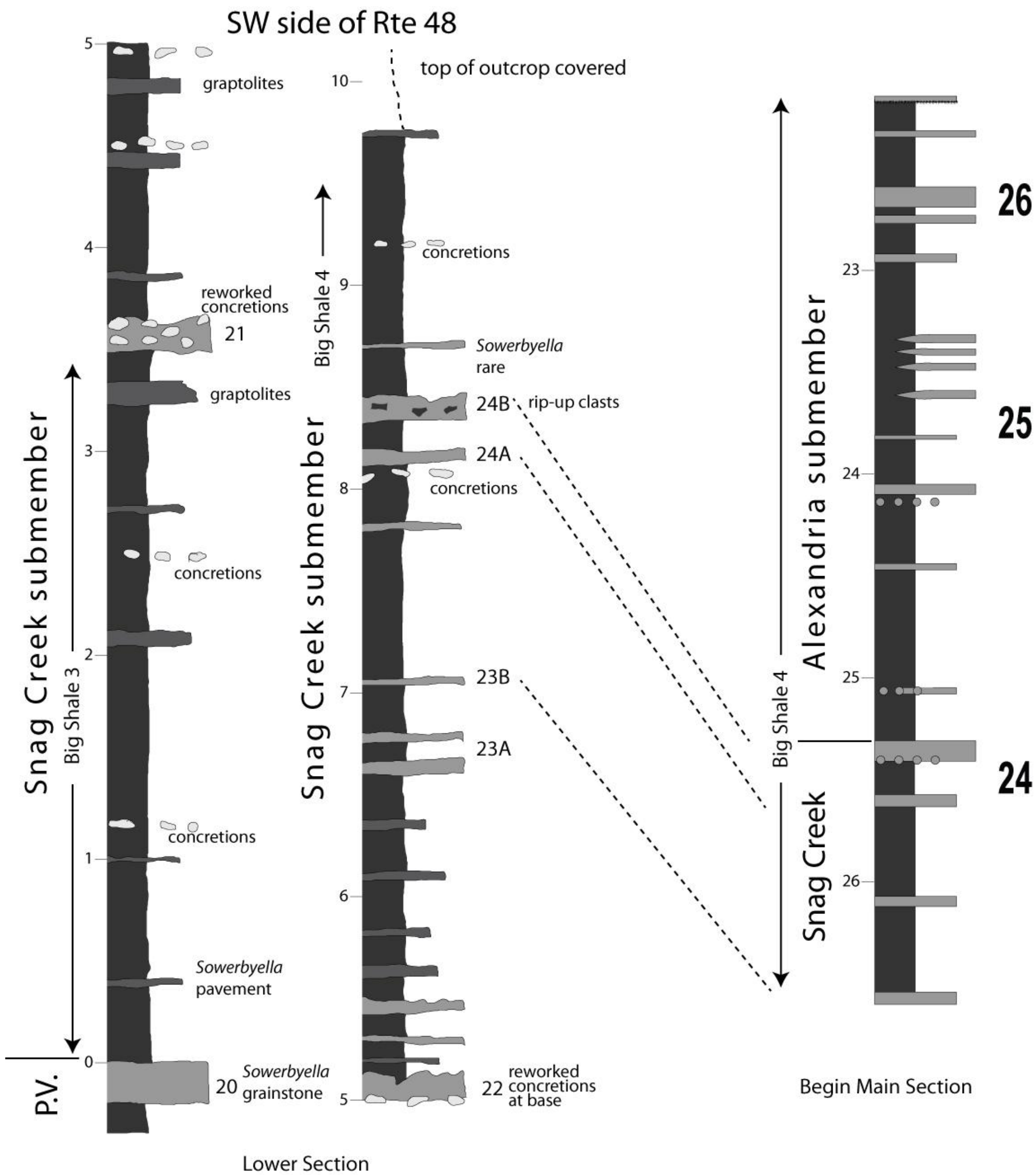

Figure 27A

Stratigraphic section of middle to upper Kope Formation in the lower part of the Route 48 road cut at Lawrenceburg, Dearborn Co., Indiana. Major beds numbers correspond to those at Cleves, Ohio.

Bed 28 is overlain by 150 cm of shale with numerous thin, lenticular packstones and siltstones, containing abundant cephala of *Cryptolithus*, and the elongate morphotype of *Sowerbyella*, as in nearly all other localities. As noted at Rivers Edge, this is one of the most faunally distinctive intervals in the upper Kope. As is typical, Bed 29, up to 25 cm-thick, shows a sharp, scoured base, a rippled top and is separated from the thinner (10-15 cm) bundle of bed 30 by ~85 cm of shale. Beds 28-30 are particularly rich in the brachiopod *Dalmanella*, which weather red on exposed slabs (red *Onniella* beds of Brett and Algeo, 2001; Fig. 27B).

McMicken Member: Grand View and Grand Avenue submembers

The overlying relatively pure shale interval marks the base of the Grand View submember. The following shale intervals are noteworthy in a general absence of siltstones (Marshall, 2011) and an abundance of bryozoans, which weather freely from the shales above limestone beds. The sharp alternation of relatively pure shales, lacking siltstones, and discrete, orange-weathering limestone bands (Beds 32-34) imparts a distinctive appearance to the Grand View submember, exposed to good advantage in this section.

The thick (~40-45 cm) bundle of 5-7 limestones, comprising Bed 31, poorly exposed at this outcrop is both underlain and overlain by ~2m of shale. Bed 32 is another relatively thick bundle of three-four individual limestone bands, whereas Bed 33 is a distinctive, generally single, tabular band, as at the Rivers Edge locality. The overlying, meter-thick shale was recognized as the base of the Grand Avenue submember by Brett and Algeo (2001).

A 2.5meter thick interval of closely spaced bryozoan-rich limestones, subdivisible into about four clusters of beds (Beds 34-37) separated by sparsely fossiliferous shales marks the Grand Avenue submember. This interval is particularly well exposed in nearly continuous outcrops up into a gully of a small stream that runs sub-parallel to the road and ends in the main ditch on the north side of the road (Fig. 27B).

Taylor Mill submember of the Kope Formation

Following a short covered stretch, the cuts continue on both sides of the highway exposing the upper or Taylor Mill submember of the McMillan Member, Kope Fm. up into the Fairview Formation. Silty-mudstones of the Taylor Mill submember (Brett and Algeo, 2001) compose the uppermost deposits of the Kope Formation. The Taylor Mill submember is equivalent to the thick Garrard Formation (up to 30 m), to the southeast near Lexington, KY composed of thick, soft sediment deformation bearing siltstone rich strata in more proximal Kentucky. These strata are regionally truncated by the Z-bed of the Kope Formation. In Lawrenceburg, Indiana the Taylor Mill submember is approximately 8 meters thick, and siltstone rich (containing some bryozoan colonies in its upper portions). In this section, three major clusters of packstones, each with three to five beds, all rich in *Dalmanella* and bryozoans, standout against thicker, ~2 m-thick intervals of silty shale, Beds 38, 39, and 40, also referred to as the X, Y, and Z beds (Fig. 27B). Siltstone beds up to about 10 cm thick are abundant in the shale rich intervals, probably a distal expression of the thick Garrard Siltstone. Two particularly prominent light gray siltstones with very abundant *Diplocraterion* and *Chondrites* traces occur at about 30 and 50 cm below Bed 39 (“Y bed”).

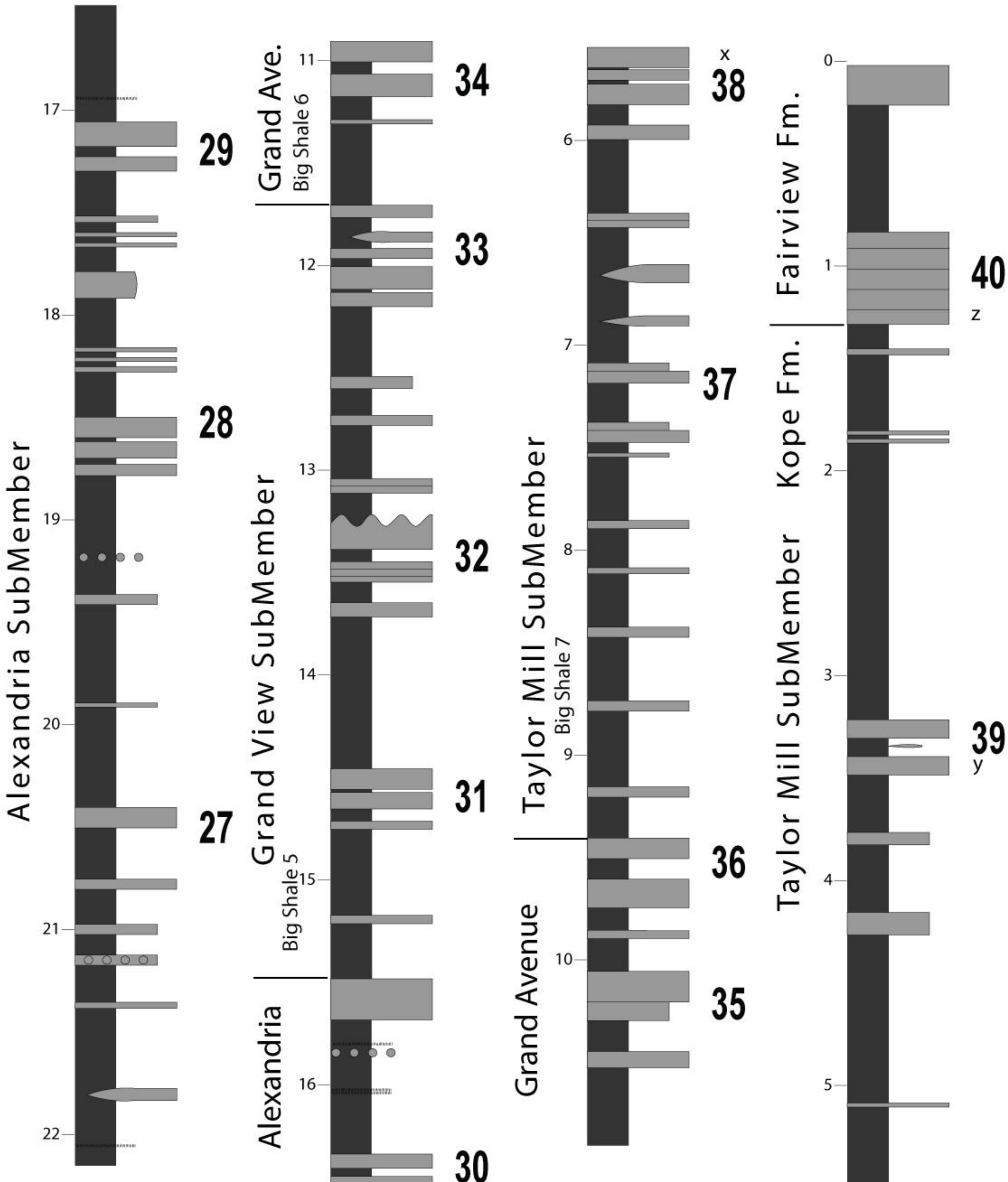

Figure 27B
Stratigraphic section of upper Kope Formation (Alexandria-Taylor Mill submembers) in the lower part of the Route 48 road cut at Lawrenceburg, Dearborn Co., Indiana. Major beds numbers correspond to those at Cleves, Ohio.

Fairview Formation

Originally named by Bassler (1906), the Fairview Formation is a combination of the previously named Mt. Hope and Fairmount divisions (Nickles, 1902); all of these names refer to localities in Cincinnati proper. Unfortunately, most of the original type sections in the city of Cincinnati are now largely covered making comparisons with the type area somewhat difficult. However, the Rte. 48 cut at Lawrenceburg provides an excellent surrogate reference section. It shows close similarities with those portions of the section still exposed at Cincinnati. Schramm (2011) has established a series of correlations throughout the shallower water dominantly carbonate facies of the Maysvillian Stage, with the purpose of providing a detailed stratigraphic framework for future studies. Several traceable horizons have been recognized throughout the Fairview Formation.

The Kope-Fairview-Bellevue succession has been regarded as a shallowing upward succession (Anstey and Fowler, 1969; Tobin, 1982; Weir et. al., 1984; Holland, 1993; Jennette and Pryor, 1993; etc.); however, the results of the current study imply a much more complex sea-level history for this interval. This stop will showcase a series of key stratigraphic horizons at Lawrenceburg Indiana, utilizing these features to demonstrate a fine scale sequence stratigraphic model for the Fairview Formation, Miamitown Shale, Bellevue Member interval (Fig. 28). (Blue Marks have been painted on the outcrop at one-meter intervals above the base of the Z-bed).

Z-Bed and Two Foot Shale

Bed 40, the “Z” limestone cluster is assigned herein to the base of the Fairview; at this locality it is about a 50 cm-thick cluster of brachiopod pack- to grainstone overlain by 67 cm of gray clay shale, the so-called “2-foot shale” (Fig. 28A). The Z-bed and overlying “2- foot shale” (actually ranging from 60-90 cm-thick) have been traced over the entire outcrop belt of the Cincinnati Arch forming an excellent marker (Brett and Algeo, 2001). The Z-bed matches the descriptions of Nickles (1902) of an 8-16 inch thick limestone bed overlying the “Utica Shale” (Kope Formation). This (Z-bed) was considered to represent the base of the Maysvillian Stage by Fenneman (1916) and the base of the Fairview Formation Mt. Hope Member (Nickles 1902; Fenneman 1916), and according to Fenneman, it (the Z-bed) is locally more than one foot thick bed, “probably the thickest (*bed*) in the Cincinnatian” which can “easily be recognized by its fossils without expert knowledge” and, “Commonly, though not always, the bed including the fossils (*Dalmanella multisecta*) is reddish or reddish brown.” Subsequent workers regarded the Z-bed and two-foot shale as the uppermost units of the Kope Formation (Holland, 1993; Jennette and Pryor, 1993; Brett and Algeo, 2001). We favor the original definition, however, not simply for historical reasons, but because the Z-bed is inherently related to the Fairview Formation. Moreover, the Z-bed overlain by a two-foot shale interval has been identified to the south (Schramm, 2011), where it sharply overlies, and truncates the deformed siltstones of the Garrard Formation, equivalent to the Taylor Mill submember of the Kope Formation. Hence, the base of Z-bed records a sequence boundary.

The distinctive “two-foot” clay shale carries an unusual fauna including *Platystrophia* cf. *hopenesis,* the gastropod *Cyclonema* and small crinoids, locally as obrution type deposit, containing intact, well preserved crinoid stems formed into large bundles (“log jams”) at several locations in northern Kentucky as far south as Clays Ferry.

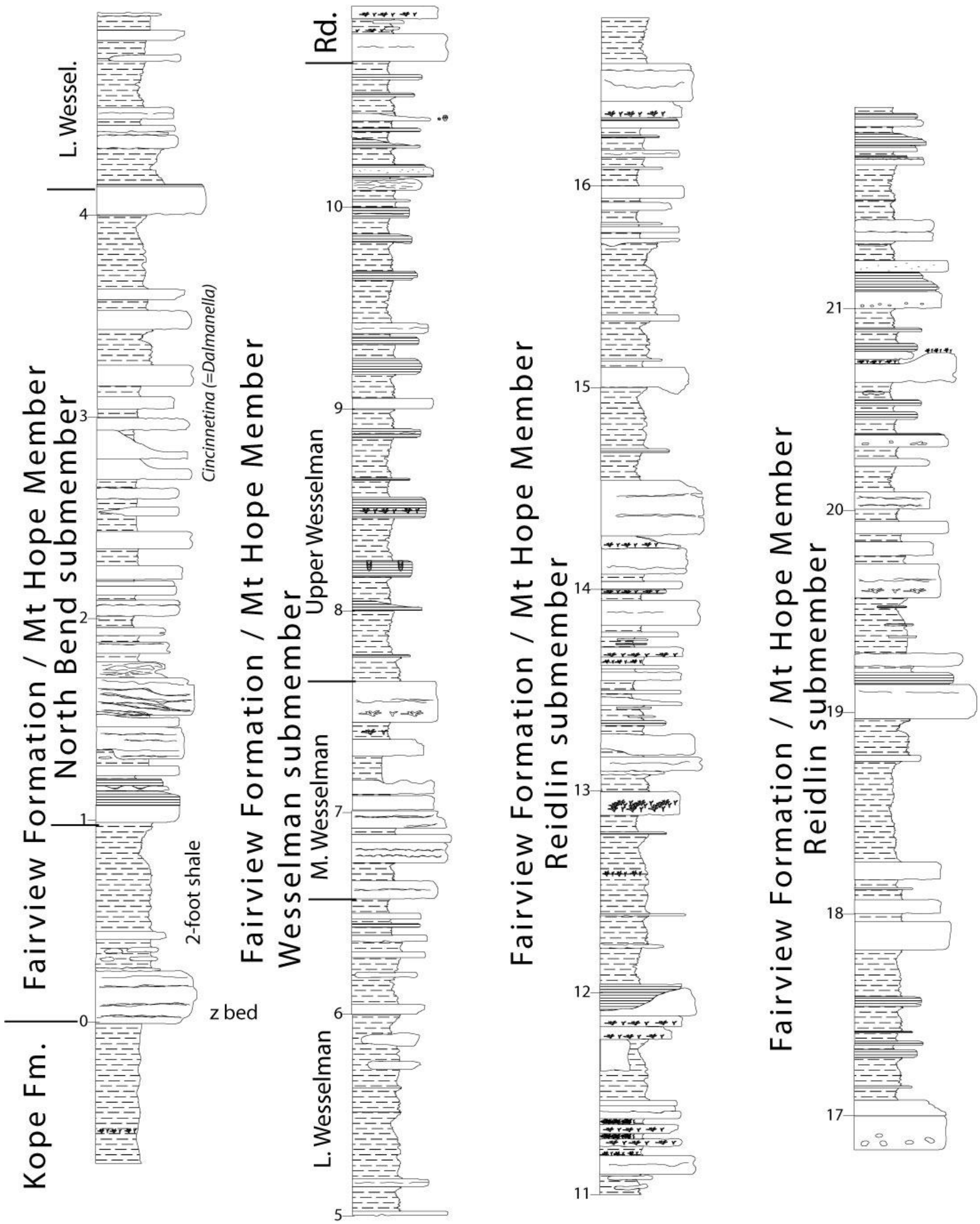

Figure 28A

Stratigraphic section of the lower portion of the Fairview Formation along the lower part of the Route 48 road cut at Lawrenceburg, Dearborn Co., Indiana.

North Bend submember

The, originally named "North Bend Tongue of the Fairview" by Ford (1967), this interval represents lower deposits of the Fairview Formation, Mt. Hope Member. Its base is formed by a widely traceable single thin limestone bed and ~15 cm (6 inch) thick mudstone couplet occurring above the 2-foot shale (Fig. 28A). This three meter-thick unit renamed the North Bend submember (Schramm, 2011) as no interfingering between between the Kope Formation and Fairview Formation occurs. This unit is composed of a carbonate-rich lower portion, consisting of approximately five limestone beds, a thin shaly middle portion, and an upper limestone portion again containing five major limestone beds. Beds of the upper North Bend submember are very compact, and coquinoid with abundant edgewise, fragmental brachiopods, primarily the orthid *Dalmanella*. More proximal facies, as Maysville Kentucky, are extremely rich in the diagnostic brachiopod *Strophomena maysvillensis* but only rare specimens of this brachiopod have been obtained at this outcrop. The upper contact of the North Bend submember exhibits, a phosphatic, or limonitic stained surface. This unit is exposed approximately 4 meters above the base of the Z bed.

Wesselman Tongue-submember

Directly overlying the North Bend submember is the Wesselman submember, a shaly unit, previously considered to be a tongue of the Kope Formation (Ford, 1967); however, this interpretation resulted, at least in part, from the miscorrelation of the Wesselman with the upper or Taylor Mill submember of the Kope Formation at its type locality (S. Felton, pers. comm.). The Wesselman submember, is completely separated from the Kope Formation by the underlying North Bend Tongue and has been reassigned as a submember of the Mt. Hope Member (Schramm 2011, and herein). The Wesselman submember is thickest in more distal, deeper water settings, such as this locality, where it is approximately 7 meters thick. This unit is exposed at marked meters 4-11(Fig. 28A).

Across the Cincinnati Arch the Wesselman submember exhibits a three part motif, with a lower mudstone rich portion, a lower middle limestone portion, and an upper shaly siltstone portion, each traceable over large differences. Siltstones up to 10 cm thick in the lower and upper divisions show excellent trace fossils including a broad-based form of *Diplocraterion*. The lithology and fauna of these shales very closely resemble those of the Taylor Mill submember of the Kope.

Reidlin submember

A unit, similar in lithology to the North Bend-Wesselman interval, the "un-named submember" of Schramm (2011), occupies the upper ~13 meters of the Mt. Hope Member, occurring at meters 11-24 (Fig. 28A). Herein we, name/rename this interval (top of Wesselman submember to the top of the Mt. Hope Member) the Reidlin submember for well-studied and famous exposures at Reidlin-Mason Road at Taylor Mill Kentucky. This mudstone rich interval is set apart from the underlying Wesselman Tongue by a cluster of grainstone beds, about 1 meter thick. Within this interval four major limestone bands are present; each in turn containing five thinner divisions; several of the basal beds contain rip-up clasts of calcareous mudstone. Above the basal grainstone the Reidlin submember consists mainly of shale and mudstone that becomes increasingly siltstone rich in its upper portions. Frondose bryozoans are also common within this interval. A distinctive bed rippled grainstone bed at about 14m forms a platform on the SW side of the roadcut near road marker 62. This bed marks an approximate division between the lower Mt. Hope and upper Mt. Hope faunas. Typical forms below this level include *Strophomena maysvillensis*, *Plectorthis* sp., the bryozoan *Escharopora*, and the gastropod *Cyclonema gracile*. These taxa are rare or absent in beds above the ripple marked marker bed (S. Felton, personal communication).

Hooke-Gillespie submember

An approximately 30cm thick rip up clast bearing grainstone bed marking the Mt. Hope-Fairmount Member faunal boundary (Nickles, 1902) and the base of the Hooke-Gillespie submember occurs at approximately meter 24 in this rodcut (Fig. 28B). This grainstone bed, informally termed "*Strophomena* Bed" is unusually rich in the brachiopod *Strophomena planoconvexa* at Maysville Kentucky. Mudstones immediately below this bed contain frondose colonies of the bryozoan *Constellaria*. This horizon is easily recognizable and has been traced across southern Ohio, southeastern Indiana and northern Kentucky. Beds above this level yield an abundance of the small orthid *Dalmanella multisecta*.

The Hooke-Gillespie submember (Schramm, 2011) is a name herein assigned to lower strata of the Fairmount Member, above the base of the *Strophomena* Bed composed dominantly of silty mudstones with thick (up to 1 m), locally channeled and deformed siltstones, that extends upward to a series of thick rip-up clast bearing grainstone beds. This interval is named for the intersection between the AA highway, and Hooke and Gillespie Lanes, near Augusta, Bracken County Kentucky, where a series of three thick deformed siltstones, interpreted as seismites, are exposed. This same stratigraphic interval has been well studied in the Maysville Kentucky region (Schumacher 2001; Brett, Zambito and McLaughlin, 2008) where it contains massive ball and pillow seismite horizons, siltstone infilled channels, and large encrusted limestone blocks associated with these seismite horizons, and is widely traceable; however, no deformed beds have been found at Lawrenceburg. At the Rte. 48 outcrop, this unit is approximately 3 meters thick and occurs at marked meters 24-27 (Fig. 28B).

Lawrenceburg submember

A cluster of three thick carbonate beds bearing rip-up clasts up to 20 cm across and interbedded shale and thin limestone marks the base of the Lawrenceburg submember of the Fairmount Member (Schramm, 2011). These are exposed in an embayment in the outcrop directly opposite the sloping concrete pavement surface/drain at the upper parking area (Fig. 28B; 39°05'56"N 84°52'38"W). This submember consists of over 4 meters medium bedded skeletal grainstones (meters 27-32), well exposed above the parking pull-off/drain area on the upper end of this Rte. 48 roadcut, which constitute its type locality. This same series of three rip-up clast bearing beds has also been observed in proximal settings of the Maysville region. The uppermost of these compact skeletal carbonates has a sharp, somewhat corroded mega-ripple hardground top at Lawrenceburg Indiana, which is directly underlain by an interval up to 10 cm thick comprised of pale orange weathering phosphatic granules with abundant phosphatic steinkerns of minute gastropods (B. Heimbrock, pers. comm.). Thinner stringers of orange phosphatic grains occur near the top of the rippled bed and in overlying lenticular hardgrounds. The Lawrenceburg beds also contain an index fossil of the interval, the brachiopod *Orthorhynchula*, (S. Felton, pers. comm.), which has been found rarely at Lawrenceburg, and abundantly in the coeval strata at Richmond, Point Leavell, and Springfield Kentucky.

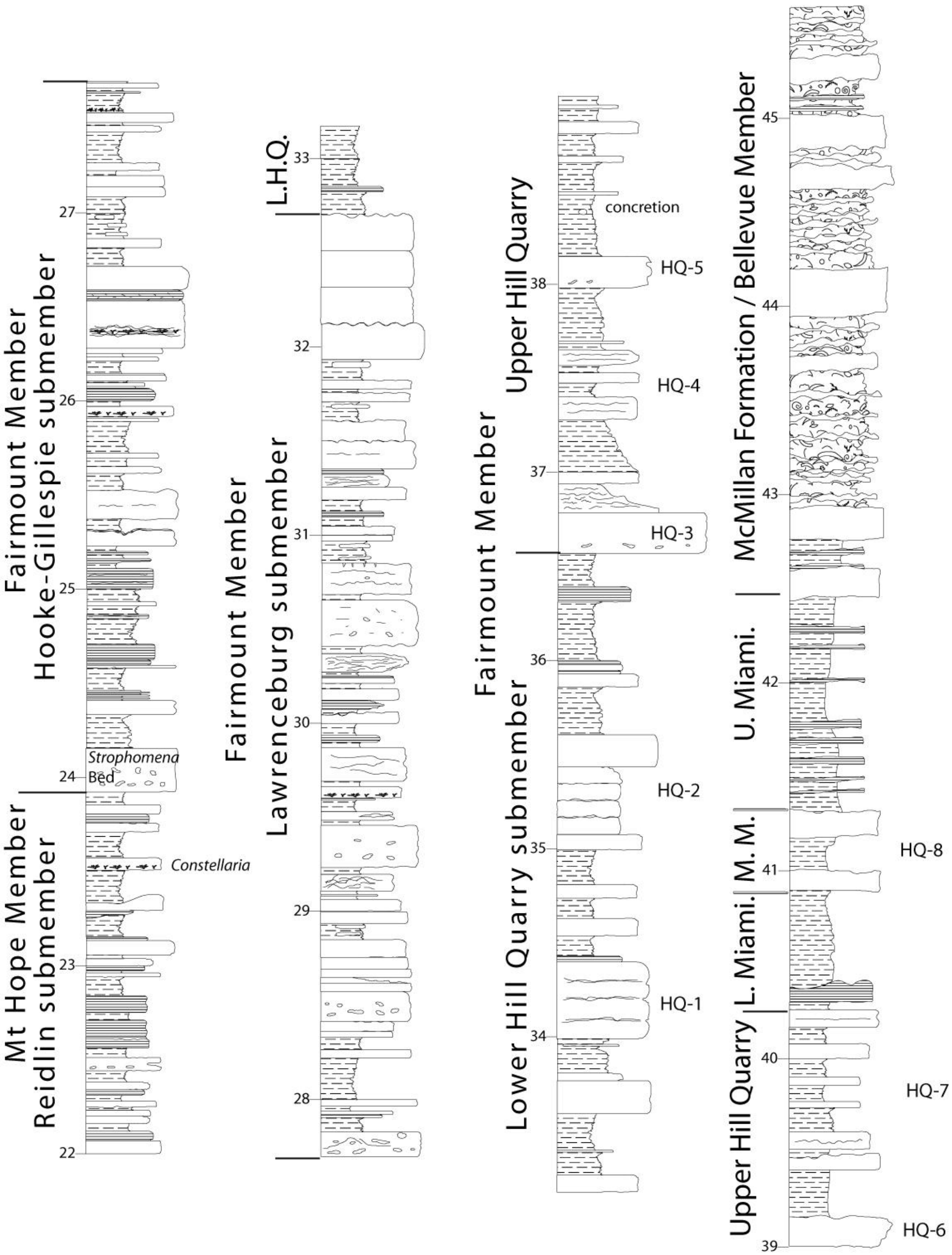

Figure 28B

Stratigraphic section of the upper portion of the Fairview Formation, including the Miamitown Shale, and the lower Bellevue Member (McMillan Formation) along the lower part of the Route 48 road cut at Lawrenceburg, Dearborn Co., Indiana.

Lower Hill Quarry submember

Interbedded, discrete limestones and shales of the upper Fairmount Member resting sharply on top of the tightly bedded carbonates of the Lawrenceburg submember have in the past been referred to as the "Hill Quarry Beds" based upon former building stone quarries in this interval in the hills surrounding Cincinnati (Nickles, 1902). This shaly interval sharply overlies a distinct rippled grainstone at the top of the Lawrenceburg sub-member the forms the first bench,, easily accessible above the upper parking area. Hill Quarry cycles are typically composed of a lower prominent compact skeletal carbonate pack-grainstone overlain by a mudstone interval, which coarsens upward into silty mudstone, with possible siltstone beds in the upper portions of the cycle (Fig. 28B). This series of beds has proven to be extremely traceable and widespread, in outcrop and into the subsurface (Dattilo, 1998; Dattilo *et al*., in press).

In the present paper, we subdivide the Hill Quarry beds into two distinct packages at a very sharply based grainstone ledge, herein termed the lower Hill Quarry submember and upper Hill Quarry submember. The lower Hill Quarry submember, approximately 5m thick, directly overlies the Lawrenceburg submember at its type locality and consists of the lower three of the cycles of the "Hill quarry beds", terminating with a distinctive meter-thick, silty shale that is sharply (erosionally) overlain by a very discrete, ledge-forming grainstone (Third Hill Quarry Bed). The meter-thick shale interval contains siltstone interbeds; the uppermost siltstone bed contains abundant traces (*Diplocraterion*) and scolecodonts (Fig. 28B).

Upper Hill Quarry (Fracta) submember

The upper three beds of this interval have also been referred to as the "shingled *Rafinesquina* zone", or "*fracta"* Beds (after *Rafinesquina fracta*) (Caster *et al*., 1961), and are characterized lithologically by a rubbly fossiliferous, possibly orange weathering, packstone interval. These (*fracta*) beds were numbered from the top down (Forsyth, 1946), but have been referred to as lower, middle, and upper shingled zones, in order to avoid confusion by Dattilo (1998), who also demonstrated the traceable nature of these horizons. Herein, we redesignate this informal interval as the Upper Hill Quarry submember, for an excellent exposure in a hillside cut along Gage Street at the intersection of Rice Street, below the helicopter pad of the Christ Hospital, Cincinnati, Ohio.

A prominent 30 cm thick, ledge-forming grainstone sharply overlies the meter thick mudstone siltstone at meter 37 (Fig. 28B). This limestone, termed "third Hill Quarry Bed" (HQ-3) contains small granules of orange weathering phosphate, and is easily distinguishable from the other Hill Quarry Beds. Overlying the third Hill Quarry Bed is a somewhat rubbly, muddy packstone interval. The fourth Hill Quarry Bed is generally somewhat thinner, and less prominent than the third Hill Quarry Bed, although may vary and increase in thickness locally, and possibly more so than the underlying third Hill Quarry Bed on occasions. The seventh Hill Quarry Bed is also a very widespread compact pack-to-grainstone occurring directly below the Miamitown Shale interval (Fig. 28B). The upper Hill Quarry submember is exposed from 37 to 40 meters stratigraphic height. These are the highest units exposed directly above the parking area but the Miamitown Shale and Bellevue Limestone may be accessed by walking carefully southward across the grassy knoll above this outcrop to the uppermost platform of the roadcut (Fig. 28B).

Miamitown Shale submember (of the Fairview Formation)

The Miamitown Shale (Ford, 1967) is a dominantly mudstone unit rich in gastropods and bivalves, marked by the index fossil *Heterorthina*. For more information on the widespread nature and morphology of this unit see Dattilo (1994, 1998). The exact stratigraphic position of the Miamitown has been poorly defined. Herein, we define the Miamitown as the uppermost submember of the Fairview Formation, Fairmount Member. Here as elsewhere the Miamitown can be subdivided into three units: a lower mudstone portion, a middle limestone portion containing five limestone interbeds, and an upper silty mudstone portion containing current aligned siltstone gutters northwest of Cincinnati. Each of these three intervals can be traced over long distances west of Cincinnati, and has been found as far as Madison, Indiana where the unit is a greenish gray mudstone. Meanwhile, this same seemingly widespread unit thins drastically southeast of Cincinnati, and is less than one meter thick at Reidlin/Mason road Fort Wright-Taylor Mill, Kentucky (St. Louis Diekmeyer, 1998); to the southeast of this area the unit disappears. At Lawrenceburg the main upper Miamitown Shale is poorly exposed, but spans about 2 meters, from 40.4 to 42.5 m above the base of the Fairview Formation (Fig. 28B);

McMillan Formation

Bellevue Member

The Bellevue Member of the McMillan Formation is a fossiliferous, rubbly packstone and grainstone, rich in *Rafinesquina* and *Hebertella* and bryozoans, especially *Monticulipora* which sharply overlies fossiliferous mudstones of the Miamitown Shale. This contact is interpreted as major sequence boundary. Schramm (2011) recognizes a significant unconformity at its base (Fig. 12). The Bellevue Member type is located at the intersection of Rice and Gage Streets, Cincinnati, Ohio (Ford, 1967). Within this unit several traceable horizons exist. A fossiliferous mudstone interval within the Bellevue is referred to as the "*Rafinesquina* shale" (Dattilo, 1998). Differences have been recognized by Nickles (1902) and Dattilo (1998) between the lower, bryozoan rich portion of the Bellevue, and upper fossiliferous pack and grainstone portion, lying above the *Rafinesquina* Shale. In general this upper portion of the Bellevue is increasingly compact grainstone rich, and less mud-rich than the lower portion. In downramp settings the Bellevue becomes a more compact skeletal-crinoidal pack-to-grainstone is reduced more in thickness, and has additional phosphate. In upramp portions of the basin, where it is included as the basal part of the Grant Lake Formation, the Bellevue becomes increasingly argillaceous and shows a more rubbly, fossiliferous packstone lithology, and often includes *Vinlandostrophia ponderosa* (formerly *Platystrophia ponderosa*).

STOP 3: Trammel Fossil Park, Sharonville, Ohio 39°17’47”N 84°24’ 15 ”W

Figure 29
Part of the Trammel Fossil Park outcrop showing most of the Miamitown Shale.

This is a classic and often-visited site, which has been designated as a Fossil Park, open to amateurs and interested citizens as well as to professional paleontologists. The property was generously donated to the city of Sharonville in 2003 by Mr. R.L. Trammel, a local developer and builder. The development and upkeep of the signage and an exhibit of an edrioasteroid pavement has been facilitated by cooperative efforts of the city of Sharonville, Dr. David Meyer (Department of Geology, University of Cincinnati) and the Cincinnati Dry Dredgers (North America’s oldest amateur paleontology organization), in particular Mr. Stephen Felton. The park includes a total of ten acres with a hiking trail to the hilltop; the main focus of paleontological and stratigraphic interest is the long southwest facing hillside which has been cleared down to bedrock and exposes a section totaling some 25 meters. This is an excellent outcrop to observe fossils because of bedding plane exposures (Fig. 29). Exposures extend SE from visitor parking area along long SW-facing hillside exposure to west-facing steep bank south of the official Fossil Park boundary just east of parking behind building of Morris Technologies, Inc. and further south.

The stratigraphy and paleontology of this site has been well documented (Dattilo, 1996; 1998; Holland, 2008; Dattilo *et al.*, 2008; Dattilo *et al.*, in press). Earlier field guides to the site were produced by Dattilo (1998), Holland (2008), and Holland and Patzkowsky (2009). This report extends the stratigraphic section somewhat lower than previously published column of Holland (2008) owing to newly measured sections behind industrial buildings to the south of the main park boundary. The ~25m section extends from the base of the Hill Quarry submember, through the Miamitown, Bellevue, and lower Corryville (Fig. 30).

Fairmount Member: Lower Hill Quarry submember

Lowest exposures of Hlll Quarry beds are in small gullies near SE end of parking lot/storage area at SE corner of building (39°17'43"N 84°24'15"W), and hillside banks extending southward behind buildings to the south of Morris Technologies. **It should be noted that access to those sections is strictly limited and requires permission.** Thick beds of the Hill Quarry submember of the Fairmount Member of Fairview seen near the top of the previous outcrop in Lawrenceburg at Stop 2 are exposed in the base of the small gully. The lowest readily accessible exposures shows a thick bed (up to 42 cm) of fossiliferous grainstone which is underlain by a succession of gray shale and thin bedded packstone; the top of this bed is rippled with symmetrical crests oriented at about 85° (nearly E-W). This bed is equated with Hill Quarry bed 2 (HQ-2) at the Lawrenceburg cut.

This bed is overlain by about a meter-thick shale and siltstone interval with abundant trace fossils including *Diplocraterion*; it is overlain by a prominent ledge, about 30 cm thick with shale clasts. This is very similar to the succession of "scolecodont shales" and bed HQ-3 at Lawrenceburg.

Upper Hill Quarry (Fracta) submember

The 2.2 meter interval above what we currently call the third Hill Quarry bed consists of increasingly stacked pack and grainstone beds includes three shingled *Rafinesquina* "zones", packstone beds with edgewise-stacked brachiopods (also referred to as "Fracta beds", Forsyth, 1946) were recognized discussed above. This succession of upper Hill Quarry beds was traced in detail (Dattilo, 1996; Dattilo *et al*., in press) throughout the Cincinnati regions. Dattilo *et al*., (in press) further traced two of these cycles into the subsurface and demonstrated that continuity of this succession for up to 150 km to the northwest.

Miamitown Shale submember

The Miamitown at this locality is a ~5-meter thick interval, dominated by pale olive gray, light weathering silty mudstone with thin siltstones and silty wackestones (Fig. 30). Thin, silty limestone beds within the unit yield an abundance of small *Rafinesquina* and *Zygospira* and more notably well preserved bivalve molds (*Ambonychia, Modiolopsis, Lyrodesma, Caritodens*), some of which show dark periostracal films. These beds present good examples of shell concentrations with little to no winnowing as the shells are supported by silty micritic mud. Small edrioasteroids (*Isorophus cincinnatiensis*) occur attached to bivalve molds and less commonly *Rafinesquina* shells in at least two levels and beds, including gutter fills packed with high-spired gastropods.

The base of the Miamitown shale is marked by a thick ledge of packstone (unit N of Lawrenceburg) an abundance of the orthid brachiopod *Heterorthina fairmountensis*, which forms an epibole that can be traced into subsurface (Dattilo, 1996; Dattilo *et al*., in press).

Here, as at its type section Miamitown has three divisions: A) a lower interval, slightly more than a meter thick, of mainly olive gray shale with some thin siltstones and packstones (informally the Sharonville beds); B) a middle limestone dominated division (informally termed the Hauck Road beds) consisting of stacked tabular and wavy nodular packstones rich in *Rafinesquina* and bryozoans; C) a thicker (about 3 m) upper silty olive gray shale with thin to medium siltstones and thin silty to micritic wacke- to packstone with small *Rafinesquina* and abundant bivalves and upper gastropod rich beds (Fig. 30).

One of the notable features of this outcrop is the good exposure of a pavement of convex up bivalve molds and *Rafinesquina* with abundant attached edrioasteroids that occurs near the top of the Hauck Road beds about 2 m above the base of the Miamitown; a portion of this surface is protected in a display box near the parking area. This horizon has been recognized at several other localities as far west as the Miamitown type section. A second bivalve rich pavement with scattered edrioasteroids, together with dalmanellid brachiopods, occurs about 2.7 m higher and about a meter below the top of the Miamitown (a part of the topmost meter-scale cycle). Slightly below this level and again at the very top of the Miamitown are prominent gutter casts filled with brachiopod, bryozoan and molluscan shell material; high-spired gastropods (*Loxoplocus* sp.) are especially common in the upper gutter cast beds.

The Miamitown shale has been the primary focus of previous studies by Dattilo (1996; 1998) to test the usefulness of faunal ordination in generating curves that could be correlated over long distances. This was the pioneering study that eventually led to the faunal correlation of the Kope cycles as seen at Stop 1 and Stop 2 by Miller *et al*. (2001)

This is one of the deepest expressions of the Miamitown Shale that crops out near Cincinnati. This interval is thicker here than at Lawrenceburg and Cincinnati. Moreover, at Sharonville the Miamitown appears to show an extra cycle with a basal 30-40 cm series of silty packstones overlain by 60 cm of mudstone; this succession is absent in outcrops to the southwest. In contrast, the well-correlated interval of upper Hill Quarry beds and the remainder of the Miamitown show little change in thickness between Miamitown and Sharonville. Thus, the decrease in thickness toward the south appears to be largely the result of erosion beneath a sub-Bellevue unconformity (Fig. 12; Schramm 2011). Interestingly, farther north, presumably beyond the influence of the thick deposition in the Sebree Trough, the Miamitown shale thins again. If any thickening were due to bypass sedimentation off of upramp limestones, it was minor, and did not lead to a substantial increase in thickness.

Bellevue Member

At Sharonville the Bellevue Member of the McMillan (or Grant Lake) Formation is relatively thin, consisting of about 5 meters of ledge-forming, compact pack- to grainstone alternating with rubbly fossiliferous mudstones (Fig. 30; Schramm 2011). Brachiopods typical of most Bellevue outcrops, for example, *Vinlandostrophia* (*Platystrophia*) *ponderosa* and *Hebertella occidentalis* are relatively uncommon and the fauna is dominated by large *Rafinesquina*, which may occur in edgewise-shingled beds, and large ramose to frondose bryozoans.

The basal contact of the Bellevue is sharply demarcated below an approximately 30 cm ledge formed of stacked *Rafinesquina*-rich packstones (Fig. 30). As noted above, this contact is apparently an erosive surface and is herein interpreted as a sequence boundary. The basal ledge is set off by about 36-40 cm of gray silty shale, from the main meter thick basal Bellevue limestones. Hence, the base of this sequence shows close analogies with the base of the Fairview with an analog of the “Z-bed” and “Two-foot” shale at the base. In both cases the continued in flux of muds in small-scale cycles and a slight upward shallowing trend may suggest that this package represents lowstand deposits above an erosional sequence bounding unconformity. The middle portion of the Bellevue is poorly exposed but consists of rubbly packstones and

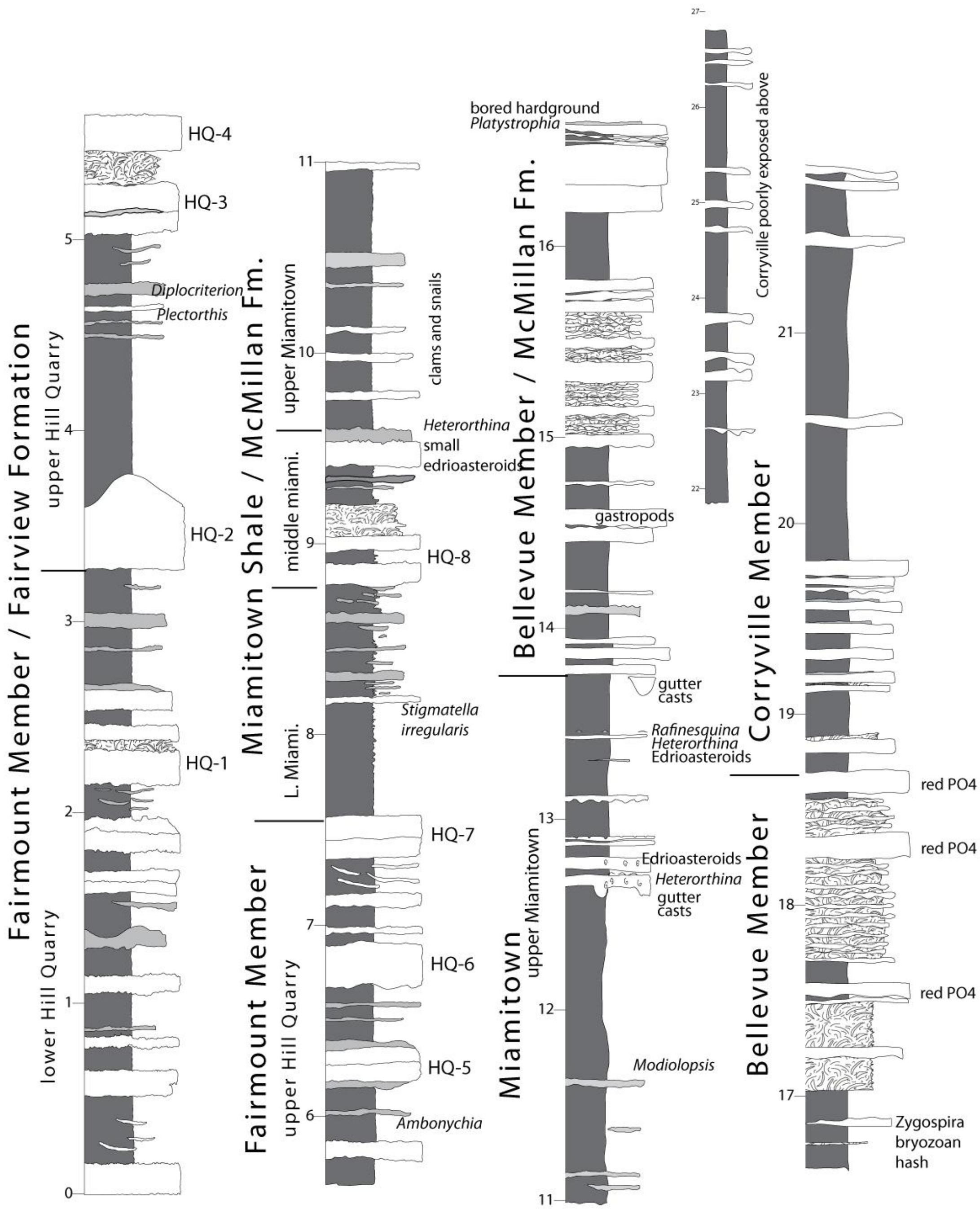

Figure 30

Stratigraphic section of the upper portion of the Fairview Formation, including the Miamitown Shale, Bellevue Member, and lower portion of Corryville Member (McMillan Formation) at Trammel Fossil Park, Sharonville, Hamilton Co., Ohio.

fossiliferous mudstones probably equivalent to the "*Rafinesquina* shales" division seen at Cincinnati. Upper beds form a persistent ledge along the poutcrop face; it show abundant reddish orange weathering phosphatic granules.

In Cincinnati and at Lawrenceburg the Bellevue Member is thicker and consists of rubbly-bedded limestone. Yet has a clearly shallower water fauna than it does at Sharonville. Grainstone is not always caused by winnowing removal of fine material. This is an example of grainstone developing more in deeper quieter water than it does in shallower more agitated water, suggesting a completely different origin for grainstones than is typically thought. In this case the thinner, more compact limestone beds may result from a lack of mud in deeper water where fine particulate carbonate may not have been produced or may have been too unstable to accumulate.

Corryville Member

The Corryville Member is not seen at other stops on this fieldtrip, and is not spectacularly exposed here. About 6 meters of the unit crops out in small patches largely covered with limestone rubble at the top of the hillslope at Sharonville. The outcrop shows a series of thin intervals of shale and mudstone alternating with brachiopod-rich packstones.

The original type area of the Corryville in the division of Cincinnati just south of the University is almost completely covered by buildings and pavement and there are relatively few good outcrops. Therefore, long, semi-continuous exposures along Stonelick Creek near were

designated as a reference section for this interval (see Goldman, 1994; Dattilo, 1998). Schramm (2011) included the Corryville in his study and observed that thicker ledge-forming pack- and grainstones rich in *Rafinesquina*, frequently shingled, and *Platystrophia*, divide the

Corryville into a series of three, as yet unnamed submembers (Schramm, 2011); preliminary studies suggest that these divisions can be correlated around the Cincinnati area.

Despite its relatively limited exposure, it is one of the most famous of the fossil bearing strata of the Cincinnatian; in the Cincinnati region this unit has yielded some remarkable fossils including large enrolled and prone specimens of the trilobite *Flexicalymene retrosa*, crowns of the camerate crinoid *Pycnocrinus*, some with attached commensal individuals of the gastropod *Cyclonema*. These fossils are primarily derived from thicker intervals of soft, blue gray mudstones referred to as "butter shale" by local collectors.

A remarkable pavement of mostly convex upward *Rafinesquina alternata*, many encrusted by large specimens of the edrioasteroid *Isorophus cincinnatiensis* (Cincinnati's official "city fossil") was discovered during excavation for a parking lot at the Florence Mall in Florence, Kentucky in the late 1970s. This pavement, in the upper Corryville Member, was documented extensively by Meyer (1990). Similar, and probably correlative, edrioasteroid-encrusted shell pavements have been recognized at several other localities including Blue Rock Road near Cincinnati and Stonelick Creek. The latter site provided a sample *Rafinesquina* pavement still on display at the USNM, and the immediately overlying shale yielded evidence of death traces associated with several specimens of the strophomenid brachiopod Rafinesquina alternata (Dattilo *et al.*, 2009) as it was buried alive during a storm-generated sedimentation event. If as suspected this is the same encrusted pavement at these disparate localities it provides an example of an extraordinarily of widespread mud obrution bed. The pavement has not been identified at Sharonville but scattered specimens of *Rafinesquina* shells encrusted with edrioasteroids have been collected on the slope.

STOP 4: Caesar Creek Spillway Access and roadcut on Clarksville Road (39° 28'49'' N, 84° 3'25'' W).

Figure 31
Roadcut on Clarksville Road at intersection with Caesar Creek emergency spillway.

The Caesar Creek Dam spillway and adjacent roadcut and creek sections provide an excellent overview of a major portion of the Richmond Group (Richmondian Stage). It is often regarded as the most accessible fossil-collecting locality in Ohio although collection is limited and visitors are required to obtain a free permit at the Caesar Creek Visitors Center. See popular field guide by D. Shrake (1992)"Excursion to Caesar Creek State Park in Warren County, Ohio: A Classic Upper Ordovician Fossil-collecting Locality" Fieldtrip guide Caesar Creek Lake is a large multi-purpose reservoir, about 7 miles long and covering more than 2600 acres, in Warren, and Clinton Counties, with an average pool elevation of about 850' above sea level, maintained by a large dam 165' high and more than half a mile long, parallel to Clarksville Road four miles east of Waynesville, in Massie Township, Warren County, Ohio. In places the lake is more than 100' deep as it occupies the former gorge of Caesar Creek (a tributary of the Little Miami River, named for a runaway slave nicknamed Caesar who found refuge among the Shawnee Indians in this area during the late 1700s). The dam was built by the Army Corps of Engineers, with

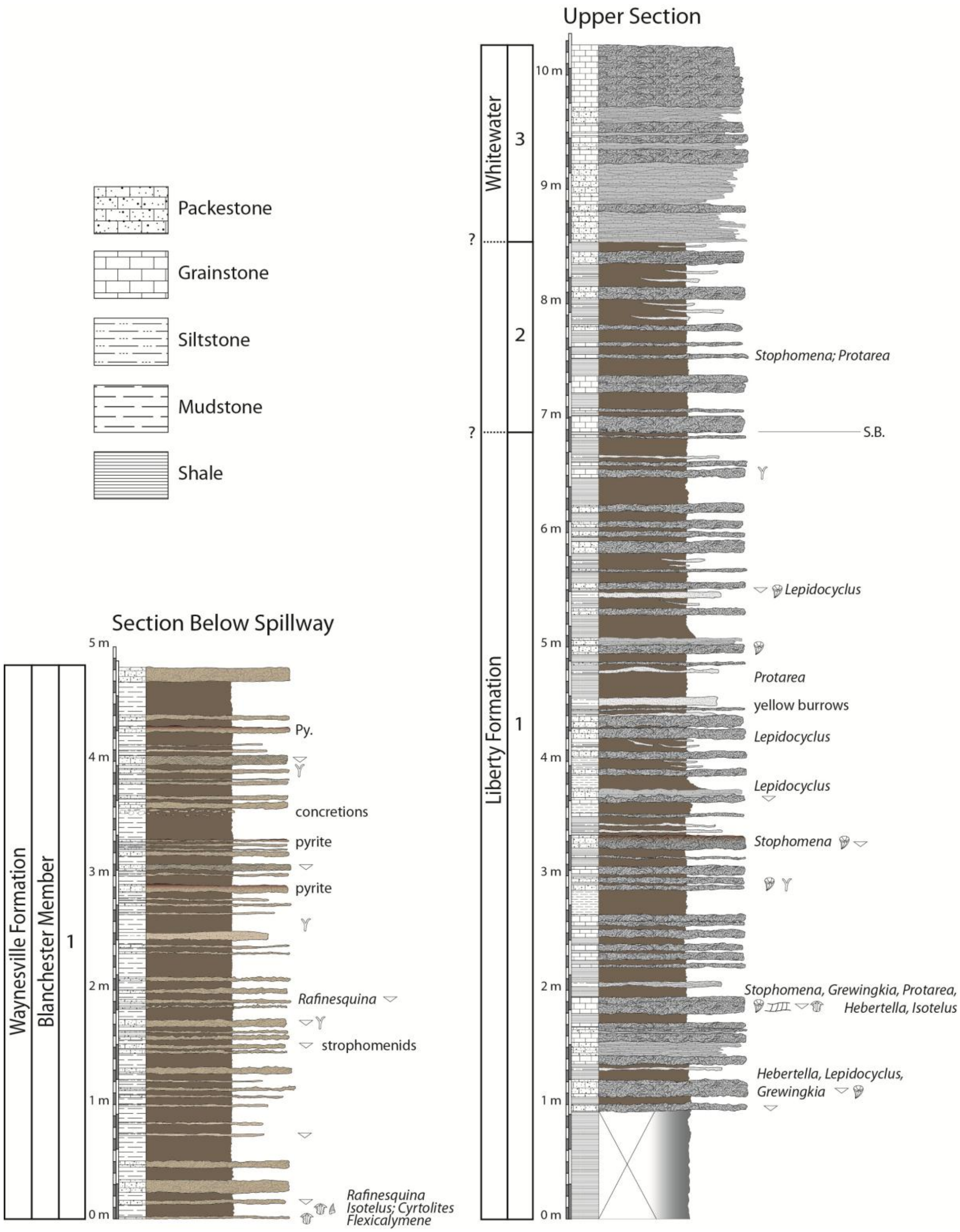

Figure 32
Stratigraphic sections at emergency spillway at the Caesar Creek Dam near Waynesville, Massie Township, Warren Co., Ohio. Left column is section of the Blanchester Member, Waynesville Formation below west end of spillway. Right column Liberty and lower Whitewater formations along Clarksville Road. Diagram by N. Sullivan.

construction initiated in 1971 and completed in 1978. A large open–cut emergency spillway was constructed by bulldozing the Upper Ordovician shale-limestone succession east of the dam; this broad spillway (over 150 m wide) provides a safety valve to prevent water from flowing over the top of the dam with possible damaging consequences during extreme floods. The spillway is cut to a level ~ 4 m (12') below the top of the dam; it commences at the shore of the reservoir, crosses Clarksville Road and slopes gently for more than 900 m to the west southwest into a tributary to Caesar Creek. The 4 m high walls of the spillway and a 9 m high roadcuts along both sides of Clarksville Road immediately southeast of the spillway provide a stratigraphic section in the Liberty and lower Whitewater Formations (Fig. 32).

Arnheim and Waynesville Formations

Roaring Run, a north-flowing tributary of Caesar Creek below the end of the spillway and some 600 m WSW of Clarkesville Road, provides intermittent outcrops that commence in nodular, silty limestone and calcareous mudstones of the Oregonia Member of the Arnheim formation near the junction of the tributary and Caesar Creek below the dam. Three major bank sections upstream from the lowest bank up to the base of the spillway, display beds of the Waynesville Formation, including the shaly Fort Ancient Member with soft shales containing well preserved trilobites and molluscs, interbedded with limestones (packstones) comprised mainly of shells of the small orthid *Dalmanella*. These are the famed "*Treptoceras duseri*" shales and *Dalmanella* limestones discussed by Frey (1987, 1988, 1997). Good exposures of the Clarksville and Blanchester Members are exposed in gullies running down the steep bank of the creek at the western end of the emergency spillway, which also provide access to the creek (Fig. 32). If time permits we will walk down the spillway to examine these sections. The lowest exposures in the gullies near the level of the creek are in soft bluish gray mudstones in the Clarksville Member typical of the noted "butter shales" facies, which yield articulated and frequently enrolled *Flexicalymene* and *Isotelus* trilobites, lingulids, molds of cephalopods, gastropods, and valves as well as intact, in situ molds of bivalves (*Ambonychia*, *Modiolopsis*), some with black periostracal films. Upward, the mudstones are interbedded with thin sub-tabular packstone beds containing prolific *Rafinesquina* and *Strophomena* in some cases in nested and edgewise concentrations representing storm amalgamation. A meter thick ledge formed of stacked brachiopod packstones forms the western edge of the spillway.

The floor of the spillway WSW of Clarksville Road is flat and largely covered with debris but a few ledges of limestone low in the Liberty Formation crop out; some are rich in nautiloids as well as the typical brachiopods (*Strophomena*, *Rafinesquina*, *Hebertella* and others). A band of white-weathering clay about 2/3 the way along the spillway marks the position of a distinctive light gray shale interval about 1 m thick that has been assigned to the top of the Waynesville Formation. Shortly after the construction of the dam and spillway this shale yielded thousands of specimens of tiny, enrolled trilobites (*Flexicalymene retrorsa minuens*) as well as large *Isotelus* such as the specimen on display at the visitors center (see Schumacher and Shrake, 1997; Hunda and Hughes, 2007). This interval with its distinctive trilobites has been traced at least as far as Oldenburg, Indiana, some 85 km to the southwest (D. Cooper, personal communication 2011).

Liberty and Whitewater Formations

The walls of the spillway and the lower roadcut on Clarksville Road provide sections of the upper Waynesville and Liberty Formation, although the base of section is everywhere covered by talus. Slabs of fallen limestone from the Liberty Formation show prolific faunas of brachiopods (*Strophomena, Rafinesquina, Hebertella*, *Platystrophia*, *Hiscobeccus* [*Lepidocyclus*]), varied ramose bryozoans, the rugose coral *Grewinkia*, the small tabulate *Protarea*, and trilobite fragments as well as moldic nautiloids, gastropods, and bivalves. This provides a very good overview of the prolific Richmondian faunas.

The roadcut in particular exposes a ~9 meter section of the middle to upper Liberty Formation and the basal Whitewater Formation (Figs. 31, 32). The 7 meters show an alternation of clusters of brachiopod, bryozoan and coral-rich pack to grainstones, with shaly mudstones and thin siltstones, calcisitites. Most are wavy and somewhat lenticular, but thicker shell beds have sharp bases and maybe graded with a thin caslcisiltite cap that is typically burrowed with *Planolites*, *Trichophycus*, *Chondrites* and other traces. Shell beds show a variety of taphonomic indicators including variably articulated, disarticulated, as well as rounded and corroded shell fragments. This is a particularly good locality to observe diverse epibionts encrusting brachiopods and corals, including expanded bases of ramose bryozoans, encrusting bryozoans, and the small button-like tabulate coral *Protarea*. Most of the aragonitic fossils such as bivalves, gastropods and nautiloid cephalopods are reserved as cemented mud-filled molds.

Pack- and grainstone beds are separated by recessive weathering argillaceous intervals including a) barren gray to greenish gray claystones, b) calcareous mudstones with abundant scattered brachiopods, bryozoans and corals, and c) pale gray silty mudstones and shales and thin siltstones, with abundant trace fossils, especially *Teichichnus* spreite that may extend for up to 5-6 cm into the mudstone. Such intervals may also yield inflated, concretionary molds of bivalves, gastropods and nautiloids.

Many of the brachiopods are distarticulated and some of the valves are corroded, darkened and or encrusted with bryozoans, *Protarea* and/or bored. Some thicker brachiopods and most of the larger rugose corals are riddled with borings (*Trypanites*) suggesting prolonged residence time on the seafloor. The varied preservation of shells from articulated and closed to heavily corroded, together with their multi-colored nature ranging from pinkish to nearly black (see Kolbe *et al*., 2011), indicate a strong degree of time-averaging in most thicker shell beds.

In addition, there are a few distinctive beds of fine grained grainstones (“calcarenites”), most notably a distinctive bed of barren medium gray weathering, parallel laminated limestone, at about 4 m above the base of the section shows a sharply scoured base with sub-parallel gutters and one channel-like feature over a meter across. This bed and similar lithologies higher in the section appear to reflect single events of rapid deposition. We suggest that these persistent bands may record extraordinary events such as super-hurricanes or tsunamis that exported large volumes of shore-processed carbonate carbonate sand and silt into shallow offshore areas.

Two or three beds of grainstone around 7 meters in the roadcut show distinctive, roughly polygonal grooves, resembling mudcracks on their upper surfaces. These grooves are slightly sinuous and in some areas show comminuted debris linings together with rusty staining suggesting the presence of minor pyrite. These enigmatic features may either record an unusual type of surficial pascichnial trace, or atypical syneresis cracks. They are almost certainly not subaerial desiccation cracks as they are associated with typical offshore faunas.

The contact between the Liberty and lower Whitewater formations is indistinct but is interpreted to occur at a relatively thick ledge at about 7 meters above the base of the section;

this is overlain by a distinct, recessive weathering shaly zone and that, in turn is overlain by the upper two meters of stacked wavy crinoidal, bryozoan grainstones.

Depositional environments recorded in the Liberty Formation are interpreted as shallow muddy to shelly substrate seafloors below wave base but above average storm wave base. This accords well with abundant storm evidence in these beds, including graded bedding, rippling of bed tops, edgewise stacking hummocky lamination, rip-up clasts, and irregularly scoured bases with gutter like features on some beds. Brachiopod shells from the Waynesville and Liberty Formations at other localities with identical biofacies, have yielded abundant microendoliths that place these facies firmly in the upper euphotic zone only a few tens of meters deep (Vogel and Brett, 2009).

Storm waves and currents surely played a strong role in the final appearance of many beds. Nonetheless, we argue that the thicker beds, which can be seen to persist along the walls of the spillway for nearly a kilometer, are not primarily attributable to storm winnowing. Rather, these as with other shell beds in the Cincinnatian reflect millennial scale interludes of low sedimentation during which skeletal material built up on the seafloor and was variably processed by episodic storm reworking.

Meter-scale cycles are evident in parts of the Waynesville Formation. Decimeter-scale ledge-forming, shell-rich limestones are sharply overlain by intervals of clay shales. At least three intervals within the Waynesville show thicker intervals of relatively limestone-free clay shale, the so-called “butter shales” noted for their trilobite and molluscan faunas, that appear to be analogous to the “big shale” intervals recognized in the Kope Formation (Brett and Algeo, 2001) and these have been traced over 100 km between Caesar Creek and southeastern Indiana.
Small, scale cyclicity is not as prominent in much of the upper Richmondian strata as in the lower Cincinnatian. However, subtle packages of pack- and grainstone alternating with thin but persistent intervals of shale, including the *F. retrorsa minuens* shale at the top of the formation. These alternations appear to be analogous to meter scale cycles in shalier successions, but they are less clear-cut because of the occurrence of thin, lenticular packstones within the shaly successions in these upramp sections.

The diverse faunas of the Richmond Group show a higher diversity of fauna than those of the lower Cincinnatian including a number of taxa that are rare or absent below the Richmondian: these include the rugose (*Grewinkia*, *Streptalasma*) and tabulate (*Protarea*) corals and the brachiopods *Hiscobeccus* (*Lepidocyclus*), *Eochonetes,* and *Leptaena* The abrupt influx of these taxa apparently from warmer water source areas to the northwest, has been referred to as the Richmondian invasion (Holland, 1997; Patzkowsky and Holland, 2007). Remarkably, there was little extinction of endemic species such that the invading taxa appear to co-exist with earlier Cincinnatian taxa such as Rafinesquina and the trilobites *Flexicalymene* and *Isotelus*. This bioevent is thought to record a slight warming trend in the late Cincinnatian (Ashgill or late Katian) time, which permitted the immigration.