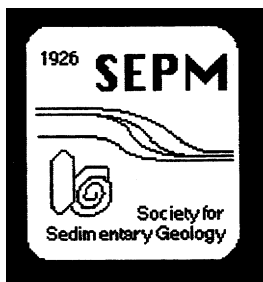


# SEQUENCE, CYCLE & EVENT STRATIGRAPHY OF UPPER ORDOVICIAN & SILURIAN STRATA OF THE CINCINNATI ARCH REGION

*Edited by*  
*Thomas J. Algeo and Carlton E. Brett*



**Field Trip Guidebook**  
*in conjunction with the*  
**1999 Field Conference of the Great Lakes Section**  
**SEPM-SSG (Society for Sedimentary Geology)**  
*and the*  
**Kentucky Society of Professional Geologists**  
**October 8th-10th, 1999**

**Kentucky Geological Survey**  
James C. Cobb, State Geologist and Director  
University of Kentucky, Lexington

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## **Earth Resources—Our Common Wealth**

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For further information contact:

Manager, Communications and Technology Transfer

Kentucky Geological Survey

228 Mining and Mineral Resources Building

University of Kentucky

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**1999 SEPM-GLS / KSPG FIELD CONFERENCE**  
**Cincinnati, Ohio**  
**Oct. 8<sup>th</sup>–10<sup>th</sup>, 1999**

**FOREWORD**

The Upper Ordovician to Silurian stratigraphic succession of the Cincinnati Arch region in the Tristate area (Ohio-Kentucky-Indiana) is a classic sedimentary package. These highly fossiliferous strata comprise in part a global reference section for the Upper Ordovician, the eponymous Cincinnati Series. These strata and their enclosed fossils have been studied intensely from the time of James Hall (ca. 1840s). The concepts of diastrophism and eustatic sea-level fluctuations were important themes developed by the early workers such as E.O. Ulrich and H. Bassler, among others. Although these early workers advocated a perhaps overly simplistic “layer-cake” view of the regional stratigraphy, in recent years the pendulum may have swung too far in the opposite direction as stratigraphers have revised and combined many of the early-defined biostratigraphic units into larger lithotopic mapping units.

Recent years have seen a resurgence of interest in the Upper Ordovician and Silurian rocks of the Cincinnati Arch region from the standpoint of process-based sedimentology, stratigraphy, and paleoecology. This reflects both the rise of new paradigms, such as sequence and event stratigraphy, as well as newly available outcrops resulting from highway construction. In this regard, construction of the Alexandria-Ashland or AA Highway (Kentucky Rtes. 9 and 546) and the Greater Cincinnati highway system (I-275, I-471, etc.), as well as local excavations for industrial parks, has opened large tracts of fresh bedrock that provide a dramatically better view of parts of the section that were inaccessible to earlier workers. In particular, recent work by Steven Holland, Arnold Miller, Dave Meyer, the late Wayne Pryor, and their students has paved the way to a much better understanding of sedimentary and faunal events and cycles in the Cincinnati Series.

When we began compiling material for this guidebook, we intended this trip to represent primarily an overview of the considerable body of existing work on the Ordovician to Silurian strata of the Cincinnati, Ohio, to Vanceburg, Kentucky, region. While we were cognizant of the large amount of existing work on these units, we were struck by the potential of the string of relatively fresh outcrops along the AA Highway for further innovative research. Indeed, there are more than 60 outcrops in the Cincinnati Series along the AA Highway between Alexandria (near Cincinnati) and Maysville, a distance of some 80 kilometers, and there are few stretches of any length along this transect in which Upper Ordovician rocks are not exposed. This seemed to us an ideal situation in which to undertake a detailed stratigraphic correlation study, with a view toward examining the degree of lateral continuity of facies, cycles, and event horizons. Further, if features such as tempestites (storm beds) are lateral continuous over some distance, this offers real potential to examine lateral variation in the character of individual units, e.g., with a view toward understanding proximality gradients on an ancient epicratonic marine ramp. Thus, throughout the spring and summer of 1999, we persevered in measuring outcrop after outcrop (all included in this field guide!) and in identifying key lithologic, biostratigraphic, and taphonomic horizons that could be used in correlation. In this period, we have made tremendous progress to our goals, although much remains to be accomplished.

In this context, the present guidebook is a progress report on the results of our recent work. Although this work has led to a number of interesting discoveries, one that stands out perhaps above all others is the degree to which individual stratal packages (cycles, bed bundles, and event horizons) in the Kope Formation can be correlated along the length of the AA Highway. To put tongue in check (and why not?), we note that a recent guidebook on the Upper Ordovician Cincinnati Series (Davis and Cuffey, 1998) was subtitled “Sampling the Layer Cake that Isn’t”—well, we have been thoroughly enjoying that layer cake all summer.

## ACKNOWLEDGMENTS

We are very grateful to many people who helped to make this effort a reality. We are especially appreciative of the several authors of supplemental papers to this volume: Susan Barbour (U. of Cincinnati), Kees DeJong, Craig Dietsch, and their students (U. of Cincinnati), Steve Holland (U. of Georgia), Arnie Miller and David Meyer (U. of Cincinnati), Charles Mason (Morehead State University), Greg Schumacher (Ohio State Geological Survey), and Colin Sumrall and Paula Work (Cincinnati Museum of Natural History). These individuals came through with fine contributions on relatively short notice, and we are very happy to have their work represented in the present guidebook.

Special thanks go to Steve Holland (U. of Georgia) for thoughtful and timely reviews of our papers. Steve, together with Kees DeJong, Frank Etensohn, Steve Felton, Charles Mason, Arnie Miller, Dave Meyer, Greg Schumacher, and Tom Weaver, shared with us some of their knowledge and insights on the geology of the Cincinnati Series and on regional Silurian stratigraphy. Paula Work provided excellent assistance with specimen photography, Ginny Chasteen helped with manuscript preparation, Heather Ellington cut and polished rock slabs, and Susan Barbour, Forest Gahn, David Ray, Andrew Webber and, most notably, Sean Cornell provided invaluable assistance and support in the field.

For sponsorship of this event, we thank the Great Lakes Section of SEPM-SSG (Society for Sedimentary Geology) and the Kentucky Society of Professional Geologists (KSPG). Thanks in particular to Janis Treworgy and to John Popp, presidents of the respective organizations, for organizational assistance.

Making the 1999 SEPM-GLS / KSPG Field Conference a reality has required the contributions of many individuals. If we have overlooked anyone in this brief list, our sincerest apologies. To all, our sincere appreciation. We are looking forward to an excellent weekend of Cincinnati geology.

Tom Algeo and Carl Brett  
Field conference co-leaders & field guide co-editors  
October 1st, 1999

## FIELD TRIP ITINERARY

**Saturday, October 9<sup>th</sup>:** Upper Ordovician-Lower Silurian sequences, cycles, and event horizons along the Alexandria-Ashland (AA) Highway, Kentucky Rtes. 9 and 546

- 8:00 A.M. Departure from U.C. Geology Department and Kingsgate Conference Center  
(*sharp!*)
- 8:45-9:15 **Stop 1. Holst Creek (AA Hwy. outcrop 27):** Pt. Pleasant-Kope contact; lowermost Kope Fm. (Fulton submember)
- 9:30-9:45 **Stop 2. East Snag Creek (AA Hwy. outcrop 34):** Mid-Kope ball-and-pillow deformation (seismites?); type section of Snag Creek submember of Kope
- 10:00-10:30 **Stop 3. Rte. 1159 junction (Brooksville Turn):** Upper Pt. Pleasant ball-and-pillow deformation (seismites?)
- 11:00-11:15 **1<sup>st</sup> rest stop** at Marathon station in Maysville
- 11:30-12:00 P.M. **Stop 4A. Rte. 3071, west Maysville:** Middle Kope to Kope-Fairview contact; upper Southgate and McMicken members of Kope Fm.; decameter- and meter-scale cyclicity
- 12:00-12:30 **Stop 4B. Rte. 3071, west Maysville:** Fairview ball-and-pillow deformation (seismites?) and Bellevue hardground; stratigraphic condensation
- 12:40 Pull-by stop at faulted Fairview section, Rte. 3071 (do not leave vehicles)
- 1:00-1:45 **Lunch stop** along Rte. 11, east Maysville (bag lunches provided)
- 1:45-2:30 **Stop 5. Rte. 11, east Maysville:** Ball-and-pillow deformation (seismites?) in Fairview Fm.
- 2:45-3:00 **2<sup>nd</sup> rest stop** at Marathon station in Maysville
- 3:30-3:45 **Stop 6. Tollesboro cut, near Cabin Creek:** Contact between Ordovician strata and Silurian Brassfield Fm.
- 4:00-4:30 **Stop 7. Charters cut:** Silurian Crab Orchard and Bisher formations: sequences and facies comparison with Kope Fm.; newly discovered bentonites
- (*reverse direction*)
- 4:45-5:30 **Stop 8. Poplar Flat Road, Herrin Hill:** Silurian Bisher Fm. and unconformable contact with Upper Devonian Huron Shale; unconformities, sequence stratigraphy of Silurian, and bioherms vs. paleo-karst structures
- 5:45-6:00 **3<sup>rd</sup> rest stop** at Marathon station in Maysville
- 6:00-7:30 P.M. Return drive to Cincinnati

**Sunday, October 10<sup>th</sup>:** Sequence and event stratigraphy of the Kope Formation in the Greater Cincinnati area

- 9:00 A.M. Departure from U.C. Geology Department and Kingsgate Conference Center
- 9:30-10:30 **Stop 1. Rte. 445 roadcut, Brent, Kentucky:** Lower to middle Kope Fm. (Economy-Southgate members; middle part of Composite Reference Section of Brett and Algeo, this volume); decameter- and meter-scale cyclicity; comparison of facies, fauna, and sequence stratigraphy with Rte. 3071 section in Maysville
- 10:45-11:30 **Stop 2. Duck Creek stream cut:** Lowermost Kope Fm. and contact with underlying Pt. Pleasant Limestone; lower part of Composite Reference Section of Brett and Algeo (this volume)
- Beginning after this stop, some vans will head back to U.C. Geology Department and to Kingsgate Conference Center, as requested by fieldtrip participants; more vans will follow after stop 3*
- 11:45-12:30 **Stop 3. Pioneer Valley industrial park (“White Castle site”):** Comparison with Rte. 445 roadcut; details of lower-mid Kope cycles
- 12:45-1:45 P.M. Lunch (no bag lunches; will stop at fast food restaurant)
- 2:00-3:00 **Stop 4. Mason/Reidlin Road:** Uppermost Kope (Taylor Mill submember, including X-Y-Z beds) and Kope/Fairview contact
- End of formal fieldtrip; all vans return unless any remaining “die-hards” are determined to see more rock!*

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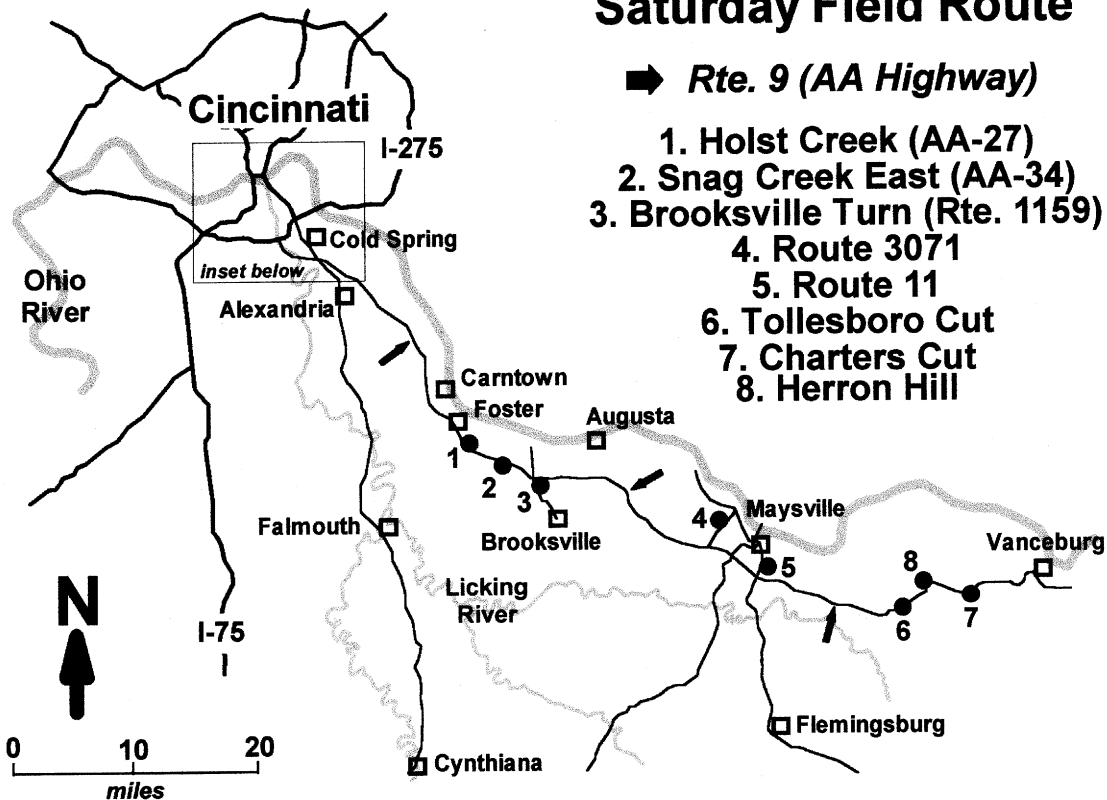
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## Saturday Field Route

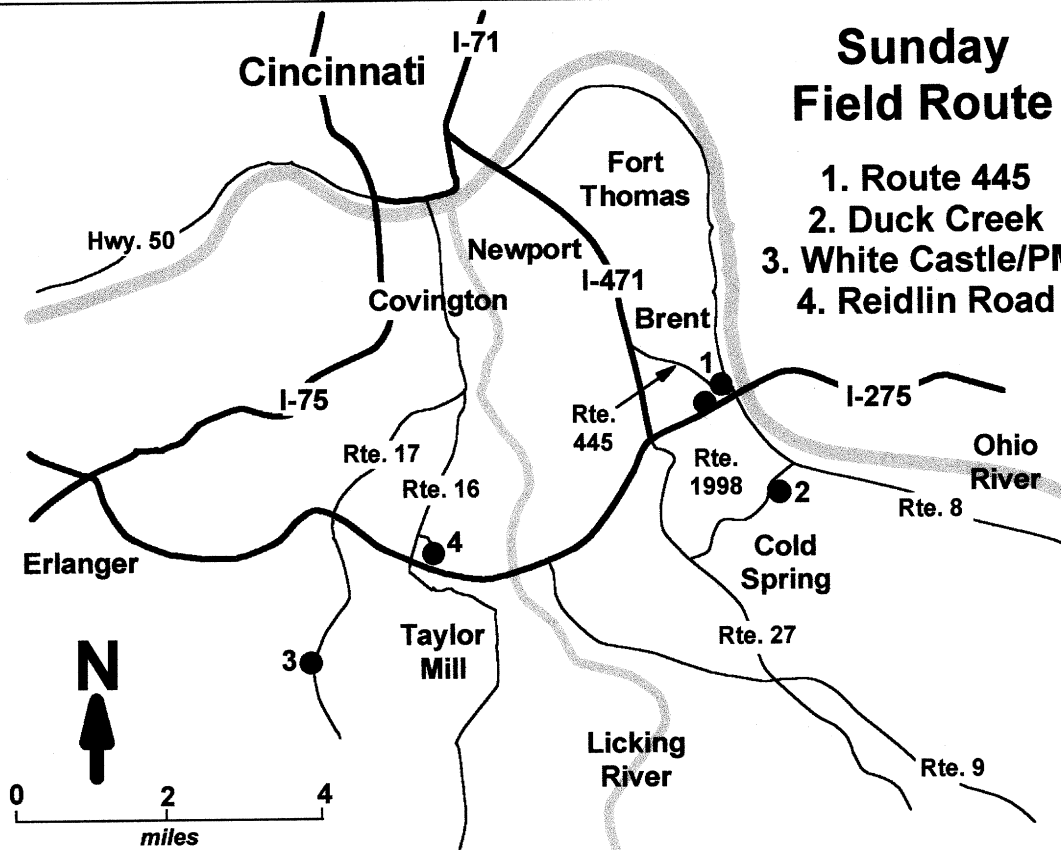
➡ *Rte. 9 (AA Highway)*

1. Holst Creek (AA-27)
2. Snag Creek East (AA-34)
3. Brooksville Turn (Rte. 1159)
4. Route 3071
5. Route 11
6. Tollesboro Cut
7. Charters Cut
8. Herron Hill



## Sunday Field Route

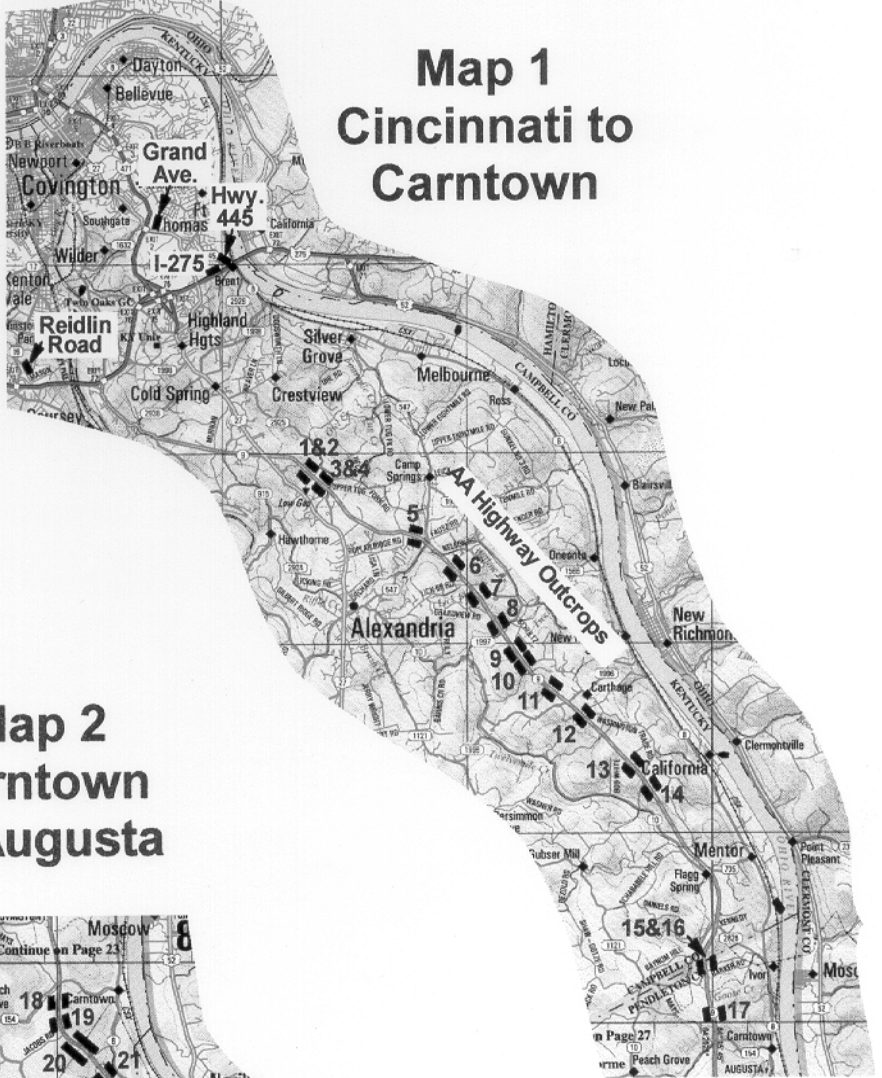
1. Route 445
2. Duck Creek
3. White Castle/PMI
4. Reidlin Road



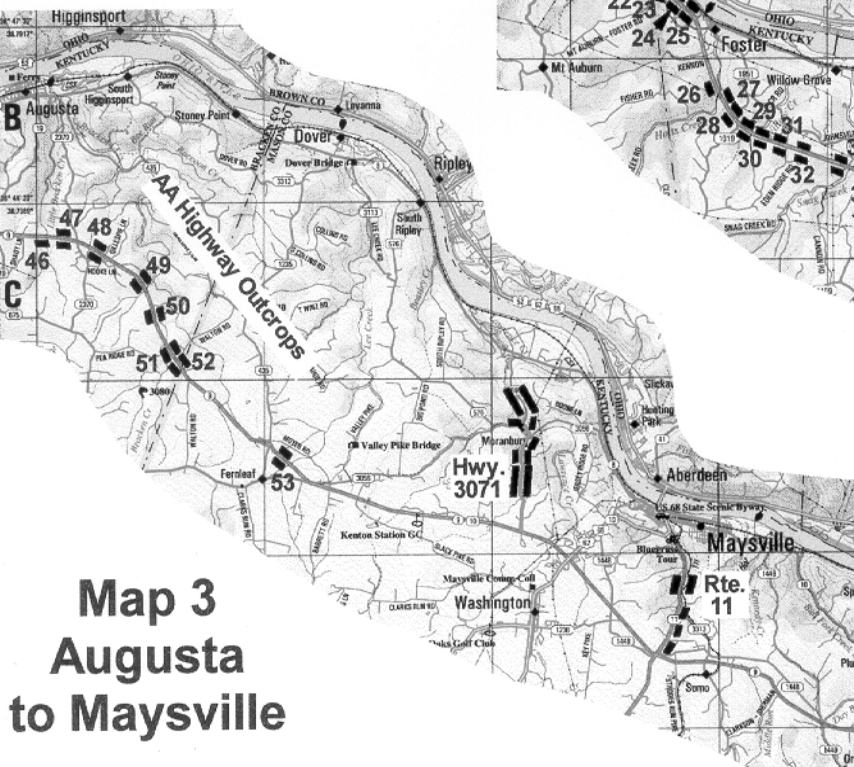
**Figure 2. (A)** Maps of study outcrops of Brett and Algeo. Note locations of Cincinnati-area outcrops (e.g., Hwy. 445; map 1), of numbered outcrops along AA Highway (maps 1-3), and of Hwy. 3071 and Rte. 11 outcrops near Maysville (map 3). See roadlog for description of individual outcrops. From DeLorme's Kentucky Atlas and Gazetteer (1997). **(B; next page)** Stratigraphic intervals of study outcrops from Cincinnati area (top) toward Maysville (bottom); outcrop numbers as in A. Solid bars represent measured sections reproduced in roadlog or appendix of guidebook, and hachured bars represent unmeasured outcrops. Roadlog mileage bar (bottom) is keyed to mileage in roadlog for AA Highway (p. 4f). Note that the road level of the AA Highway traverses the full stratigraphic range of the Kope Fm. several times, providing 5-30-m "snapshots" of portions of the ca. 74-m-thick Kope along the Cincinnati-Maysville transect. Stratigraphic nomenclature is that of Brett and Algeo (this volume).

## Cincinnati

### Map 1 Cincinnati to Carntown

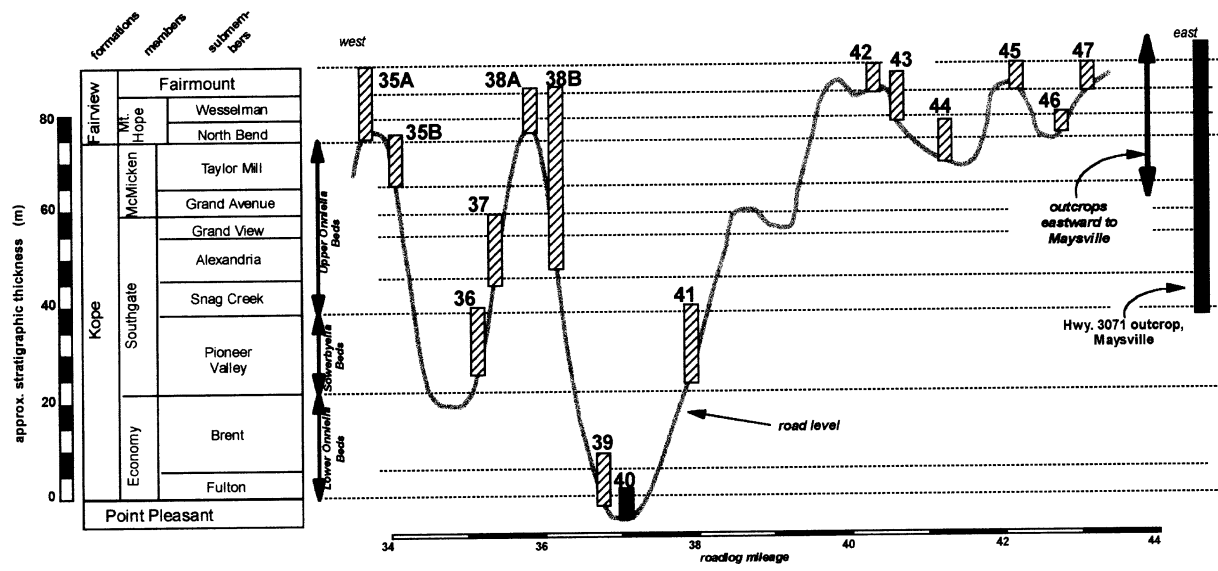
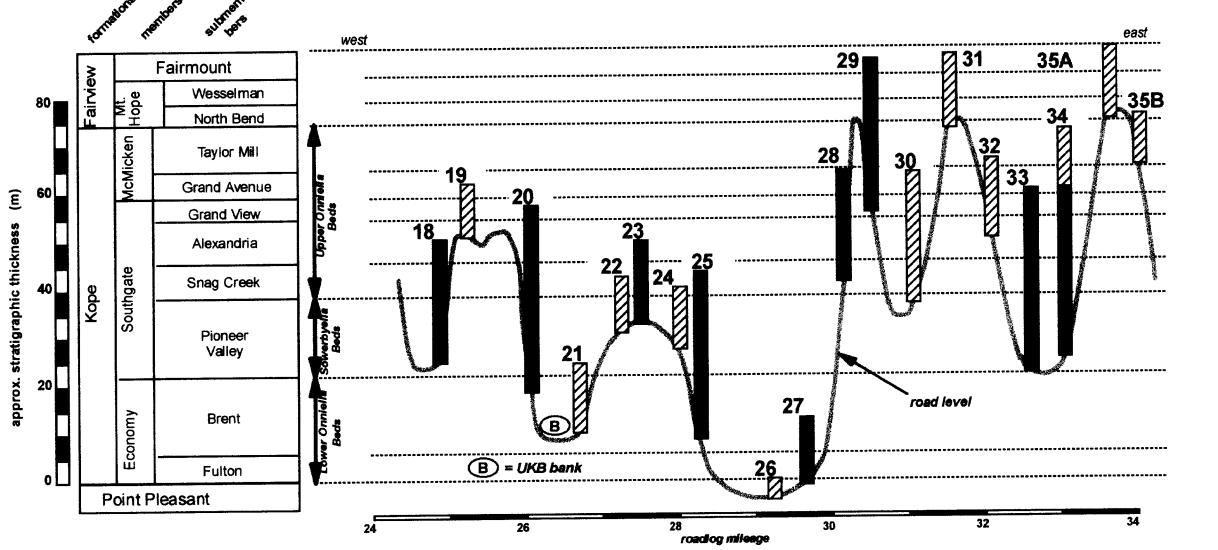
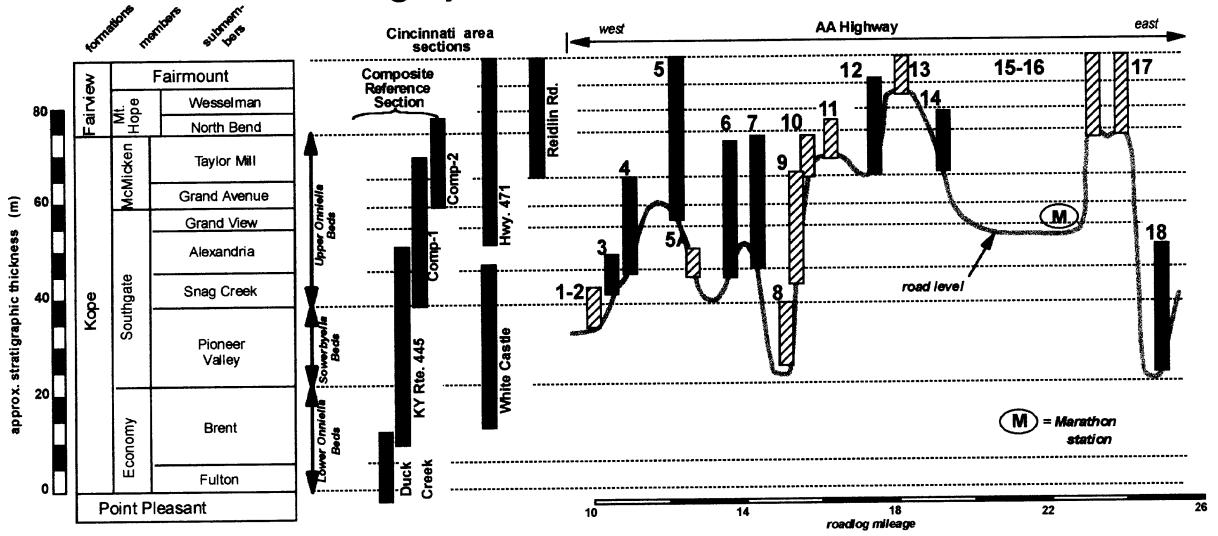


### Map 2 Carntown to Augusta



### Map 3 Augusta to Maysville

# Stratigraphic Intervals of Study Outcrops



## ROADLOG

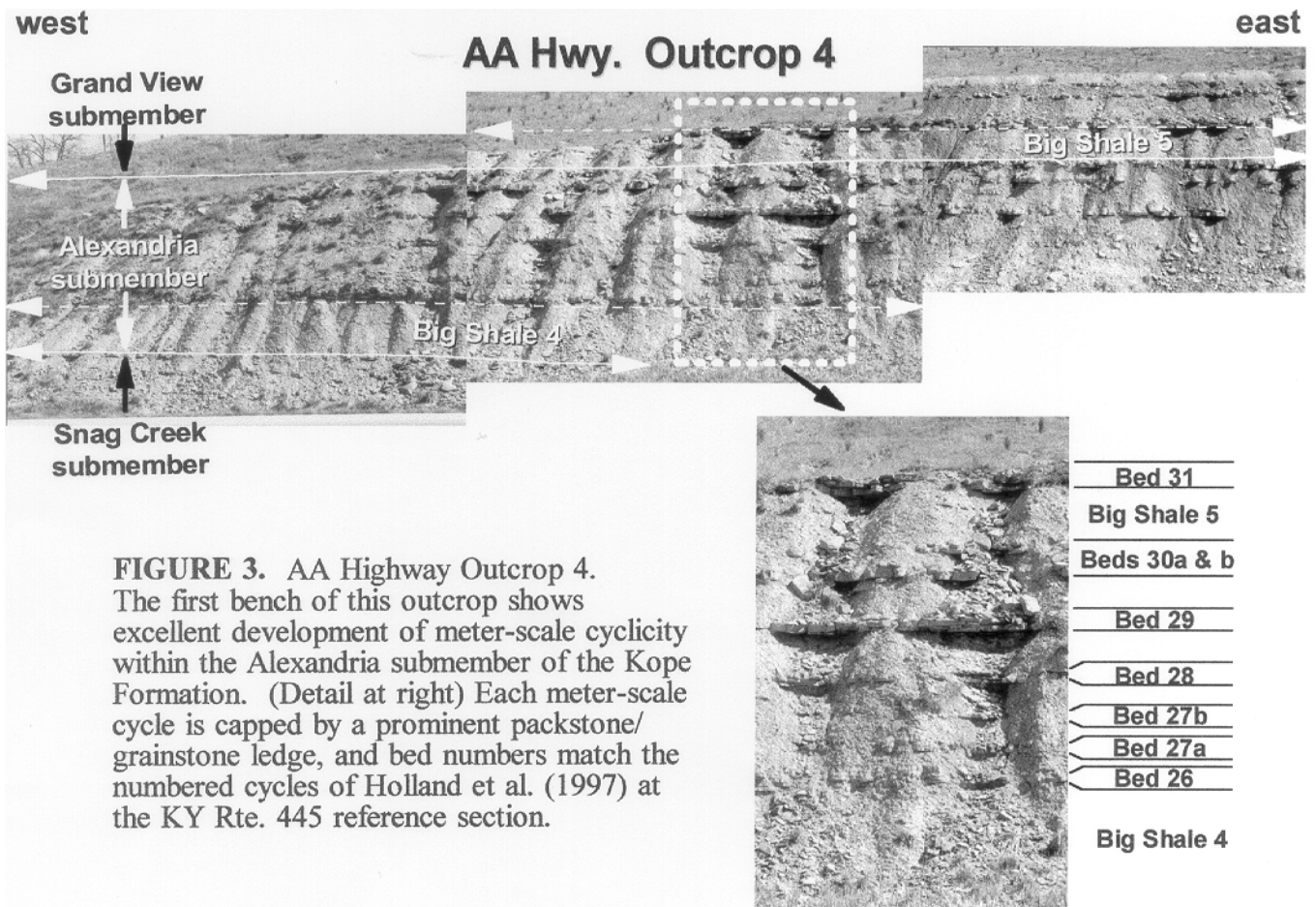
Saturday, October 9<sup>th</sup>, 1999

### KY RTE. 9 (AA HIGHWAY) ALEXANDRIA to MAYSVILLE, KENTUCKY

Note: Mileage begins at Kentucky State Line on I-471 bridge over Ohio River, Cincinnati, Ohio/Newport, Kentucky.

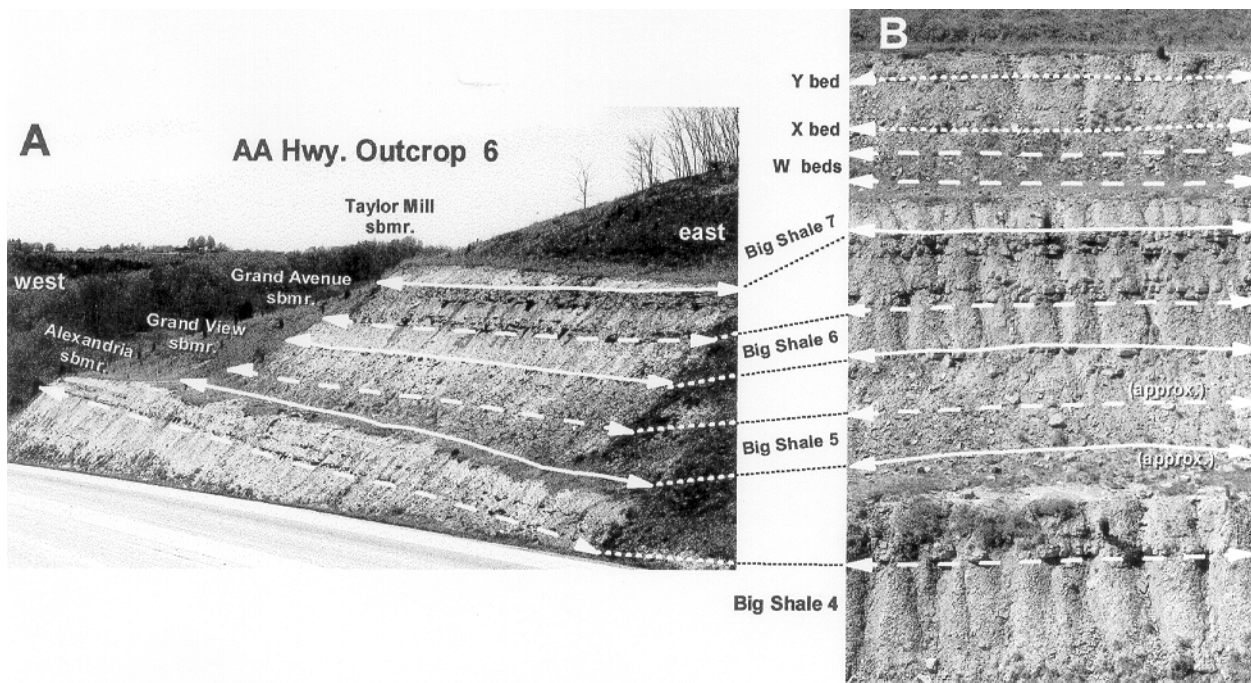
#### Total Mileage

- 0.0 I-471, southbound; bridge over Ohio River; enter Kentucky; view of Newport-Dayton-Ft. Thomas area ahead
- 0.3 South end of bridge; ascending south side of Ohio River Valley
- 0.4 Exit 4; Ft. Thomas
- 1.5 Exit 3 to Grand Avenue, Ft. Thomas; outcrops of Kope Fm. on left
- 1.6-2.0 Outcrop of Kope Fm. with Grand Avenue submember at entrance ramp on right
- 2.7 Outcrop in upper Kope-Fairview formations on right
- 2.9 Exit 2 for US Rte. 27; Ft. Thomas, Kentucky
- 3.5 Poor exposure of upper Kope-Fairview formations on right
- 4.0 Outcrop in upper Kope Fm. on both sides of road
- 4.2-4.3 Outcrop in upper Kope Fm.
- 4.4 Exit for I-275 on right; good outcrop of Kope-Fairview contact on exit ramp
- 4.8-5.0 Crossing under I-275; Fairview Fm. exposures
- 5.6 I-471 ends and flows onto US Hwy. 27 south; at Sunset Drive
- 6.6 Junction KY Rte. 1998 (Industrial Road) leads to Ohio River
- 8.5 Junction KY Rte. 9 (AA Highway); prepare to exit right
- 8.7 Exit to right onto AA Highway southeast toward Maysville, KY
- 9.2 Merge left onto AA Highway at underpass beneath Rte. 27
- 10.0 Rocky View Drive
- 10.1 **Outcrop 1, Rock View Drive:** Middle Kope Fm.; bundle of limestones in lower half of outcrop is upper part of Pioneer Valley submember; overlying thick shale is Big Shale #3 at base of Snag Creek submember
- 10.3 **Outcrop 2:** Poor exposure of Kope Fm.
- 10.5-10.8 **Outcrop 3:** Good exposure of middle Kope Fm. (Snag Creek submember); upper part of Big Shale #3 is overlain by limestone bed bundle (cycles 23-24)
- 10.8-10.9 **Outcrop 4, East Alexandria Pike (Fig. 3):** Excellent exposure of middle Kope Fm. (Alexandria submember; type locality); note regularly spaced marker beds, including "red *Onniella* beds" (cycles 26-30) and prominent Grand View bed (cycle 31) which forms an overhanging ledge near top of 1.8-m-thick Big Shale #5 (base of Grand View submember)
- 11.0 Stop light at East Alexandria Pike; just west of 84 Lumber
- 11.5 Einzweiler Road
- 11.5 Poplar Ridge Road
- 12.2-12.3 **Outcrop 5A, Poplar Ridge:** Large, rubbly outcrop of Fairview Fm. extending downward through Taylor Mill and Grand Avenue submembers of Kope Fm. toward lower end of cut; W-X-Y-Z marker beds, *Diplocraterion* beds, and the "Two-Foot Shale" are well displayed
- 12.6 **Outcrop 5B, lower Poplar Ridge:** Base of Snag Creek submember of Kope Fm. with 2-m-thick Big Shale #3
- 12.6 KY Rte. 547; Alexandria [mile marker 10]

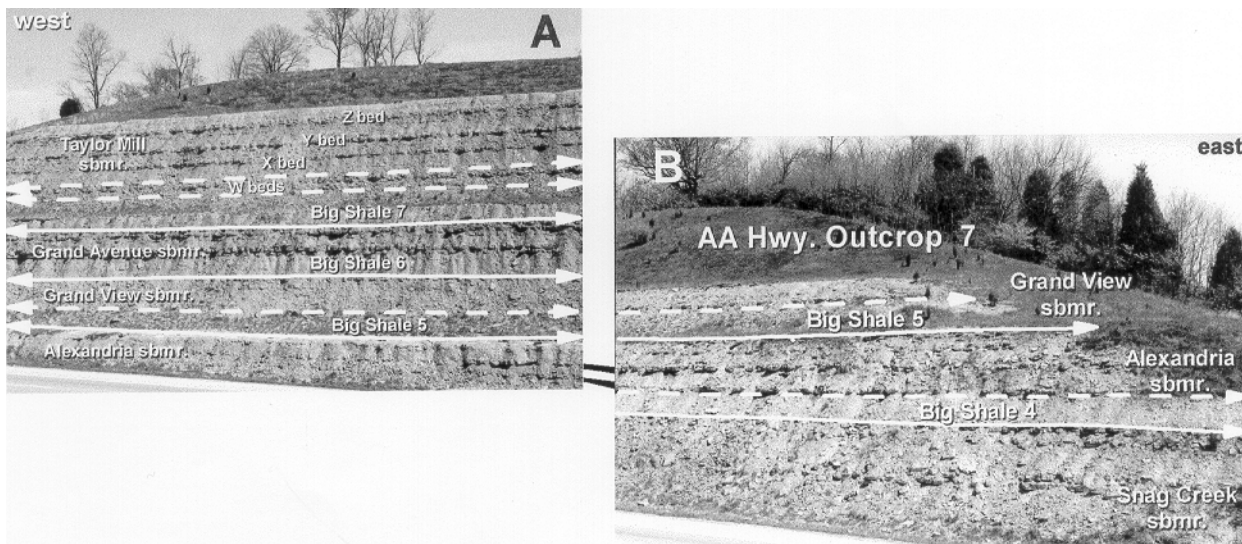


**FIGURE 3.** AA Highway Outcrop 4. The first bench of this outcrop shows excellent development of meter-scale cyclicity within the Alexandria submember of the Kope Formation. (Detail at right) Each meter-scale cycle is capped by a prominent packstone/grainstone ledge, and bed numbers match the numbered cycles of Holland et al. (1997) at the KY Rte. 445 reference section.

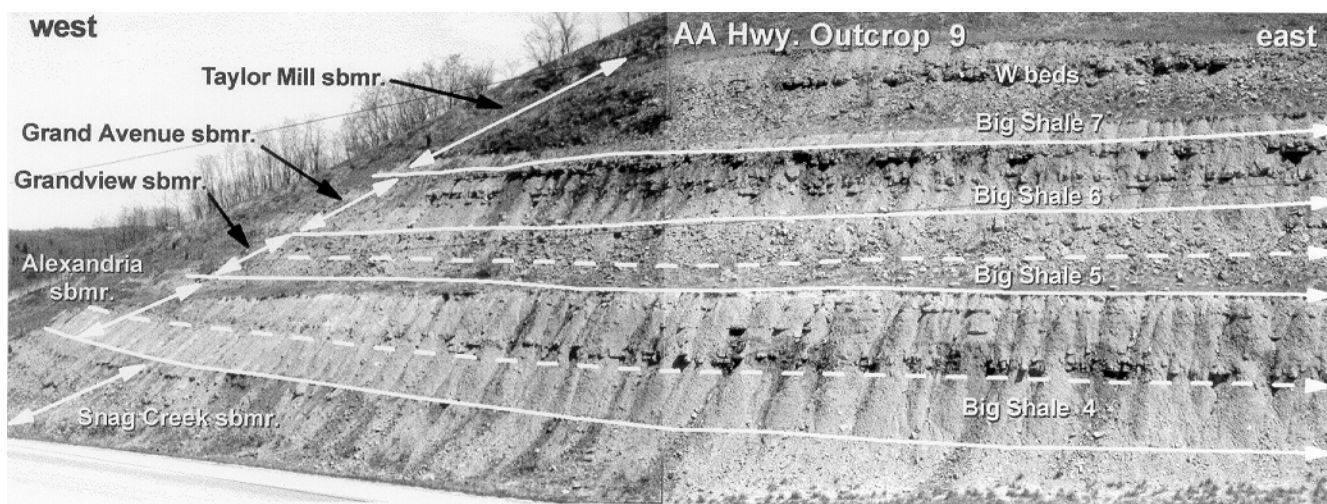
- 13.5-13.7 **Outcrop 6, Upper Lick Branch (Fig. 4):** Large outcrop of middle Kope Fm.; twin ledges just below first bench are capping beds of cycles 24a and 24b (top of Snag Creek submember); located opposite sign for "Upper Lick Br. Rd." are the distinctive red *Onniella* marker beds (cycles 25-30) at the top of Alexandria submember, also seen at Outcrop 4, with nearly identical spacing; upper part of roadcut is mainly in Grand Avenue submember; limonitic *Diplocraterion* burrows and millimeter ripples are present near top of outcrop (W beds of Taylor Mill submember)
- 13.9 Upper Lick Branch Road
- 14.2-14.5 **Outcrop 7, Grand View (Fig. 5):** Large outcrop of middle Kope Fm.; section is comparable to that seen at Outcrop 6; beds 24a and 24b are just below first bench; section above "deer crossing" sign is in "red *Onniella* beds" at top of Alexandria submember; Big Shale #5 and Grand View bed (cycle 31) are just below the base of Grand Avenue submember and are well displayed
- 14.6 Grand View Road
- 14.9 **Outcrop 8, Twelvemile West:** Lower to middle Kope Fm.; limestone beds of Pioneer Valley submember, full of *Sowerbyella rugosa*
- 15.1 KY Rte. 1997; near Twelvemile Creek
- 15.6 **Outcrop 9, Twelvemile East (Fig. 6):** Middle Kope Fm.; very shaly interval is Big Shale #4 at base of Alexandria submember
- 15.8 **Outcrop 10:** Upper Kope Fm. (Taylor Mill submember)
- 16.2 **Outcrop 11:** Small outcrop of upper Kope Fm.; same as last
- 17.0 KY Rte. 1996
- 17.35 Dead Timber Road



**Figure 4.** AA Highway Outcrop 6. Exposed are the upper half of the Southgate Member (Alexandria and Grand View submembers) and most of the McMicken Member (Grand Avenue and Taylor Mill submembers) of the Kope. (A) North side of highway; (B) South side of highway, showing higher beds of the Taylor Mill not exposed on north side. The first and second benches are at the level of “Big Shales” 5 and 7, respectively.

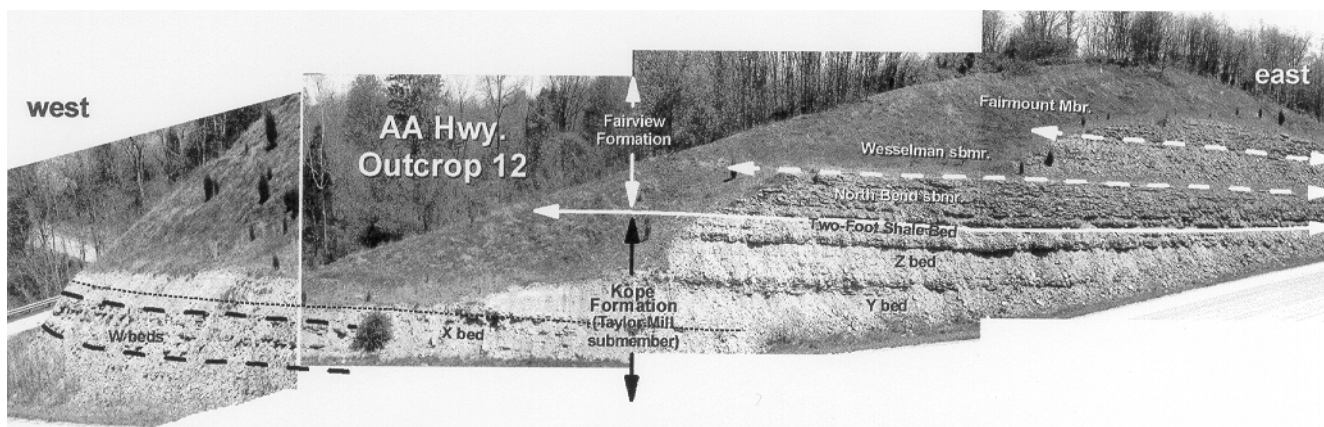


**FIGURE 5.** AA Highway Outcrop 7. Roughly the same stratigraphic interval as in Outcrop 6; again, the benches are at the level of “Big Shales” 5 and 7. Note that the Grand Avenue submember is readily identified as two 0.5-1.0-m-thick sets of amalgamated beds separated by 0.5 m of shale; this is a key marker interval. Note also well-developed meter-scale cyclicity in the overlying Taylor Mill submember. (A) Central part of north side of highway; (B) East end of north side of highway.



**Figure 6.** AA Highway Outcrop 9. Roughly the same stratigraphic interval as in Outcrops 4 & 7, although exposure quality is inferior. Despite this, prominence of the Grand Avenue beds aids stratigraphic assignments: bed bundles at the top and base of the 1st bench belong to the Alexandria and Snag Creek submembers, respectively; above Grand Avenue beds are the W beds of Taylor Mill submember.

- 17.4-17.5 **Outcrop 12, Dead Timber (Fig. 7):** Large exposure of upper Kope and lower Fairview formations; below the formation contact are the “Two-Foot Shale” (here a two-part unit totaling almost 4 ft., or 1.3 m in thickness) and the W-X-Y-Z beds, representing most of the 10-m-thick Taylor Mill submember of the Kope Fm.; above the formation contact is the “non-cyclic” interval of the Fairview Fm., and above the 1st bench is Miller’s marker bed
- 17.6 Unnamed exit road



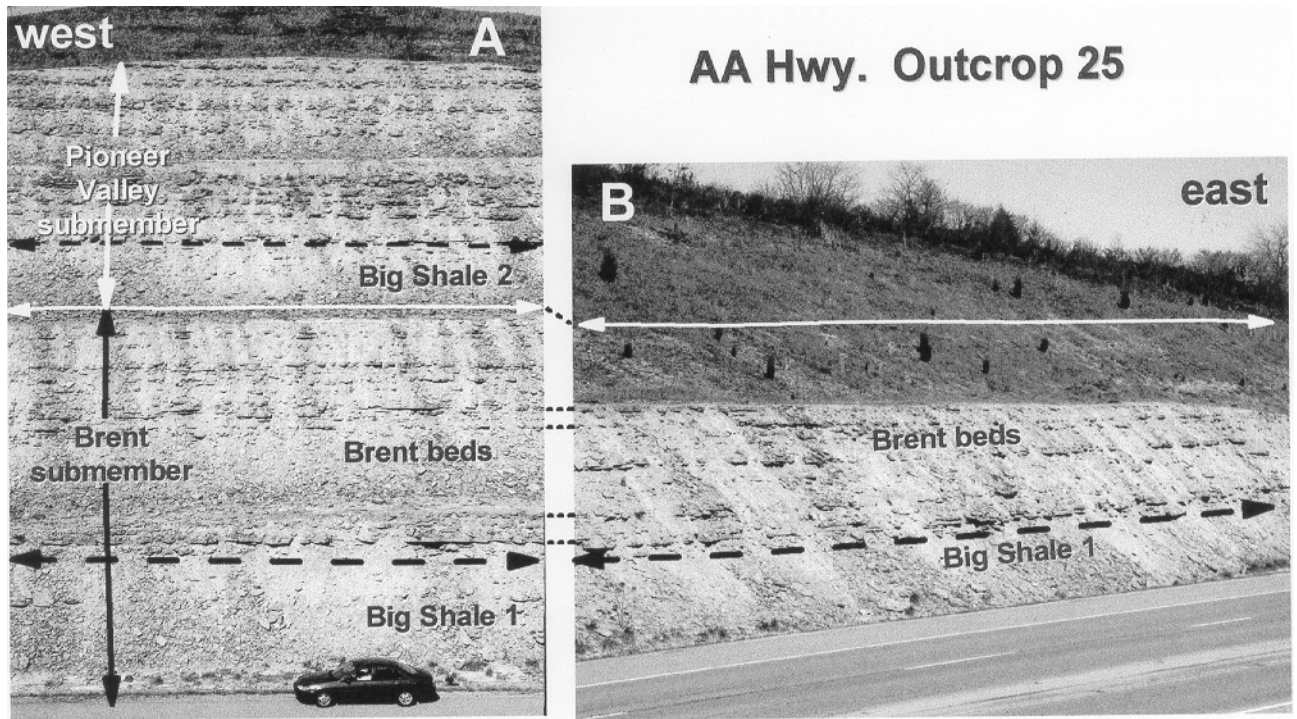
**FIGURE 7.** AA Highway Outcrop 12. Excellent exposure of Taylor Mill submember of Kope Formation. The W-X-Y-Z beds represent caps to cycles 38 (lower), 38 (upper), 39, and 40 of the KY Rte. 445 reference section (see Holland et al., this volume); note upward thinning of meter-scale cycles to base of Fairview Formation. In this composite view, the section shown in leftmost photo is not contiguous with the rest of the outcrop shown.

- 17.8 Lick Hill Road  
 18.2 **Outcrop 13:** Scree covered exposure of Fairview Fm.  
 18.9 East California Crossroad  
 19.0-19.2 **Outcrop 14A, East California:** Fair outcrop of upper Kope-Fairview; upper three cycles of Taylor Mill submember  
 19.2 West California Crossroad  
 19.3 **Outcrop 14B, West California:** same as Outcrop 14A  
 21.0 Washington Trace; note that the road traverses a relatively flat stretch with no outcrops for 3 miles; probably represents a broad pre-glacial valley  
 21.4 KY Rte. 735  
 22.2 Kennedy Road  
 22.4 Ivor Road West  
 22.6 Ivor Road East; Marathon gas station  
 23.1 Pendleton County line  
 23.3 **Outcrop 15:** Large, rubbly outcrop of Fairview; note closely stacked limestone beds typical of upper Fairview (Fairmount Member)  
 23.5 **Outcrop 16:** Rubbly outcrop similar to Outcrop 15, although slightly lower stratigraphically (North Bend and shaly Wesselman submembers of Fairview)  
 23.6 Barker Road  
 23.9-24.0 **Outcrop 17:** Shaly lower Fairview; Kope-Fairview contact is poorly exposed  
 24.6 KY Rte. 154; Peach Grove Road  
 24.8 **Outcrop 18, Peach Grove (Fig. 8):** Large outcrop of middle Kope (Southgate Member) up to base of Grand Avenue beds; limestone bundle near base of outcrop is top of Pioneer Valley submember overlain by Big Shale #3 in lower Snag Creek submember  
 25.1 **Outcrop 19A:** Shaly upper Kope (Taylor Mill submember)  
 25.2 **Outcrop 19B:** Upper Kope; base of Grand Avenue submember including Big Shale #5 and Grand View bed (cycle 31)  
 25.8 Jacobs Road  
 25.9-26.1 **Outcrop 20, Jacobs Road:** Excellent large outcrop of Southgate Member of



**Figure 8.** AA Highway Outcrop 18. Section through lower and middle Kope Formation (lower Pioneer Valley through lower Grand View submembers); note good development of decameter-scale cyclicity. The two benches in roadcut on north side of highway are at the level of “Big Shales” 3 and 4.

- Kope Fm.; platform above road level is capped by 25-cm-thick limestone ledge representing top of Pioneer Valley submember; weakly exposed slope overlying this ledge is Big Shale #3, the base of the Snag Creek submember; highest beds near top of NE side are shales and distinctive red *Onniella* limestones of Alexandria submember
- 26.3 UKB Bank
- 26.7 **Outcrop 21, New Hope:** Large outcrop of lower-middle Kope Fm.; limestones at top of Pioneer Valley submember are near road level
- 27.1 New Hope Road
- 27.2 **Outcrop 22:** Small outcrop of middle Kope Fm. (Big Shale #3; base of Snag Creek submember)
- 27.4 **Outcrop 23, Bracken County Line:** Large outcrop of Kope Fm., including upper Pioneer Valley, Snag Creek, and lower Alexandria submembers; Red *Onniella* beds at top
- 27.9-28.0 **Outcrop 24:** Rubbly outcrop of lower middle Kope Fm.
- 28.05 Old Carntown Road
- 28.1-28.3 **Outcrop 25, Old Carntown (Fig. 9):** Large section in lower to middle Kope Fm.; near crest of Moscow-Carntown anticline (Potter, 1997); note minor anticlinal fold apparent at scale of outcrop. Lowest prominently rippled beds in ditch are in Brent submember of Economy Member; excellent gutter casts and pyritic hardground are present on top of first bench; shale and overlying cycles 10-20 of Pioneer Valley submember of Economy Member are well exposed in small gully on NE side of road; the uppermost bench is in Snag Creek submember.
- 28.5 KY Rte. 2228

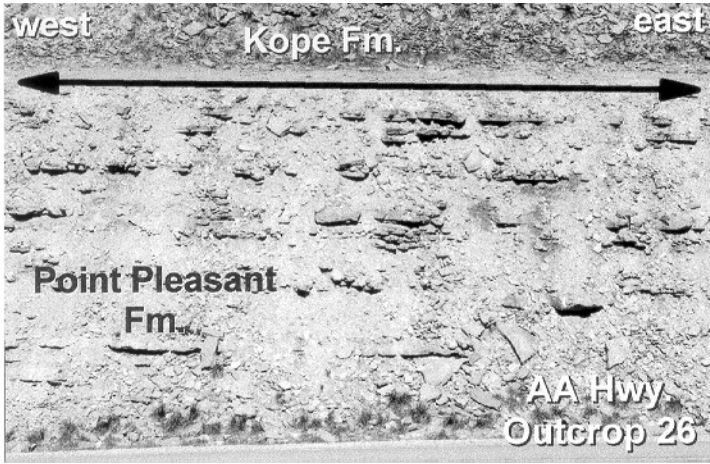


**FIGURE 9.** AA Highway Outcrop 25. (A) Center part of north side of highway; (B) East end of north side of highway. Photo B shows better the development of the lower Brent beds, which are concealed in the covered interval above the first bench in Photo A.

28.6 KY Rte. 8; road to Foster

29.0 Kennon Road

29.6 **Outcrop 26 (Fig. 10):** Small outcrop on SW side of road in Point Pleasant Formation; contact with Kope Fm. at top

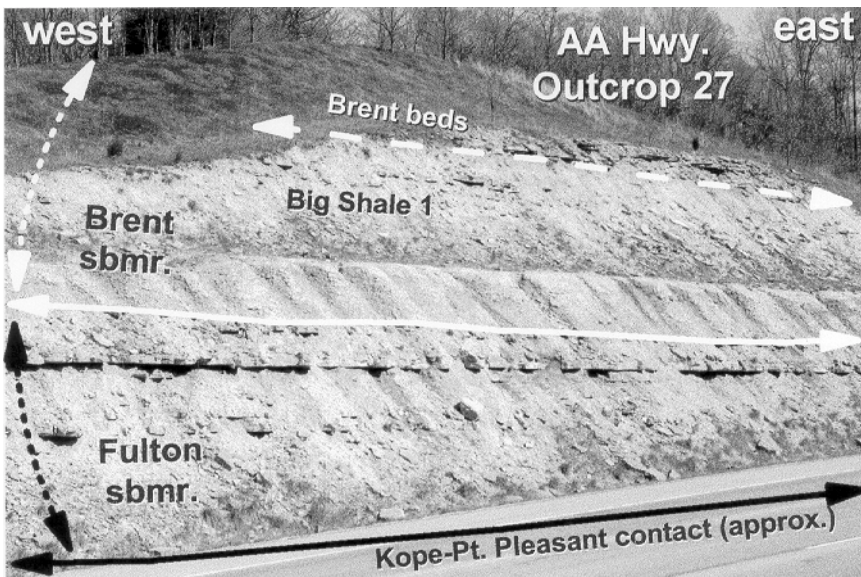


**Figure 10.** AA Highway Outcrop 26. Base of Kope Fm. and underlying Point Pleasant Fm. Note very dark gray shales at base of Kope (locally covered).

29.5 Holst Creek Road and Holst Creek bridge

29.6 **Outcrop 27, Lower Holst Creek (Figs. 11-12):** Roadcut on left side is in upper Point Pleasant-lower Kope formations; contact appears conformable. In the lowermost Kope, about ten thick crinoidal grainstones are present in lower 10 m of shale; these are rich in nautiloids and contain the crinoid *Merocrinus* and the trilobite *Cryptolithus*. At the level of the 1st bench, very large gutter casts occur in a siltstone bed; just above this, the outcrop becomes very shaly (Big Shale #1); thin siltstones exhibit excellent trace fossils and sedimentary structures. At the level of the 2nd bench are found beds with excellently developed *Kinneyia* structures; also present are “log jams” of *Ectenocrinus*; the outcrop culminates in a few thicker limestones apparently belonging to the Brent submember.

30.1 **Outcrop 28, Middle Holst Creek:** Large outcrop of middle Kope Fm.



**Figure 11.** AA Highway Outcrop 27. See STOP 1 description (next page).

### **STOP 1:** Lower Holst Creek (outcrop 27) on AA Highway (Rte. 546).

This outcrop provides an exposure of one of the lowest units of the Cincinnati Arch region (Fig. 12). Due to the presence of a small anticline (the Moscow-Carntown anticline; Potter, 1996), the Middle Ordovician Point Pleasant Ls. and its contact with the overlying Kope Formation are well exposed here. The Point Pleasant consists of medium- to thick-bedded crinoid, brachiopod, and bryozoan packstones and grainstones, alternating with fine-grained, pelletal grainstones or calcisiltites, and medium gray shales.

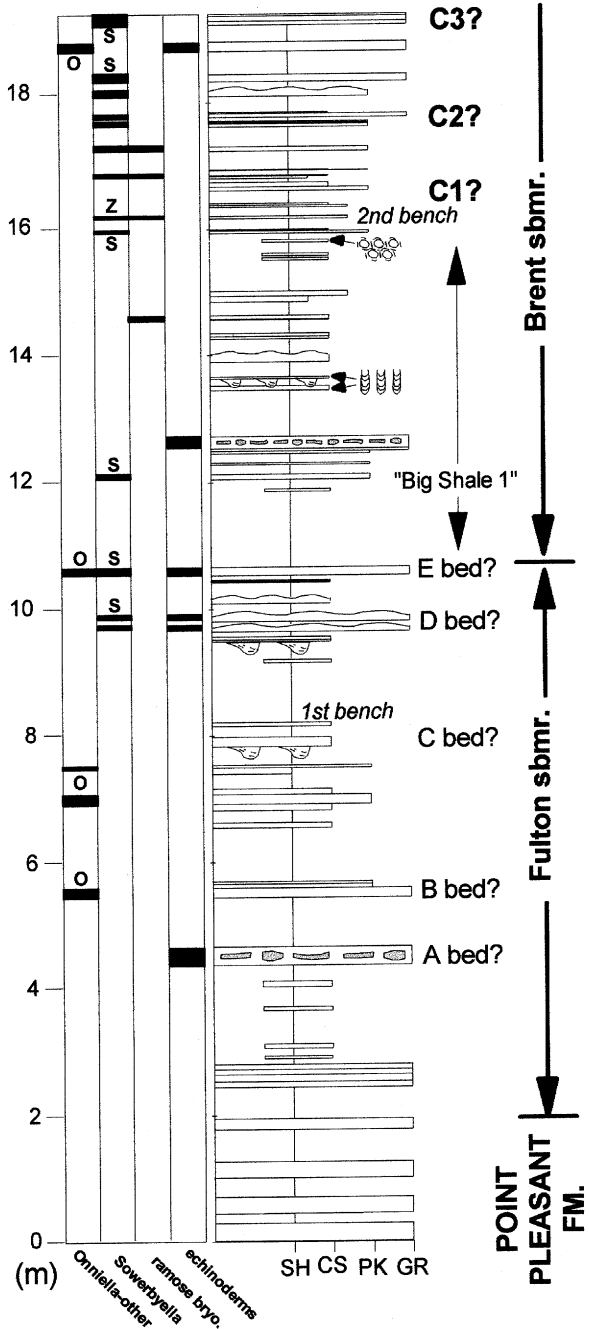
The contact with the overlying Kope Fm. appears interbedded and gradational at this locality, but it is drawn at the base of the first substantial (0.5 m) shale interval. The basal shale (base of Fulton submember) is relatively dark grey but is not the dark brownish gray shale which characterizes the basal Fulton beds farther to the northwest near Cincinnati. The Middle-Upper Ordovician boundary coincides approximately with this level, as does the base of the Cincinnati Series. The lower 4 meters of the Kope Formation consists of an alternation of shales and relatively massive crinoidal limestones (mainly grainstones). Certain unusual fossils are found in this interval including the rare cystoid "*Glyptocystites fultonensis*" and the crinoid *Merocrinus typus*. The brachiopod *Sowerbyella* and the trilobite *Cryptolithus* both make an appearance in these lower levels. Certain of the shales are rich in the gastropods and clams, as are the basal shale beds of several higher Kope submembers. The limestone ledges are strikingly set off from the underlying shales at sharp erosional boundaries and the beds contain large yellowish clasts of dolomitic mudstone, evidently eroded from the underlying beds. Above the highest major limestone, the upper 10 meters of Kope in this outcrop consists primarily of shale or mudstone with thin- to medium-bedded, planar to hummocky laminated calcisiltites or siltstone beds. This represents most of the thickness of the first major shale unit of the Kope and most of the Brent submember, as defined herein.

A small gully on the east end of this outcrop displays an interesting limestone bed near the top of the basal Kope (Fulton) interval; the top of this bed is cut by shale-filled scour channels. The sides of the larger channels have been extensively burrowed by epichnial tracemakers. These features may be comparable to large gutter casts that have been cut into the top of a limestone bed and infilled with shale. Approximately one meter above this horizon is a relatively thick hummocky cross-laminated calcisiltite bed with large (up to 20 cm across and 10 cm deep) gutter casts. The bed sole also shows excellent preservation of tool marks and trace fossils. This gutter cast horizon is readily traceable along the outcrop just below the first bench in the roadcut.

The second bench also shows some interesting features. Toward the top of the Brent shales are a series of thin siltstones, the upper surface of one of which shows a low-relief, pitted or furrowed topography identifiable as *Kinneyia*. These features are of enigmatic origin. Once considered a trace fossil, they are relatively common in some Proterozoic deposits and have therefore been interpreted as an inorganic structure. Pflieger (1999) inferred that *Kinneyia* are commonly associated with dysoxic conditions that might inhibit burrowing, and that these features developed as a result of expulsion of gas bubbles along the interface between a silt layer and an overlying bacterial mat. *Kinneyia* is commonly associated with millimeter-scale ripples, i.e., a series of parallel, slightly sinuous, furrows and ridges typically about three to five cm across. These are also present in the Kope Formation and may be observed at this location, where they occur penetratively through multiple laminae of calcisiltite beds. Both features have been considered as possible evidence of seismic shaking.

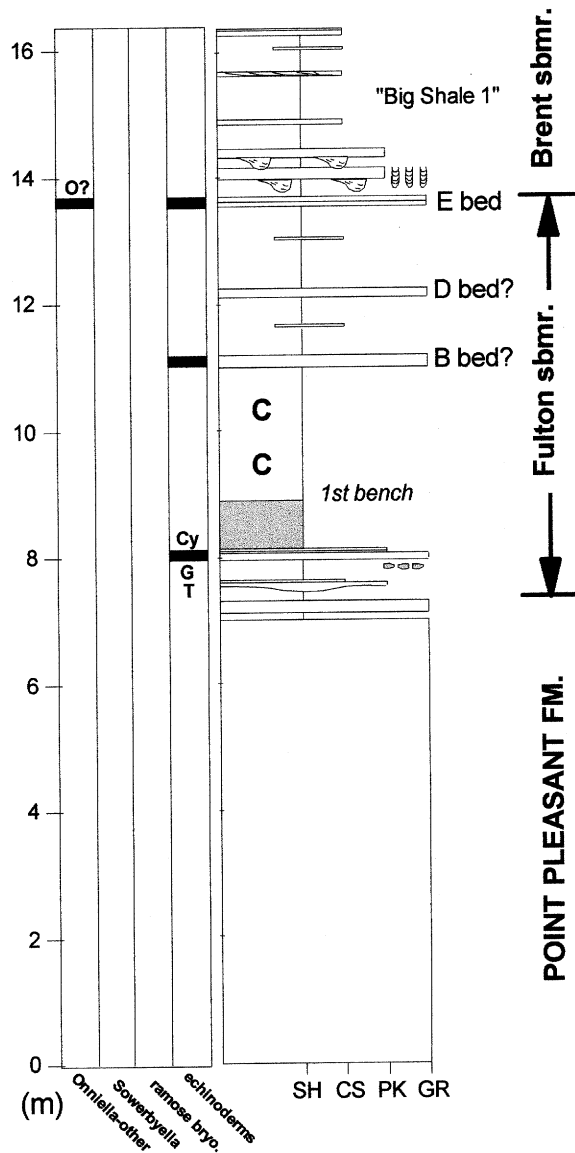
Another interesting feature present in the upper portion of the Holst Creek outcrop are "log-jams" of long crinoid stems, primarily of *Ectenocrinus*; clusters of parallel-oriented articulated crinoid stems sometimes with small crowns intact. These were obviously buried rapidly as they have been interpreted as the effect of mass mortality of uprooted crinoids and their orientation by basal work flowing gradient currents.

# AA Hwy. Outcrop 27

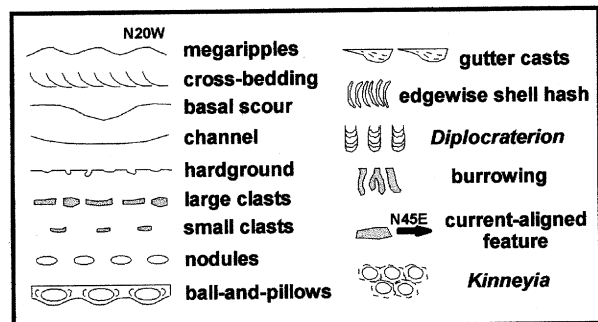


**Figure 12.** Measured section of AA Hwy. outcrop 27. Columns at left show dominant components of skeletal grainstones and packstones: O = *Onniella*, R=*Rafinesquina*, S=*Sowerbyella*, Z=*Zygospira* (cols. 1-2), ramosae bryozoans (col. 3), and echinoderms (col. 4). In stratigraphic column on right, column width represents lithology: SH=shale, CS=calcisiltite, PK=packstone, and GR=grainstone. Beds labeled per stratigraphic nomenclature of Brett and Algeo (see Table 1, p. 55, this volume). Beds inferred to be correlative with capping beds of cycles in Holland et al.'s Rte. 445 reference section (1997; this volume) are designed by "C" followed by the cycle number; uncertain cycle assignments are indicated by "?", and missing or covered cycle cap beds are enclosed in parentheses.

# Hwy. 1159 (Brooksville Turn)

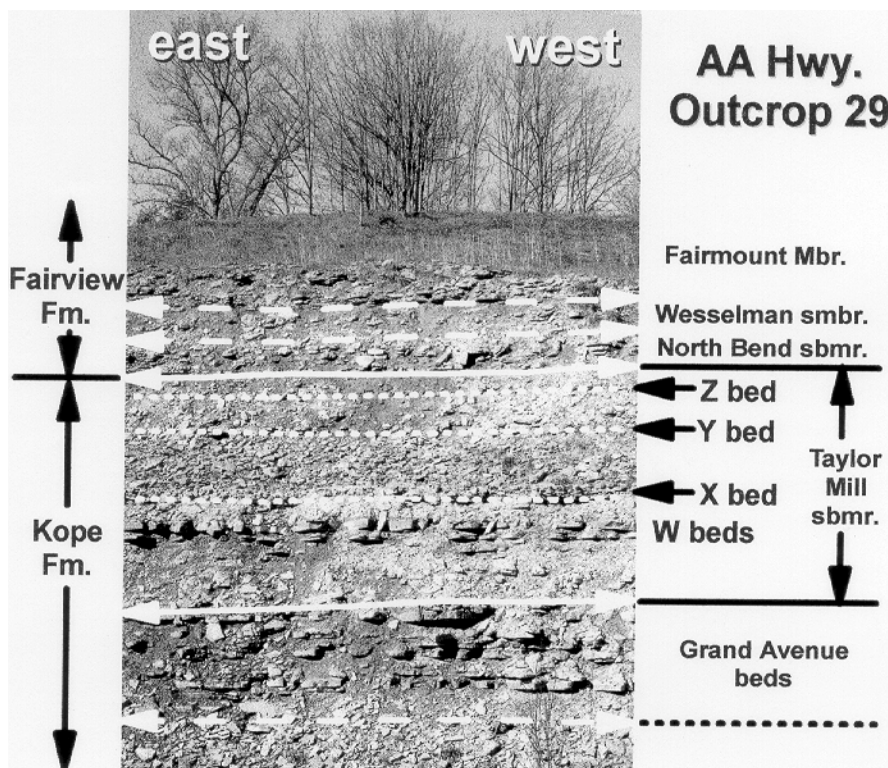


**Figure 19.** Measured section of Highway 1159 outcrop (Brooksville Turn).



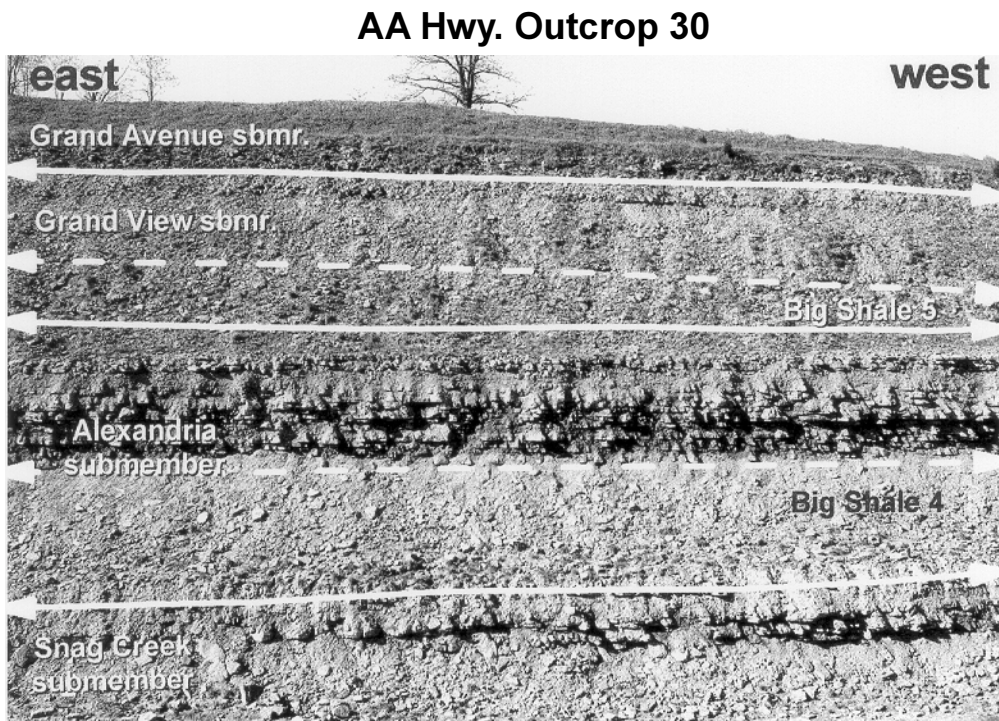
showing top of Snag Creek beds, with Big Shale #3 and upper limestones (beds 24a,b) near lower bench; Big Shale #4 and “red *Onniella* beds” of Alexandria submember are opposite the sign for KY Rte. 1019; upper part of roadcut is in Grand Avenue submember. The Snag Creek beds form a distinctive succession; note particularly the cluster of about five beds of limestone which underlie a relatively thick nearly pure shale interval. This same succession will be seen again in the upper Snag Creek submember at Snag Creek (outcrops 33 and 34; type locality of this submember).

- 30.4 **Outcrop 29A, Upper Holst Creek-A:** Roadcuts on NE side of road are in upper Kope Fm., including top of Grand Avenue submember and lower Taylor Mill submember of McMicken Member. Particularly notable is a succession of beds immediately below the Kope-Fairview contact that commence with a thick ledge of grainstone about 3 meters down and continue upward to a thick compact bundle of grainstones about 40 cm thick (Z bed) extremely rich in the brachiopod *Onniella*. This bed separated by a ~70 cm shale interval (“Two-Foot Shale”) from the overlying more compact limestone of the Fairview Formation. This contact approximates the Edenian-Maysvillian Stage boundary. This series of beds and the immediately overlying lower Fairview are readily traceable from this area to Cincinnati and will also be seen in the next outcrop (Rte. 3071) at Maysville.
- 30.5 **Outcrop 29B, Upper Holst Creek-B:** Roadcuts on main road on either side of junction with KY Rte. 1019 and extending northward along Rte. 1019; upper Kope Fm. and Kope-Fairview contact; Fairview exposures include lower compact, *Strophomena*-bearing limestones (North Bend submember) and shaley Wesselman submember of Mt. Hope Member. “Miller marker bed” and overlying Fairmount Member are in upper end of Rte. 1019 roadcut.
- 30.6 **Outcrop 29C, Upper Holst Creek-C (Fig. 13):** Large cuts on N side of AA highway just east of Rte. 1019 extend from Grand Avenue submember of Kope Fm. upward into Fairview Fm.



**FIGURE 13.** AA Highway Outcrop 29. Well exposed are the Grand Avenue beds (base of section) and Fairview Fm. limestones (top of section). In between, only the W beds of the Taylor Mill submember form a distinct ledge; other cycle caps are largely covered.

- 30.2-30.9 Willow Creek valley  
 31.0 **Outcrop 30, Willow Creek (Fig. 14):** Middle Kope Fm.  
 31.4 **Outcrop 31A, Eden Ridge West-A:** Fairview Formation  
 31.5 **Outcrop 31B, Eden Ridge West-B:** Kope-Fairview contact  
 31.6 Eden Ridge Road  
 31.7 **Outcrop 32, Eden Ridge East:** Grand Avenue submember of Kope Fm.  
 32.4-32.6 **Outcrop 33, Snag Creek West (Fig. 15):** Large high roadcut beginning low in

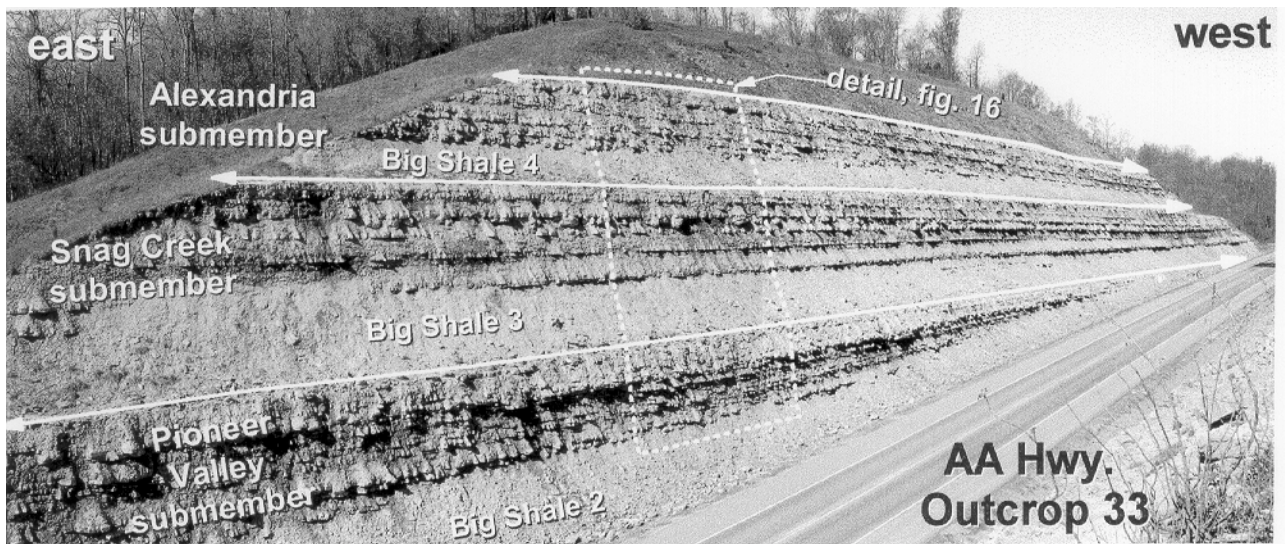


**Figure 14.** AA Highway Outcrop 30. Exposure on south side of highway of most of Southgate Member to lower Grand Avenue submember of McMicken Member. Benches at levels of “Big Shales” 4 and 5. The Alexandria beds are well-exposed and will be seen again at their type locality at Snag Creek (outcrops 33 and 34).

Kope Fm.; possibly Brent beds in ditch; bench on upper thick limestone beds of Pioneer Valley submember; thick Big Shale #3 and upper Snag Creek limestone beds high in vertical face (type section, along with Outcrop 34). A unique feature of this exposure is the presence of a zone of ball-and-pillow deformation within the limestone bundle of the upper Snag Creek submember (**Fig. 16**); this deformation does not appear at the same stratigraphic level in the Snag Creek East section (Outcrop 34).

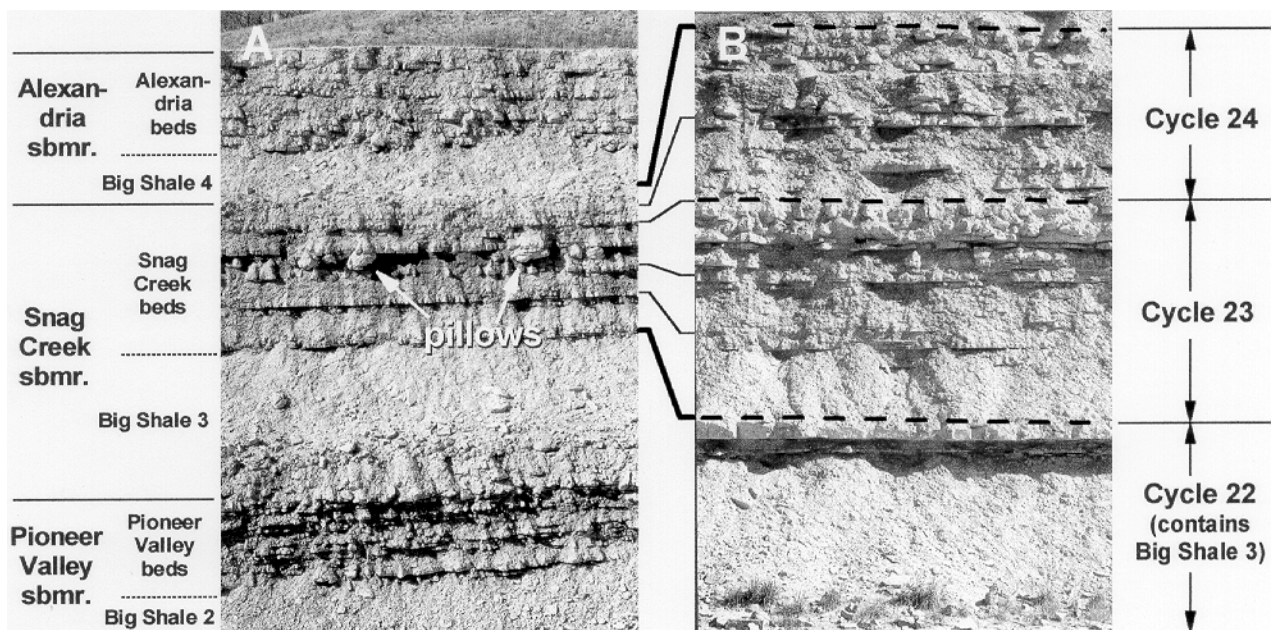
- 32.7 Snag Creek Road and bridge over creek  
 32.9-33.1 **Outcrop 34, Snag Creek East (Figs. 17-18)**

**STOP 2:** Excellent outcrop of middle Kope Fm. from top of Pioneer Valley beds through Grand Avenue submember. A bed of edgewise *Rafinesquina* shells occurs at the top of the Pioneer Valley submember; ca. 150 cm higher (in Big Shale #3 but below bench) is a bed rich in *Flexicalymene* trilobites. The Snag Creek submember is well exposed (type section, along with Outcrop 33); note that no pillows or deformed beds are present here.

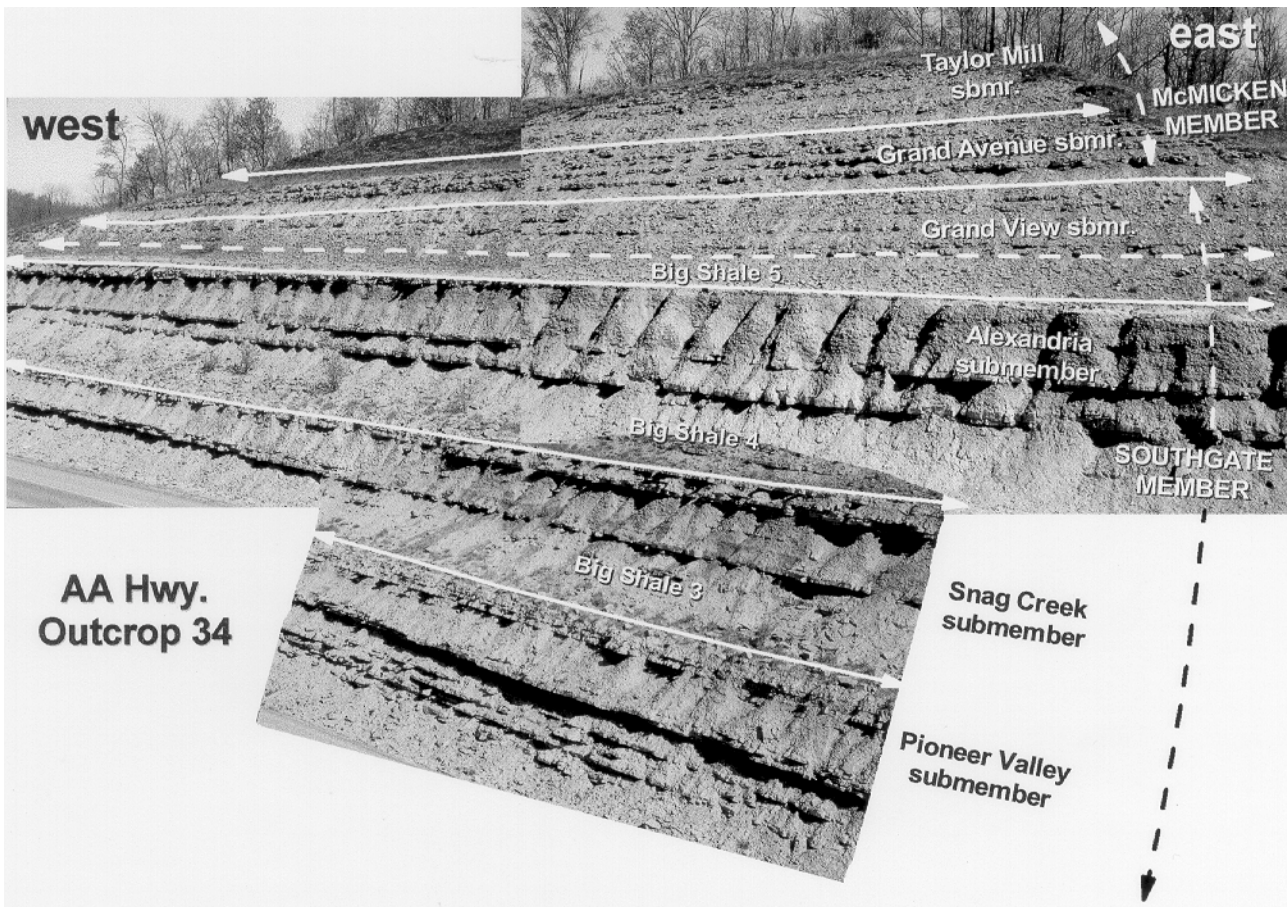


**FIGURE 15.** AA Highway Outcrop 33. Exposure of Pioneer Valley through Alexandria submembers; type locale of Snag Creek submember of Southgate Member. Excellent development of both decameter- and meter-scale cyclicality (detail below). Note differences in bundling patterns of limestone beds in the upper portions of each dm-scale cycle; such differences are useful in “fingerprinting” individual submembers.

### Detail of AA Hwy. Outcrop 33



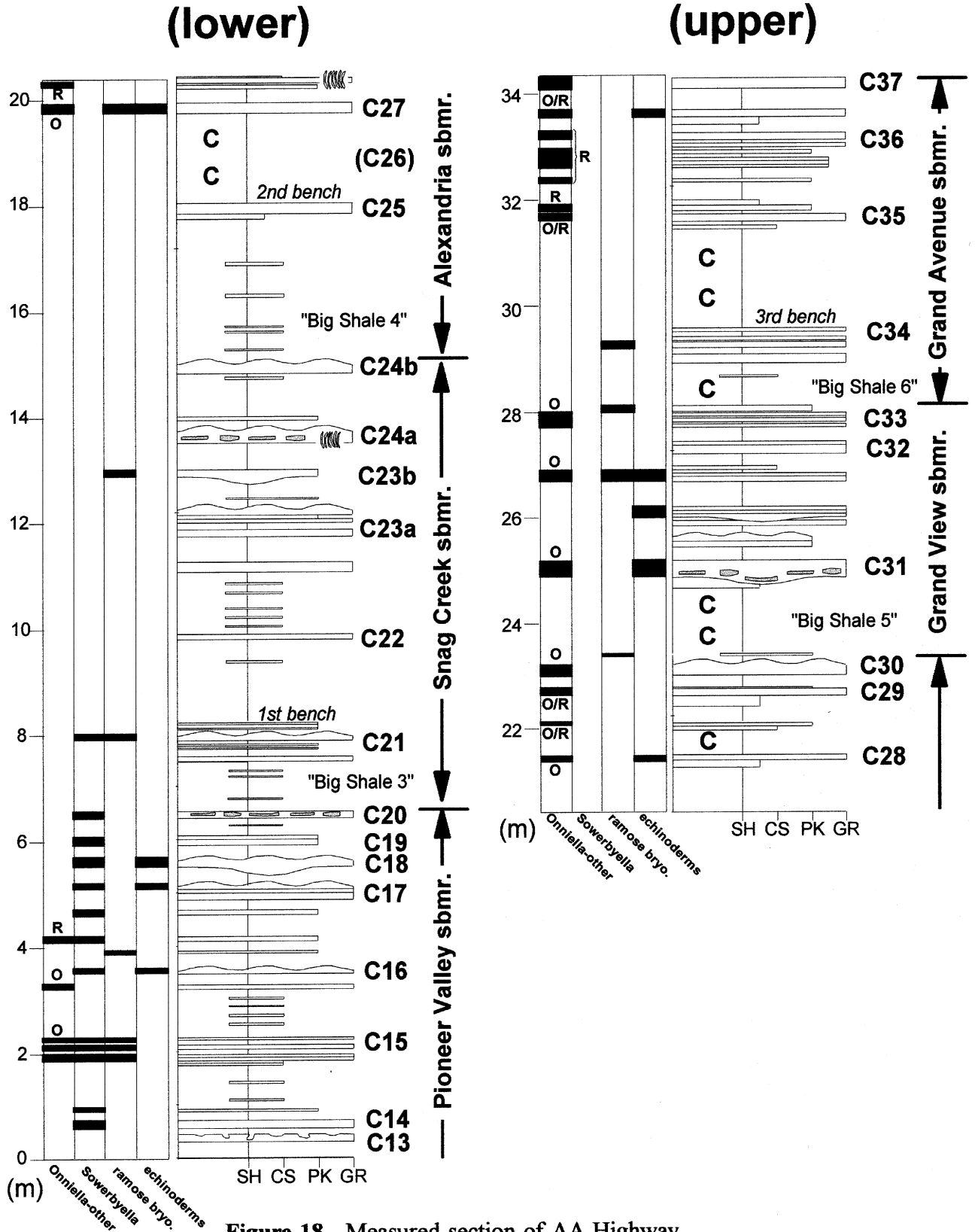
**FIGURE 16.** Detail of AA Highway Outcrop 33. (A) Three dm-scale cycles, each corresponding to a submember of the Kope Fm.; note pillows in upper Snag Creek beds; location of photo is shown in Fig. 15. (B) A close-up of the Snag Creek submember showing meter-scale cyclicality; note amalgamation of limestone beds toward top of each cycle. This photo is not an enlargement of photo A but was taken further west on same outcrop.



**FIGURE 17.** AA Highway Outcrop 34. Exposure of Pioneer Valley through Taylor Mill submembers (upper two-thirds of Kope Fm.); type locality of Snag Creek submember. Note: the lower part of this composite photo was taken at west end of outcrop (to left in photo) and was spliced with a view of the central part of the outcrop in order to show the full stratigraphic range present.

- 33.7 KY Rte. 1109; "Park and Pool" parking lot  
 33.8 **Outcrop 35A, Johnsville West:** Fairview Fm.; very tightly stacked limestones; base of section near Kope-Fairview contact  
 34.0 **Outcrop 35B, Johnsville East:** Upper Kope Fm., Taylor Mill submember; lower portion atypically silty; road heading sharply downhill  
 35.0 **Outcrop 36, Big Run West:** Rubbly exposure of middle Kope Fm.; Pioneer Valley limestones overlain by Big Shale #3 at base of Snag Creek submember  
 35.2 **Outcrop 37, Big Run East:** Upper part of middle Kope Fm.; Alexandria submember with Big Shale #5 and Grand View submember at top  
 35.7 Hilton Lane  
 35.75 **Outcrop 38A, Hilton Lane West:** Poor exposure of Fairview Fm.  
 35.9 **Outcrop 38B, Hilton Lane East:** Rubbly outcrop beginning in Fairview and continuing down long grade to Big Shale #4 of Alexandria submember of Kope Fm. at lower end  
 36.7 Salem Ridge Road; (optional) turn left here for a spectacular section of Point Pleasant Ls. with deformed beds in the floor of Locust Creek (see DeJong and Dietach, this volume). The same disturbed zone will be seen at the Brooksville Turn (junction with Rte. 1159) roadcut on this fieldtrip.

# AA Hwy. Outcrop 34



**Figure 18.** Measured section of AA Highway outcrop 34 (Snag Creek East). See p. 12 for general legend to stratigraphic sections.

- 36.75 **Outcrop 39, Salem Ridge:** Rubbly outcrop of upper Point Pleasant and lower Kope formations; comparable to outcrop 27 at Holst Creek
- 37.0 KY Rte 1159; to Brooksville
- 37.05 **Outcrop 40, Brooksville Turn (Rte. 1159 junction)**
- STOP 3:** Exposures along south side of Rte. 1159 just west of junction with AA Highway (Fig. 19, p. 12). This somewhat weathered road cut shows upper Point Pleasant limestones (about 7 m) and the lower Kope, Fulton submember. Note strongly deformed interval in Point Pleasant fine-grained grainstone beds near the base of the outcrop; folded and thrust calcisiltite beds sharply and discordantly overlain by skeletal grainstone bed. This 1.5 m interval is discussed in detail by DeJong et al. (this volume).
- The bench at the top of the exposure shows the Point Pleasant-Kope. Certain unusual fossils are found in this basal 1-m interval, including the rare cystoid "*Glyptocystites*" *fultonensis* and the crinoid *Merocrinus typus*. The brachiopod *Sowerbyella* and the trilobite *Cryptolithus* both make an appearance in these lower levels. Certain of the shales are rich in gastropods and clams, as are the basal shale beds of several higher Kope submembers.
- 37.5 Note small exposures of Pt. Pleasant Ls. along creek near road
- 37.8 **Outcrop 41:** Poor exposures of middle Kope; Pioneer Valley limestones
- 38.5 KY Rte. 875
- 40.1-40.3 **Outcrop 42:** Series of poor exposures, upper Fairview
- 40.6 **Outcrop 43, Turtle Creek West:** Rubbly exposures of Fairview
- 41.1-41.3 **Outcrop 44, Turtle Creek East:** Good exposure of Kope-Fairview contact
- 41.7 Route 19; Brooksville-Augusta Road
- 42.2 Shady Lane
- 42.3 **Outcrop 45, Shady Lane:** Kope-Fairview contact and upper Taylor Mill beds
- 42.7 **Outcrop 46:** Small exposure of upper Kope; Taylor Mill submember
- 43.0-43.1 **Outcrop 47:** Good exposure of Fairview Formation
- 43.5 Route 2370; Germantown
- 43.9 **Outcrop 48, Germantown:** Upper Fairview (Fairmount Member) with ball-and-pillow bed (seismite) in siltstone; on both sides of road
- 44.1 Hook-Gillespie Road
- 44.5 Hook Lane
- 45.1 **Outcrop 49, Hook Lane West:** Largely covered outcrop of Fairview
- 45.5 **Outcrop 50, Hook Lane East:** Good exposure of upper Kope (Taylor Mill submember) and lower Fairview
- 45.6 Unnamed road
- 46.1 **Outcrop 51, Bracken Creek:** Large cut in Fairview Formation
- 46.6 **Outcrop 52:** Small exposure of upper Kope
- 47.4 Mason County line
- 49.7 Route 435
- 50.1 **Outcrop 53:** Small exposure of Fairview-Bellevue interval
- 50.4 **Outcrop 54:** Small exposure of Fairview-Bellevue interval
- 50.7 Route 10
- 51.3 Route 3056; Highland Heights
- 51.8-52.0 Large silo (water tank?) on left followed by Marathon truck stop on right
- 54.0 **Outcrop 55:** Small, low exposure of Grant Lake Formation
- 54.3 Junct. with KY Rte. 3071 on left; side trip on Rte. 3071 leads to large new cuts in Kope, Fairview, Bellevue, and Grant Lake formations; also visible in roadcuts are faults and possible seismites (for **STOP 4**, see **Road Log Supplement 1**, p. 22)
- 54.3 **Outcrop 56:** Small, low cut in Grant Lake Formation

- 55.3 Industrial park
- 55.6-55.7 **Outcrop 57:** Cut in Grant Lake
- 56.1 **Outcrop 58, Blue Lick Road:** Exposures of Grant Lake Formation
- 56.4 K-Mart Plaza on right; possible rest stop
- 56.6 US Hwy. 62/68 intersection
- 57.3-57.5 **Outcrop 59:** Large low cut in Grant Lake
- 58.0 **Outcrop 60:** Small exposures of Grant Lake; junct. with KY Rte. 1448
- 58.3 **Outcrop 61:** Small exposures of Grant Lake
- 58.9 **Outcrop 62:**
- 59.0 **Outcrop 63:** Low cuts in lower Bull Fork Fm.
- 59.1 **Outcrop 64:** Low cuts in Bull Fork Fm.
- 59.5 Rte. 11/1448 junction; cuts in Bull Fork Formation; excellent exposures of possible seismites in Fairview Fm. on Rte. 11; for side trip including **STOP 5**, see **Road Log Supplement 2**, p. 26.
- 59.8 **Outcrop 65:** series of cuts in Grant Lake Fm.; KY Rte. 1448
- 60.6 KY Rte. 3313
- 61.6 **Outcrop 66:** Large cut in calcareous gray shales and thin limestones of Bull Fork Formation (= Waynesville Formation)
- 61.9 **Outcrop 67:** Low cuts in rubbly limestone of Bull Fork Formation, which yields abundant and diverse Richmondian fossils, including rugose corals
- 62.6 Mason County Line
- 63.1 **Outcrop 68:** Large, low rubbly exposures on south side of road; shaly nodular limestone is probably equivalent to the Arnheim Formation in Ohio; it yields a diverse brachiopod and bryozoan fauna; a bed of rugose corals is present
- 63.3 **Outcrop 69A:** Small outcrop in Bull Fork Fm.; KY Rte. 1449
- 63.7 **Outcrop 69B:** Small outcrop in Bull Fork Fm.
- 64.1 Marathon Station on right; view of Muldraughs Hill and the Allegheny Plateau escarpment in distance; the hills are underlain by Mississippian sandstones
- 66.5 KY Rte. 1234/1237 south; Rectorville
- 67.7 **Outcrop 71:** Exposure of bluish gray shales of Drakes Formation (near top of Richmond Group)
- 67.9 KY Rte. 1234 north; Lewis County Line
- 68.0 **Outcrop 71:** Exposure of orange weathering limestone ledges and shales in upper part of Silurian Brassfield Formation
- 69.8 KY Rte. 57; BP gas station
- 72.6 **Outcrop 72:** Exposure of cherty Brassfield (Lower Silurian) unconformably overlying greenish gray to reddish Preachersville Member of Drakes Formation (Upper Ordovician, Richmondian)

### **STOP 6: TOLLESBORO CUT (just west of Cabin Creek bridge)**

This cut provides an excellent view of the top of the Ordovician System and base of the Silurian System. Here green- to maroon-colored bioturbated mudstones of the Preachersville member of the Drakes Formation are sharply overlain by cherty orange-buff-weathering dolostones of the lower Silurian (Llandoverly) Brassfield Dolostone.

The upper Preachersville Member yields a number of marine indicators, including gutter casts and well-preserved trace fossils (*Diplocraterion*). Some beds show bedding planes covered with current-aligned small twig-like bryozoans (*Helopora*); bivalves and small brachiopods are also present.

The reddish bed may be an oxidized paleosol developed on the marine sediments. The uppermost beds below the unconformity are greenish and may have been leached by reducing fluids. The Cherokee Unconformity surface is not exposed here (although it is well displayed at a roadcut on Rte. 10 near Cabin Creek, a few miles from here).

The basal member of the Brassfield Dolostone is somewhat thinner bedded and more

argillaceous than the overlying massive cherty wackestones; it has been identified as the Belfast Member, although it may not correlate precisely with that unit. The uppermost beds are massive dolostones that are rich in whitish chert nodules concentrated in beds or bands. This interval is notable for its coral, brachiopod, and bryozoan fauna.

- 73.0      **Outcrop 73:** Exposure of Brassfield-Preachersville contact  
 73.6      Ribolt Road, Rte. 10: good exposures of Brassfield-Preachersville contact on Rte. 10 past Cabin Creek  
 75.3      **Outcrop 74A, Herron Hill West**  
 75.8      **Outcrops 74B-C, Herron Hill Middle:** Exposures of Bisher Dolostone overlain sharply by Upper Devonian shales at junction with Poplar Flat Road  
 76.0      **Outcrop 74D, Herron Hill East:** Near the southeastern (downhill) end of the Herron Hill exposure, the greenish gray shale and thin siltstones of the Estill Member (Crab Orchard Formation; upper Llandovery) are sharply overlain by sandy dolostones of the Bisher Dolostone (lower Wenlock). Buff-weathered silty crinoidal dolostones at the base of Bisher sharply overlies hummocky cross-stratified dolomitic siltstones of the upper Estill, representing a major sequence boundary. The lower meter of punky weathering Bisher is very rich in molds of large trilobites, including large *Dalmanites* and an unidentified lichiid. Higher portions of the Bisher are inaccessible but a disconformity is evident about midway through this formation, and irregular masses are present in the overlying upper unit of the Bisher. Note the sharp, irregular upper contact of the Bisher with the overlying Upper Devonian shales; this is Sloss's Kaskaskia unconformity. The Bisher shows extensive rust staining from weathering of pyrite in the Devonian shales.  
 79.0      **Outcrop 75:** Estill-Bisher contact on hillside to left  
 89.6      KY Rte. 989  
 80.0-80.1 **Outcrop 76, Charters Roadcut**

### **STOP 7: CHARTERS ROADCUT**

This high roadcut is one of the best sections of the Lower Silurian Estill Shale Member of the Crab Orchard Formation; the maroon to greenish gray clay shale facies here resembles the coeval (upper Llandovery) Rose Hill Formation of the Appalachian Basin. About 10 m of Estill Shale is exposed here; the lower half is gray to maroon and displays a very subtle, slightly angular discordance with the overlying gray beds; this may be a regionally important sequence boundary. The upper unit shows thin dolomitic siltstones with excellent trace fossils (*Rusophycus*, *Diplocraterion*), and sole features including gutter casts. Thin brachiopod, bivalve, and bryozoan pavements are found on the soles of some siltstones. The overall appearance of this facies is similar to shaly portions of the Kope Formation, although the fauna is much more depauperate. A microfauna, including pyritic steinkerns of ostracodes and small molluscs has been described from this locality by Mason et al. (1992).

A 2-m-thick bundle of medium- to thick-bedded dolomitic siltstones occurs below the upper bench in the outcrop. These beds are overlain by more greenish gray shale and are considered to represent a lenticular siltstone body within the upper Estill Member (previously these were assigned to the Bisher; Mason et al., 1992, but they appear to be below the basal Bisher as identified in other outcrops).

Thin clay seams within this interval have been tentatively identified as K-bentonites. This package is sharply overlain by crinoidal packstones and grainstones, herein regarded as the base of the Bisher Formation. Note that the upper Estill siltstones were almost absent (only 20-30 cm thick) below the Bisher in the previous outcrop. We suggest that these dolomitic siltstones have been cut away at that location by erosion prior to Bisher deposition.

- 81.5 **Outcrop 77:** Orange-weathering Bisher Dolostone
- 82.5 **Outcrop 78:** Exposures on left; thin-bedded interval near base contains newly discovered thin K-bentonites
- 83.1 **Outcrop 79, Webster Cemetery:** This relatively small outcrop shows about 6.5 m of biostromal facies of the upper Bisher Dolostone; the basal 2 m are argillaceous, laminated dolostones and dolomitic shales. These are sharply overlain by slightly reddish gray, bioturbated dolostones with many horizons of corals (halysitids, cladoporids) and stromatoporoids; some of the stromatoporoids up to 40 cm across are overturned. Ettensohn et al. (1992) recognized six or seven meter-thick, sharply based, fining-upward cycles within the Bisher Dolostone here. These were interpreted as minor deepening upward cycles in a shallow nearshore lagoon.
- 86.5 *Turn Around and Return Westward on AA Highway (Rte. 546)*
- 94.0 Junction Poplar Flat Road; turn right, disembark and walk to upper end of outcrop in Bisher Formation; climb up onto upper contact of Bisher with overlying shale.

### **STOP 8: POPLAR FLAT ROAD, UPPER HERRON HILL**

This section displays the upper half of the Bisher Formation and its sharp contact with the overlying Upper Devonian shale. Near the base of this outcrop, note the wavy unconformity in the middle of the Bisher. This is overlain by about 8 m of irregularly bedded dolostone with lenses of greenish gray dolomitic shale. The rounded masses of rather structureless, unbedded dolostone have been regarded as collapse breccia. However, we suggest that they represent heavily dolomitized mud mounds or bioherms. Remnants of corals and crinoid debris are evident in some weathered areas.

Ascend to the top of the major ledge to examine the overlying Devonian shales. The upper contact of the Bisher is a sharp, gently undulating surface. The surface is locally impregnated with bituminous material. A thin (< 1 cm) pyritic lag deposit, rich in conodonts, locally mantles this surface. This bed contains conodonts of mixed zones but primarily of the Upper Devonian (Famennian) *rhomdoidea* Zone (Fuentes et al., this volume). Hence, the unconformity here spans some 30 million years; it represents a combination of the Walbridge and Taghanic unconformities.

The basal Devonian deposits, which are of Famennian age, are greenish gray shales about 65-70 cm thick. This has been called the Upper Olentangy Shale (Mason et al., 1992), but conodont biostratigraphy proves that this is a younger unit than the typical Olentangy (Fuentes et al., this volume). Alternating black and dark gray shales overlying this interval are largely covered; the upper portion of the cliff about 5 m above the unconformity is black, platy shale assigned to the Huron Member of the Ohio Shale.

*Return to vehicles and continue to Cincinnati, about 80 miles to northwest.*

**END OF TRIP**

## **RTE. 3071 LOOP (Road Log Supplement 1)**

### Total Mileage

- 0.0 Intersection of AA Highway and Rte. 3071
- 0.1-0.2 Low outcrop of Grant Lake Formation (Bellevue Ls.)
- 0.3 Mitsubishi Motors
- 0.5 Small exposure of Grant Lake limestones
- 0.7-0.9 Exposure of shaly Corryville Member of Grant Lake Fm.
- 1.1-1.2 Small outcrops of Bellevue Ls.
- 1.7-1.9 Large outcrops of Bellevue Ls., including sharp contact between shaly, siltstone-rich Fairview Fm. and thinner-bedded light gray Bellevue Ls.
- 2.0 Small outcrop in shaly upper Fairview Fm.
- 2.2-2.5 Large three-tiered outcrop in Fairview Formation; note following features:
  - 2.3 Upper Fairview deformed zone; ball and pillow structure
  - 2.35 Small thrust faults in Fairview appear to die out locally onto bedding planes
  - 2.5 Channel-like feature appears at the same horizon as deformed beds
- 2.6 Sign for Rte. 8
- 2.8 Bridge over large creek valley
- 2.85 Junction Rte. 3056 is at upper end of a huge new roadcut that extends from the middle Kope Fm. at its base upward to the Bellevue and Corryville members of the Grant Lake Fm. at its top
- 3.15 Bench on top of Grand Avenue submember of Kope Fm.
- 3.2 Grand Avenue submember; at Dover sign
- 3.3 Big Shale #5 (base of Grand View submember) seen just above benches
- 3.6 Sign for Maysville, Rte. 8 near base of section
- 3.8 Pull off on shoulder; disembark to examine middle Kope Fm. beds

### **STOP 4: ROADCUTS ON KY ROUTE 3071, MAYSVILLE, KY.**

These new roadcuts (late 1990s) provide an excellent and very fresh reference section of the upper half of the Kope Formation, the overlying Fairview and much of the Grant Lake Formation. Approximately 90 meters of section are exposed in this outcrop.

**STOP 4A. Lower Exposed Beds Along Route 3071 (Figs. 20-21):** Exposures at the lower end of this extended outcrop show the Snag Creek, Alexandria, and Grand View submembers of the middle Kope (Southgate Member). These units were previously examined along the AA Highway at Lower Holst Creek (Stop 1) and Snag Creek East (Stop 2). Through these intermediate outcrops, beds of the Southgate Member exposed along Rte. 3071 can be correlated with equivalents in the Cincinnati area.

Near the base of the outcrop, the upper boundary of the *Sowerbyella*-rich zone occurs in a 40-cm-thick grainstone at the top of Pioneer Valley submember. This is followed by a 1.5-m-thick shale-rich interval, corresponding to Big Shale #3, of the Snag Creek submember. The bundle of limestones overlying this shale form the top of the Snag Creek submember at about the level of the first bench. This is overlain by the thickest shale in the outcrop, Big Shale #4, at the base of the Alexandria submember. This shale is sharply overlain by the next cluster of limestones, which is rich in reddish *Onniella* grainstones and exhibits a characteristic spacing of layers that is traceable to the Cincinnati area; the top of this bundle occurs slightly above the second bench on the east side of the road. The next major shale interval (Big Shale #5) is generally obscured by talus; this forms the base of the Grand View submember, the top of which is identifiable as a “polka-dotted” bryozoan-rich limestone. Higher still, the closely packed thin limestones of the upper Grand Avenue submember form the top of the third bench on the east side.

*Return to vehicles; turn around and retrace route back south toward AA Highway.*

- 3.8 First bench on west side of Rte. 3071 is on top of Alexandria beds (above Big Shale #4)
- 4.0 Second platform on top of Grand Avenue submember
- 4.3 Sign for Rte. 3066
- 4.35 Third bench is developed on the top of Grand Avenue submember
- 4.4 Junction of Rte. 3056; upper end of large outcrop; pull off and park just before intersection

**Stop 4B. Upper Exposed Beds along Route 3071 (Figs. 20-21):** In the upper portion of the roadcut near the road level, the uppermost beds of the Kope are well exposed. Just below the Kope-Fairview contact (in the Taylor Mill submember of the Kope Fm.), note the compact, 50-cm-thick *Onniella*-rich Z bed, which forms the fourth bench near the upper end of the roadcut. This is overlain by about one meter of shale that corresponds with the last bed of the Kope Formation (“Two-Foot Shale”) seen elsewhere. At this level, there is an abrupt shift from the underlying shale- and siltstone-dominated Taylor Mill submember of the upper Kope to amalgamated grainstones of the Fairview Fm. Schumacher (1991) placed the base of the Fairview Fm. in this area at or near the base of the overlying compact limestone ledge which is rich in the brachiopod *Strophomena*. Holland (1998) also considered this to be the boundary between the first two sequences of the Cincinnati Series (C1 and C2). However, recently Holland et al. (this volume) argued that the sequence boundary should perhaps be placed higher, above the *Strophomena*-bearing limestone, at the position of incursion of supposedly shallower water faunas in the “Wesselman shaly tongue.” A case could also be made for placing a sequence boundary below the Z bed of the upper Kope. This *Onniella*-rich limestone shows a sharp base and an abrupt change to shallow compact limestone facies from the underlying shales. Fairview Formation beds are especially rich in the brachiopod *Strophomena*, which may represent the abrupt incursion of this species.

If time permits, following a brief examination of these beds we will ascend the southern end of the outcrop along the trail up to the sixth bench. At this location we may examine closely a series of thick siltstones and shales which locally display dramatic evidence of deformation (see Schumacher, this volume). On the opposite, or west, side of the roadcut a large channel-like structure is visible at this level. A series of four bands of siltstone each show ball-and-pillow deformation along the length of the outcrop, although the deformation is laterally discontinuous. These have been interpreted as seismites by Pope et al. (1997).

The seventh bench is just below the relatively sharp lower contact between shaly beds of the upper Fairview (possible Miamitown equivalent) and lighter gray, closely spaced, thin wavy packstone beds of the Bellevue Member of the Grant Lake Formation. About 30 cm below the contact is a distinctive, rusty weathering laminated siltstone with a channeled discontinuity surface along its top; this bed is extensively exposed along higher portions of the bench surface. Local pockets of shale filling hollows on this surface contain very abundant columns and crowns of the crinoid *Glyptocrinus decadatylus*. Basal Bellevue beds, immediately overlying this level, carry a series of hardgrounds with *Trypanites* borings and encrusting holdfasts of *Anomalocrinus*.

The next level of interest occurs about 150 cm below the eighth or second-to-last bench in this roadcut. The highest beds here are rubbly to wavy-bedded packstones and grainstones of the Bellevue Fm. Its basal contact with the Fairview Fm. is rather sharply defined and is located about 8 m above the highest seismites. These beds are full of well-preserved brachiopods, particularly *Platystrophia ponderosa* and *Hebertella*. A number of bedding planes within this interval also show evidence of early lithification as hardgrounds.

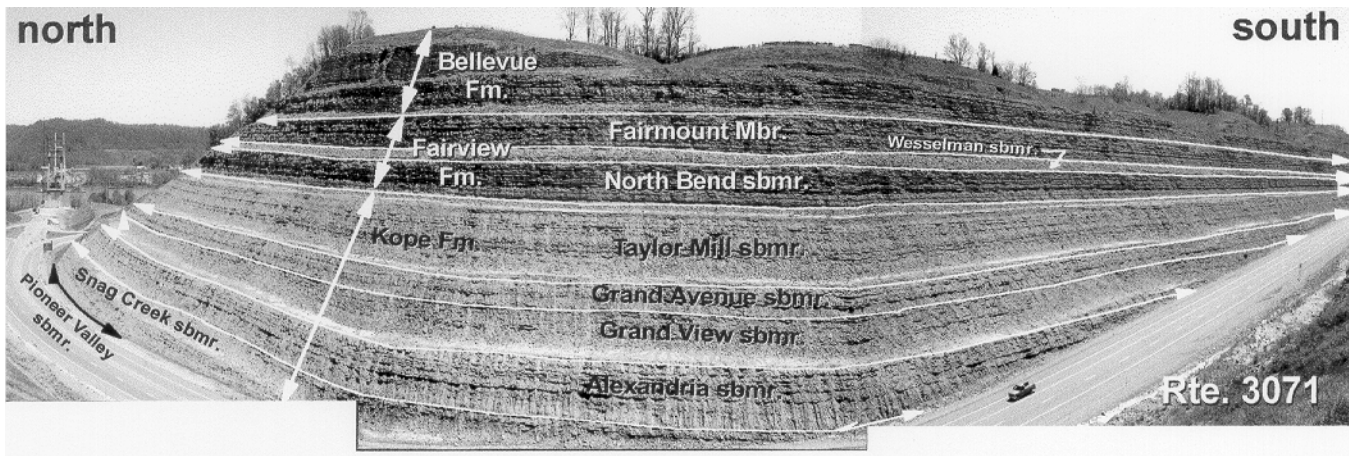
Proceeding upward, a small quarried area immediately below the uppermost bench in the outcrop was the site of excavation of a large (~5m<sup>2</sup>) hardground surface (see contribution

by Sumrall et al., this volume). This hardground was developed on the upper surface of relatively thin packstone beds rich in the brachiopod *Platystrophia ponderosa*. The surface itself was nearly planar with minor relief of a few millimeters. It is marked by large mounded colonies of bryozoans which are clearly cemented to the surface. Both the bryozoans and portions of the limestone surface itself had abundant encrusting edrioasteroids of four different species. Interestingly, the edrioasteroids occur in greatest density in elongate rows a few centimeters wide and up to a meter long; this pattern suggests that narrow portions of the surface were swept clean of mud coating and thereby were accessible to colonization by these crinoids. The hardground itself has been traced to all corners of this outcrop and in the nearby roadcuts potentially correlates also with the previously described hardground on a nearby railroad.

The uppermost beds exposed above the hardgrounds up to the distinct platform of the ninth bench are rubbly limestones. This bench is overlain by light gray, thin, wavy-bedded limestones of the upper Grant Lake Fm. (possible Corryville equivalent). Notable features include a mass of large domal bryozoans at a level of about 2 meters above the platform and a distinctive whitish-weathering amalgamated marker bed. Specimens of cyclocrinids (small ball-like green algal) have also been obtained from shaly beds slightly below this level.

*Return to vehicles and continue south on Rte. 3071*

- 4.6 Large Fairview outcrop with thrust fault(s)
- 4.8 Channelized siltstone bed with ball-and-pillow structure
- 5.0 Outcrop with Fairview-Bellevue contact
- 7.2 Junction of Rte. 3071 and AA Highway; **END OF RTE. 3071 LOOP**



**FIGURE 20.** Route 3071 outcrop, Maysville, Kentucky. View of section at northern end of highway, looking eastward. The lowest exposed beds, at road level on far left side of photo, are the upper Pioneer Valley beds; these are easily identified by the abundance of *Sowerbyella* contained therein. Overlying this is the full thickness of the Southgate and McMicken members of the Kope Formation, as well as the Fairview, Bellevue, and Grant Lake formations. The main seismite horizons are found in the upper Fairview Formation (Fairmount Member), but these are better seen on the west side of the highway than on the east side (shown here).

# Hwy. 3071, Maysville

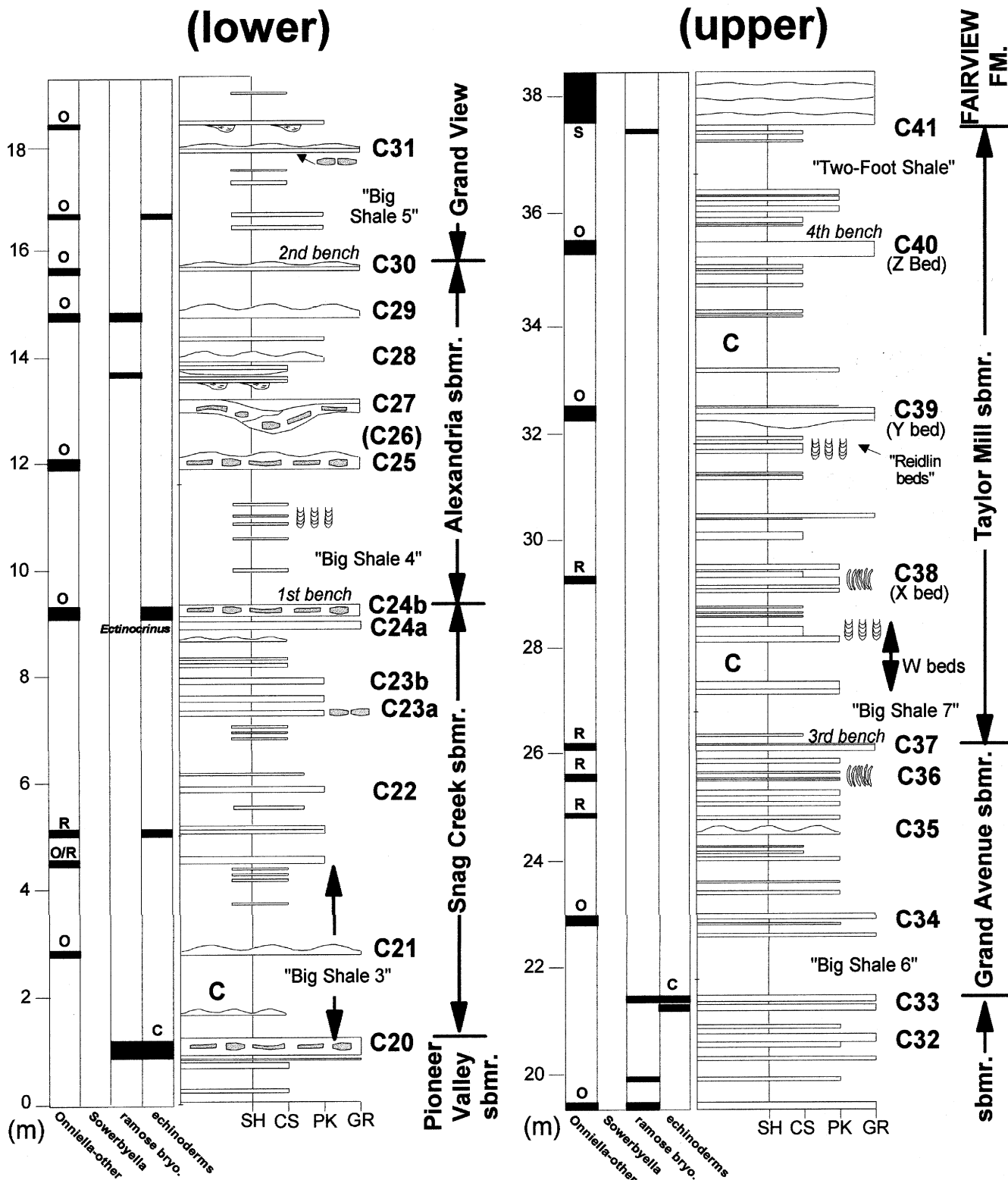


Figure 22. Measured section of Route 3071 outcrop, near Maysville, Kentucky. See p. 12 for general legend to stratigraphic sections.

## RTE. 11 LOOP (Road Log Supplement 2)

### Total Mileage

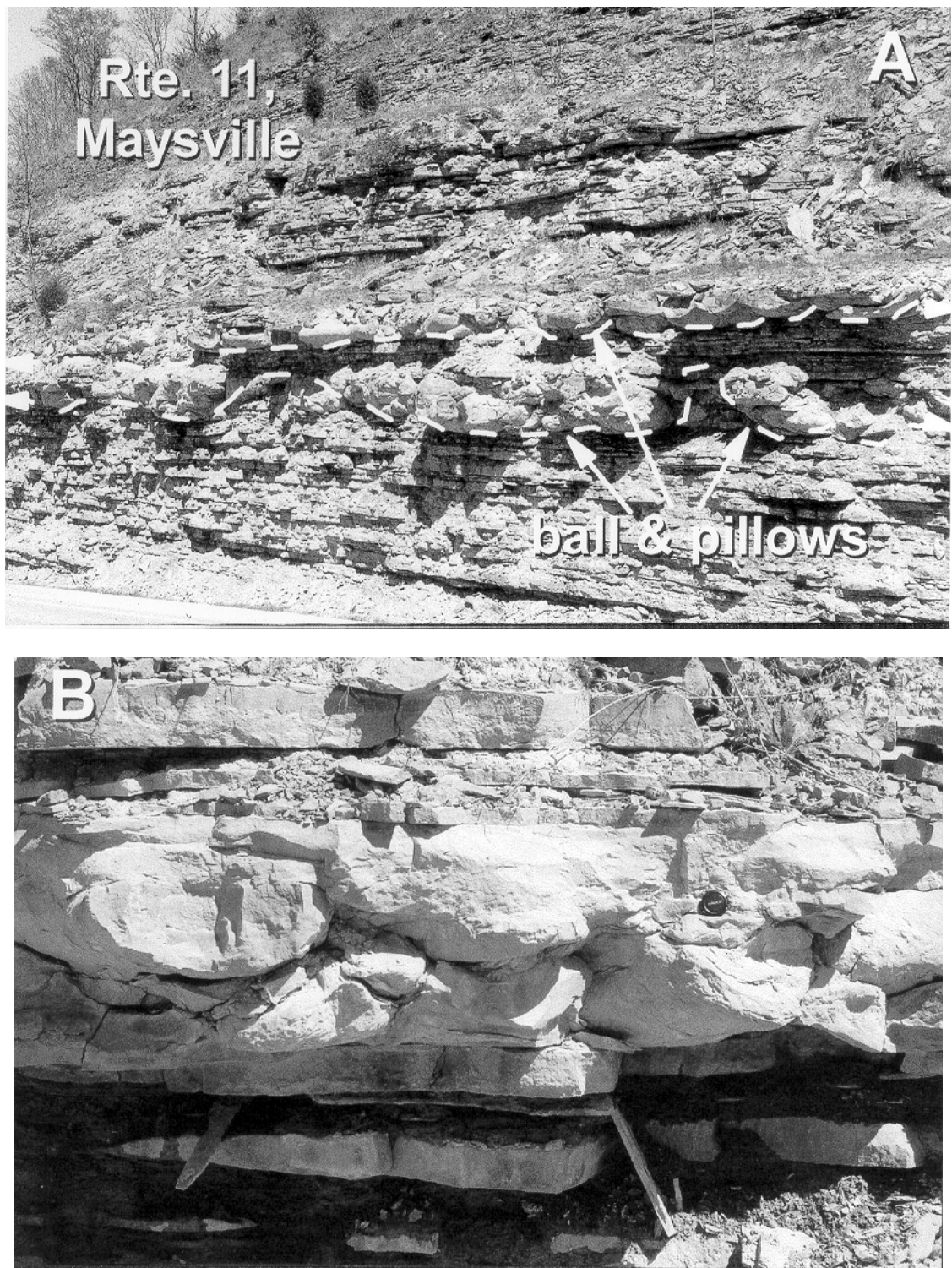
- 0.0 Rte. 11/1448 junction (for side trip, turn right); cuts in Bull Fork Formation
- 0.1 **KY Rte. 11 Outcrop A:** Fairview-Bellevue formation contact
- 0.7 **KY Rte. 11 Outcrop B:** Upper Fairview Fm.: note excellent development of ball-and-pillow deformation at three different horizons in the next 0.2 mi.
- 0.9 **KY Rte. 11 Outcrop C:** Base of Fairview and top of Kope (Taylor Mill submember of McMicken Member); *Diplocraterion*-burrowed siltstone in ditch
- 1.1 **KY Rte. 11 Outcrop D (Fig. 22):** Outcrop of Grand Avenue submember on west side with gutter cast-bearing siltstone near base of limestone bundle
- 1.6-2.1 Turn vehicles around and head back uphill on Rte. 11 toward junction with AA Highway
- 2.5 Small gravel road on right at break in guard rail; pull off and park just beyond (south of) this area. If time permits, we will walk to the older, weathered section of upper Fairview Fm.

### STOP 5: KY ROUTE 11 ROADCUTS, MAYSVILLE, KENTUCKY

This large cut was formerly the most important of the Maysville area, although it has been somewhat eclipsed by the new roadcuts of Route 3071 seen previously. At this locale is exposed the upper Kope Fm., including the Grand Avenue submember and the “Two-Foot Shale” at the top of the formation, as well as the basal Fairview Fm.

Especially noteworthy in this roadcut are the three deformed horizons seen also at the Maysville 3071 cut. These are beautifully weathered out not only on the main roadcut but also in the nearby excavation for a small side road. Here one may see in three dimensions the deformed surfaces and look at the topography of the basal surface of the deformed sediment masses. Note the sideviews of the deformation of laminae, the presence of large depressions that represent weathered-out flame structures, and a series of reticulate load cracks on basal surfaces. Loose blocks of siltstone permit views of the soles of pillows; note load cracks on bases of pillows and in a reworked clast derived from the deformed horizon. Along the old road, one may obtain an excellent view of the soles of these pillows on the base of an overhanging ledge. Also note the presence of a brachiopod rich grainstone which seems to truncate the deformed beds and therefore to postdate an event of deformation. From the top of the road, overlooking Rte. 11, is an excellent view of Outcrop D (above). Note that the ball-and-pillow structures in Outcrop D are grouped in three horizons that show lateral transitions to undeformed siltstone beds in a staggered pattern, i.e., the lowest bed transitions to undeformed beds farthest north, and each of the two higher beds transitions to undeformed beds further southward.

*Return to junction with AA Highway (Rte. 546)*



**FIGURE 22.** Rte. 11, Maysville, Kentucky. (A) Outcrop 11-D, showing ball-and-pillow structures developed in calcisiltites of the Upper Fairview Formation. Two deformed horizons are visible; together with a third, higher ball-and-pillow horizon, these exhibit a pattern of laterally offset zones of deformation that suggests a genetic relationship, e.g., via synchronous dewatering within an extended zone, perhaps accompanied by minor intraformational shearing. (B) Close-up of A.

# ROADLOG

## Sunday, October 10<sup>th</sup>, 1999

### Kope-Fairview Outcrops in the Greater Cincinnati Area, Northern Kentucky

*Note: Mileage begins at Kentucky State Line on I-471 bridge over Ohio River, Cincinnati, Ohio/Newport, Kentucky*

#### Total Mileage

- 0.0 I-471, southbound; bridge over Ohio River; enter Kentucky; view of Newport-Dayton-Ft. Thomas area ahead
- 0.3 South end of bridge; ascending south side of Ohio River Valley
- 0.4 Exit 4; Ft. Thomas
- 1.5 Exit 3 to Grand Avenue, Ft. Thomas; outcrops of Kope Fm. on left
- 1.6-2.0 Roadcut of Kope Formation with Grand Avenue submember at entrance ramp on right
- 2.7 Roadcut in upper Kope-Fairview formations on right
- 2.9 Exit 2 for US Rte. 27; Ft. Thomas, Kentucky; bear right onto exit ramp
- 3.15 Junction US Rte. 27; turn left at light and proceed under I-471 overpass
- 4.0 Junction KY Rte. 445 (Grand View Avenue) on left; turn left
- 4.2 Junction Rte. 1120, Ft. Thomas; turn left onto 1120-445
- 4.4 Junction Rte. 445 at light; turn right and follow 445 down the hill toward Ohio River
- 5.3 Pull off on right shoulder opposite upper end of large roadcut on Rte. 445 before junction with Rte. 8 along the Ohio River; note bridge for I-275 crossing the river just to the south of this junction

#### **STOP 1: ROUTE 445 ROADCUT, BRENT, KENTUCKY (FIG. 23)**

This outstanding roadcut exposes about 41 m of the lower to middle Kope Fm. on the north side of Rte. 445; the upper portion of this cut overlaps with sections exposed on adjacent I-275. Together these sections form a key composite reference section that has been studied extensively from the standpoint of graptolite biostratigraphy (Mitchell and Bergström, 1991). Recently this cut has been measured in considerable detail and divided into about 40 meter-scale cycles (Holland et al., 1997; this volume). It is also part of our Composite Reference Section for the Kope Fm. (see Fig. 5, p. 51-52, this volume).

Bundling of limestones and shales that may be interpreted as cyclicity is apparent at two scales: (1) the outcrop is divisible into four decameter-scale intervals, that correspond approximately to the four tiers in the roadcut. Each of these larger cycles, which are equivalent to the submembers of the Kope Fm. named by Brett and Algeo (this volume), commences with a thick shale-rich interval, and passes upward into a cluster of thicker limestone beds. These clusters show abrupt tops (about at the level of each bench in the outcrop). A more careful inspection of these clusters shows that they in turn are divisible into smaller, meter-scale packages of shales, calcisiltites and fossil-rich packstones and grainstones, which are the meter-scale cycles of Holland et al. (1997). The caps of these cycles are prominent, sharp-based limestone beds that form projecting ledges. Note that these smaller cycles appear to become more closely spaced toward the top of each decameter-scale cycle.



**FIGURE 23.** Photo of KY Rte. 445 outcrop (middle portion of Kope Fm.). Note decameter-scale alternations (cycles) of thick shales and bundles of ledge-forming limestones; height of outcrop ca. 35 m. Shown is the top of the Brent submember (base of photo) and the overlying Pioneer Valley submember (or “*Sower-byella* zone”; upper half of photo).

The base of this roadcut is within the middle Brent submember of the Economy Member and is estimated to be some 11 or 12 m above the base of the Kope. This interval can be examined in detail in the ditch at the base of the north (high) side of the cut. Particularly distinctive are three smaller bundles of ledge-forming limestones. Note the sparsely fossiliferous mudstones with thin siltstones and shell- and bryozoan-rich packstones. Observe also the concretionary beds that lie close below the major limestones (near the tops of putative cycles). These are overlain by limestone-rich intervals, each of which comprises two or three major grainstone beds (beds 5-8). Pairing of the major limestone ledges is distinctive and typical of this portion of the Kope. Limestone ledges show sharp, erosional bases and distinct, heavily burrowed tops that appear to be omission surfaces, possibly hardgrounds. Typical fossils include the brachiopods *Onniella* and *Sowerbyella*, and abundant small ramose bryozoans, fragments of *Cryptolithus* trilobites, and crinoidal debris. These assemblages are found in both the shales and the limestones, but are much more densely packed and typically more fragmented in the limestones. At the level of the first bench, an abrupt change to shales and siltstones is apparent.

Notice the thick siltstone beds with hummocky cross-lamination and sharp soles with tool marks and gutter casts. This is the base of the next decameter-scale cycle (the Pioneer Valley submember). “Log jam” clusters of articulated *Ectenocrinus* occur within these shales.

If time permits, climb carefully up the slope on the west end of the outcrop to view thick rusty-weathering limestones composed of intraclast-rich *Sowerbyella* grainstones (beds 16 and 18); these form the top of the Pioneer Valley submember, about 3 m above the second bench. Higher still are two thick shales capped by limestone bundles corresponding to the tops of the Snag Creek and Alexandria submembers (decameter-scale cycles) at the tops of the third and fourth benches, respectively. The shales above bed 20 are particularly rich in graptolites (commonly current aligned), and an important zonal boundary, i.e., the base of the *Geniculograptus pygmaeus* Zone, has been located above bed 24 (base of the Alexandria submember), about 33 m above the base of the outcrop.

*Return to vehicles and proceed ahead on Rte. 445 to the T-intersection with Rte. 8*

- 5.4 Junction with KY Rte. 8 (Mary Ingles Highway) along Ohio River; turn right and proceed south along the river
- 5.5 Pass under bridge of I-275

- 6.6 Junction with Rte. 1998 (Industrial Road) at yellow light; turn right and proceed up hill; Duck Creek to the left
- 7.0 Pull off and park along shoulder near yellow 45 mph sign; cautiously cross highway and walk down rip-rap embankment to shallow waterfall on Duck Creek

### **STOP 2A: LOWER DUCK CREEK**

Outcrops along Duck Creek are part of our new Composite Reference Section (see Fig. 5, p. 51-52, this volume) and provide the basal 12-13 m of the Kope Fm. missing in the Rte. 445 reference section (Stop 1). Lower Duck Creek permits a rare look at the lowermost part of the Kope Fm., the Fulton beds (or submember), and its contact with the underlying Point Pleasant Limestone. The uppermost ledge of the Point Pleasant is a 40-cm-thick crinoidal grainstone that forms the caprock of a small waterfall. The overlying Fulton beds consist of sparsely fossiliferous gray shale and argillaceous concretionary limestone. About 120 cm above the concretionary limestones are dark, brownish gray platy shales that contain abundant cranidia and some articulated individuals of the trilobite *Triarthrus becki*; this taxon is considered an indicator of dysoxic, probably deeper water, facies. The highest *Triarthrus* beds occur about 3.5 m above the base of the Kope Fm. These shales provide a marker horizon that can be correlated with beds in coeval “Utica Shale”-type facies to the north in the Sebree Trough and Taconic foreland basins. Oddly, these shales are interbedded with crinoidal grainstones composed of *Merocrinus* columnals. About 4.4 m above the base of the Kope, the highest grainstone ledge is overlain by olive gray “barren” shales and platy to flaggy siltstones of the lower Brent submember that extend upward for about 8 m. This interval is sparsely fossiliferous, although abundant trace fossils occur on the soles of some beds.

*Return to vehicles and proceed uphill on Rte. 1998*

- 7.2 Pull off on berm just before passing culvert of Duck Creek under road; cross highway and go down embankment to creek

### **STOP 2B: UPPER DUCK CREEK**

The creek bed and banks immediately below (downstream of) the culvert show the upper part of the Brent submember of the Kope Fm. A well-developed horizon of large gutter casts occurs in a bundle of siltstones about a meter above the creek bed; crinoidal grainstones found at the bank top (some 14 m above the base of the Kope) seem to represent cycle 3 of the KY Rte. 445 reference section (Holland et al., 1997; this volume) and provide a tie to that outcrop. This has enabled us to add the lowermost few meters of the Kope Formation to the Rte. 445 reference section to produce a complete Composite Reference Section for the Kope Formation in the Greater Cincinnati area.

*Return to vehicles and continue uphill on Rte. 1998*

- 8.2 Junction Winters Lane; proceed straight
- 8.75 Junction of US Rtes. 27 and 1998; turn right
- 9.0 Rte. 1998 turns right near plaza in Highland Heights, possible rest stop
- 9.8 I-471 begins, US Rte. 27 continues to right; proceed straight onto I-471
- 10.4 Stay left on I-471 at fork for I-275 East
- 10.6 Exit for I-275 west (toward airport); bear left onto ramp
- 10.9 Merge onto I-275
- 11.5 Good exposure of upper Kope Formation
- 12.1 Exposure of Fairview Formation

- 13.0 Entering Licking River Valley; nice view of Cincinnati to the north
- 13.5 Bridge over Licking River
- 14.2 Exit for KY Rte. 16; Taylor Mill Road; continue on I-275; note excellent exposures of upper Fairview Formation
- 14.7 Exposures of Bellevue Member; thin bedded light gray limestones
- 15.1 Exposures of Fairview
- 15.9 Bridge over Bank Lick Creek
- 16.3 Exit 80 for KY Rte. 17; bear right onto exit ramp
- 16.3 Junction with Rte. 17; turn right
- 16.65 Junction with Dudley Pike; continue south on Rte. 17
- 17.1 Roadcut on right exposes lower Kope (Pioneer Valley submember); stay left
- 17.45 Junction with Rolling Hills Lane (White Castle distribution center); turn left
- 17.6 Junction with Lake Park Drive; turn left
- 17.8 PMI Food Processing Equipment Co. to right; turn right into driveway and pull around to large outcrop adjacent to truck parking area behind building

### **STOP 3A: PMI INDUSTRIAL PARK (Appendix A)**

This is a large and quite fresh outcrop in the lower to middle Kope; two sides of the hillslope have been scraped clean in a large amphitheater-like region. The cleanest exposures are in a small gully at the bend in the outcrop. Here the series of beds is very similar to that of the upper Brent submember seen at the base of the Rte. 445 reference section. Note particularly the three sets of paired beds with concretionary underbeds below them. These exhibit sharp erosive bases, contain intraclasts, and are capped by large ripples trending approximately E-W. Also examine the transition from the upper limestone bundle into the overlying thick shaly interval, which (as at Rte. 445) contains a bundle of siltstones. Dark phosphatic material at the top of the highest limestone beds may represent a maximum flooding surface. Higher on the slope are more weathered exposures of higher beds, especially beds 15, 16, and 18, at the top of the Pioneer Valley submember. Excellent weathered-out fossils litter the upper slope.

*Return to vehicles and proceed back to Lake Park Drive*

- 18.5 Junction with Lake Park Drive; turn left
- 18.8 Junction with Rolling Hills Drive at Kentucky Emissions Check station; turn left and park

### **STOP 3B: WHITE CASTLE DISTRIBUTION CENTER (Appendix A)**

Here again the hillslope has been bulldozed, giving excellent slope exposures; a trench has been dug recently to divert a small stream and provides clean exposures of middle Kope shales belonging to the Southgate Member, including Big Shale #2. Note the succession of thin packstones and siltstones; some finely preserved fossils have been obtained from this trench. Slightly higher, in the gully, a series of thick limestone ledges protrude. These are beds 15-18, seen also at Rte. 445. Bed 15 is a rippled packstone containing abundant re-worked concretions, some of which are bored and encrusted by bryozoans and crinoid holdfasts; this is the Newport Plaza hiatus concretion bed. A few centimeters above this ledge, mudstones yielded a cluster of excellently preserved *Flexicalymene*, *Ceraurus*, and *Primaspis* trilobites; these were described by Hughes and Cooper (1999). The overlying beds are packstones composed largely of *Sowerbyella* brachiopods. The prominent ledges in the gully are the lower and upper "White Castle beds" (beds 16 and 18); they are rich in crinoid and *Sowerbyella* debris, and the base of bed 16 contains abundant nautiloids.

Higher exposures of the Southgate Member (Snag Creek submember) on the weathered slope exhibit a variety of interesting features, including sole-marked and burrowed orange-weathering siltstones. Near the base of the next higher bundle of three limestones (beds 23A-C) is another zone of reworked concretions, but these do not seem to be heavily encrusted. Overlying the uppermost limestone is a bryozoan-rich shale that contains numerous uncompressed gastropod and cephalopod shells. This is the well-known Carrollton gastropod bed, the presence of which in the Southgate Member of the Kope has long been noted. Thin beds full of crinoid columns and some crowns of *Ectenocrinus* occur at about this level. The highest limestones in the exposure are in the “red *Onniella* beds” of the Alexandria submember.

*Return to vehicles and turn around to exit from Rolling Hills Drive; head back to Rte. 17 and on toward the White Castle distribution center*

- 18.85 Junction with Rte. 17; turn right
- 19.2 Pass back by roadcut; note “White Castle beds” (beds 16-18) high in this outcrop; prepare to turn left
- 19.75 Stoplight at entrance ramp onto I-275; turn left onto entrance ramp
- 19.9 Note large Kope exposure in I-275 exit lane to left
- 20. Pass back over Bank Lick Creek and ascend hill
- 21.0 Exit for Taylor Mill Road, KY Rte. 16; turn right onto exit ramp, note excellent exposures of Fairview-Bellevue limestones
- 21.5 Junction with Rte. 16; turn left at light onto Taylor Mill Road
- 21.65 Avoid entrance ramp back onto I-275
- 21.7 Note panoramic view of Fairview exposures with evident cyclicity of limestone- and shale-rich intervals in proceeding down the long hill
- 22.0 Junction with Mason Road; turn right; note exposure of Kope-Fairview contact
- 22.2 Entrance to Soft Ball City ballpark on left; turn in and park without blocking entrance; proceed on foot back through outcrop on both sides of Mason/Reidlin Road

#### **STOP 4: MASON / REIDLIN ROAD (FIG. 24)**

This classic section shows the upper interval of the Kope Formation and the entirety of the Fairview Formation. Cyclicity in this section has been studied extensively by Jennette and Pryor (1993), while Diekmeyer (1998) made quantitative analyses of the fauna of these beds. Hence, this is one of the best-characterized Cincinnati sections. The large, canyon-like cut provides an excellent panorama of upper Edenian to Maysvillian strata.

The upper Kope (Taylor Mill submember; type locality) is quite shaly, but shows a series of thin limestone bundles at about 0.3, 3.0, and 5.5 m above the base of the exposure; these are the caps to cycles 38-40 of Holland et al. (1997) and the X, Y, and Z beds of Brett and Algeo (this volume). A prominent, thick siltstone-calcisiltite bed about 4 m above the base of the section shows very well preserved and large *Diplocraterion*. Note the flared corners of these U-shaped tubes; this interesting morphotype of *Diplocraterion* is common in the upper Kope Fm. and this bed, in particular, has been identified in several outcrops in the Cincinnati area (Jennette and Pryor, 1993). This bed and one other in the upper Kope also feature enigmatic millimeter ripples (see Brett and Algeo, this volume).

The upper “*Dalmanella*” bed (or Z bed) and overlying “Two-Foot Shale” are well developed here and somewhat more compact than at Maysville. The upper Taylor Mill beds are all recognizable in all local outcrops.

The overlying basal Fairview Formation, comprised of closely stacked bryozoan-rich packstone and grainstone beds and fossiliferous shales, is characterized by the brachiopod *Strophomena planumbona*. This 3-m-thick interval (the North Bend tongue of the Mt. Hope Member of the Fairview) has been referred to as the “non-cyclic interval,” although in fact Holland et al. (1997) recognized six small bundles of limestone within this zone that might be interpreted as thin (i.e., condensed) cycles.

Above the “non-cyclic interval” is a 3-m-thick, relatively shale rich interval that correlates with the Wesselman tongue of the “Kope Formation” identified north of Cincinnati. However, this shaly interval yields a diverse, shallow-water biota, including *Platystrophia* and abundant large bryozoan, that is more reminiscent of the Fairview than the Kope, and the base of this interval has recently been interpreted as a sequence boundary rather than a flooding surface (Holland et al., this volume).

The remainder of the Fairview is composed of interbedded shales and limestones grouped in distinctive 2- to 3-m-thick cyclic packages. The bases of these intervals consist of interbedded shales and lenticular wackestones and packstones, while the upper halves are more compact bundles of packstones and grainstones with much thinner shales as partings. These may be analogous to the decameter-scale cycles of the Kope Fm. (see Brett and Algeo, this volume).

The stratigraphically highest strata, exposed in the roadcut above the Ball Park drive, are in the upper shaly beds of the Fairview Fm. No deformed beds akin to those seen at Maysville are present, but beds of edgewise *Rafinesquina* shells are widely developed in the upper part of the Fairview Fm. and some have been traced regionally (Datillo, 1998). Might these represent a local response to seismic shaking of shell-rich sediments?

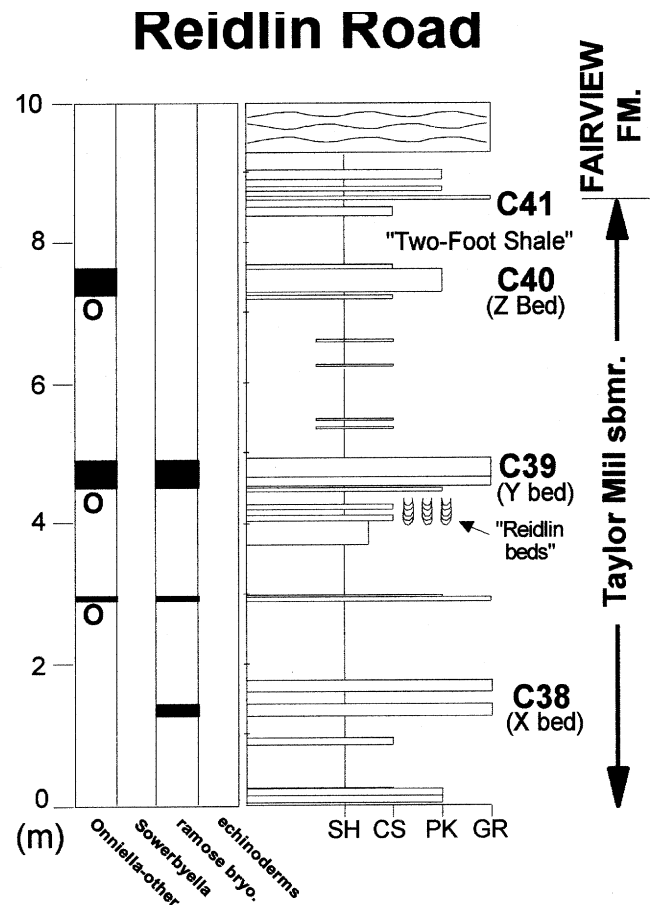
Near the top of the outcrop is a shaly zone that is rich in bivalves and gastropods; this may be equivalent to the upper Miamitown Shale further north. Again, there is clear-cut evidence for a north-dipping ramp in this area. This shaly interval is overlain by thin wavy-bedded limestones of the Bellevue Fm. Some beds in this portion of the outcrop contain hardgrounds encrusted by bryozoans and *Anomalocrinus* holdfasts.

*Return to vehicles; retrace route to Taylor Mill Road*

- 22.4 Taylor Mill Road; turn left
- 22.6 Near top of hill Fairview cuts
- 22.6 Junction I-275 east ramp; turn right
- 23.7 Kope-Fairview contact
- 24.2 Wilder Rte. 9 exit; Kope-Fairview contact
- Stay left at fork
- 26.7 Bear left at fork onto I-471-north
- 31.75 Bridge over Ohio River; re-enter Cincinnati, Ohio

**END OF FIELD TRIP**

**Figure 24.** Measured section of uppermost Kope Formation (Taylor Mill submember) and Kope-Fairview contact at Mason/Reidlin Road. See p. 12 for general legend to stratigraphic sections.



# SEQUENCE STRATIGRAPHY OF UPPER ORDOVICIAN AND LOWER SILURIAN STRATA OF THE CINCINNATI ARCH REGION

Carlton E. Brett and Thomas J. Algeo

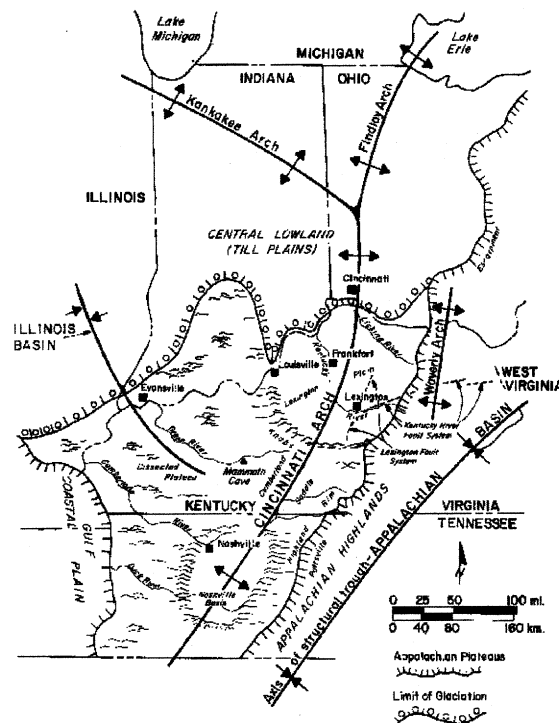
Department of Geology  
University of Cincinnati  
Cincinnati, Ohio 45221-0013

## INTRODUCTION

In recent years outcrop-based stratigraphic studies have undergone a paradigmatic shift from a primarily descriptive approach to a focus on understanding the architecture of sedimentary accumulations within a sequence stratigraphic context. This avenue of research has developed indirectly from seismic profiling of continental margin sediments and from the recognition of large, unconformity-bounded depositional wedges (“sequences”) in these profiles. Originally, sequences were defined very broadly as large intervals of strata bounded by very major unconformities (“first-” or “second-order” cycles recording tens of millions of years; see Vail et al., 1991), such as the six classic “super sequences” of Sloss (1963). Seismic stratigraphers were able to refine correlations and demonstrate that these large-scale unconformity-bounded packages are subdivisible into smaller intervals representing approximately 0.5 to 3 million years, typically termed “third-order” sequences. Sequence stratigraphers also recognized distinctive phases of sequences (“systems tracts”) as the product of sea-level oscillations translated in a biased way into the sedimentary record (Vail et al., 1977, 1991; Van Wagoner et al., 1988; Emery and Meyers, 1996). Subsequently, seismic stratigraphers working in the field recognized that third-order packages could frequently be subdivided into smaller scale, “fourth-”, “fifth-”, and even “sixth-”, “seventh-” and “eighth-order” cycles.

The purpose of this contribution is to examine and discuss classic Upper Ordovician to Silurian strata of the eastern Cincinnati

Arch region (Fig. 1) in the context of sequence stratigraphy. We believe that the application of sequence analysis to this classic stratigraphic succession is providing critical new insights into the depositional dynamics and history of this region. In turn, these well-exposed strata may potentially help to refine models and approaches to stratigraphy that will aid in interpretation of other areas.

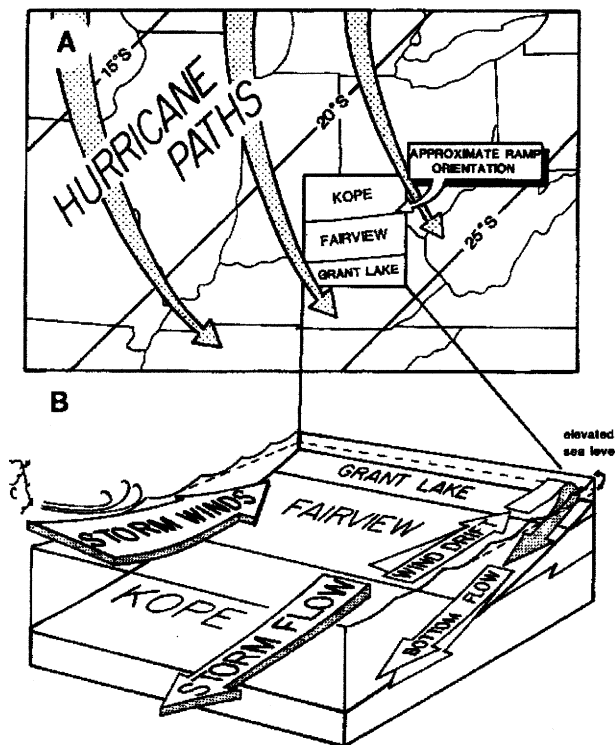


**Figure 1.** Geomorphic and structural map of the Cincinnati Arch region and adjacent geomorphic provinces. Box outlines the present study area in northern Kentucky. From Ettensohn (1992a).

## GEOLOGIC SETTING

Sediments of the Upper Ordovician-Lower Silurian of southern Ohio and northern Kentucky accumulated in a shallow-marine subtropical setting about 20-25° south of the paleoequator (Scotese, 1990; Ettensohn, 1992a, b; Fig. 2). This setting was well situated to be affected by subtropical hurricanes and there is abundant evidence for storm deposition (tempestites) in the Cincinnati Series.

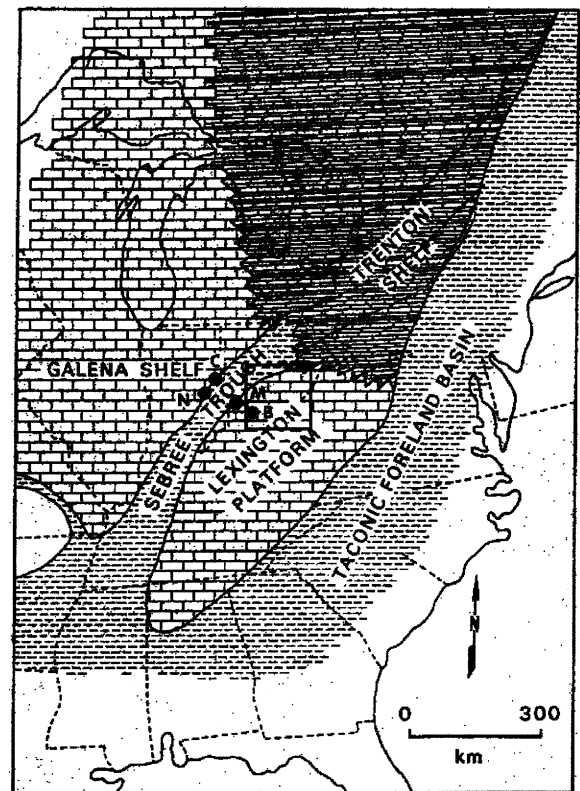
During the late Middle Ordovician, eastern Laurentia underwent collisions with island arc to microcontinental terranes, first (during the early Blackriveran) in the southern Appalachian region where collision produced the Blountian highlands and later (during the late Shermanian) in the area of the New York Promontory where the Hamburg



**Figure 2.** North-dipping ramp in the Ohio-Kentucky-Indiana area during the Late Ordovician. (A) Probable hurricane paths and approximate orientation of ramp dipping into Sebree Trough to north. (B) Inferred southward orientation of storm winds and northward flow of storm-generated gradient currents. Modified from Jennette and Pryor (1993).

Klippe (SE Pennsylvania) and Taconic allochthons were emplaced as accretionary wedges onto the Laurentian margin forming the Taconic highlands (Ettensohn, 1992c; Fig. 3). Most of the siliciclastic muds and silts of the Cincinnati Series were probably derived from these upland areas to the east and northeast. A relatively small gap existed between the two upland regions that might have served to funnel storms into the present-day Tristate region (Ohio-Kentucky-Indiana; Ettensohn, 1992b).

The Taconic foreland basin, a relatively narrow trough produced by thrust loading, extended southward from Quebec to Alabama

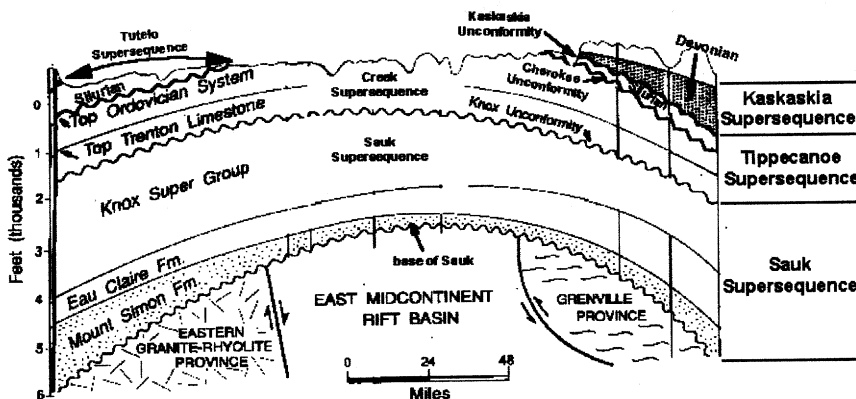


**Figure 3.** Major paleogeographic features of eastern Laurentia during early Late Ordovician (Edenian) time. The AA Highway, route of the present field trip, is located approximately along the line connecting points M to B. Note the position of the narrow Sebree Trough; the box indicates the area in which an embayment of the trough has been inferred in recent paleogeographic reconstructions (Ettensohn, 1999; in prep.). From Mitchell and Bergström (1991).

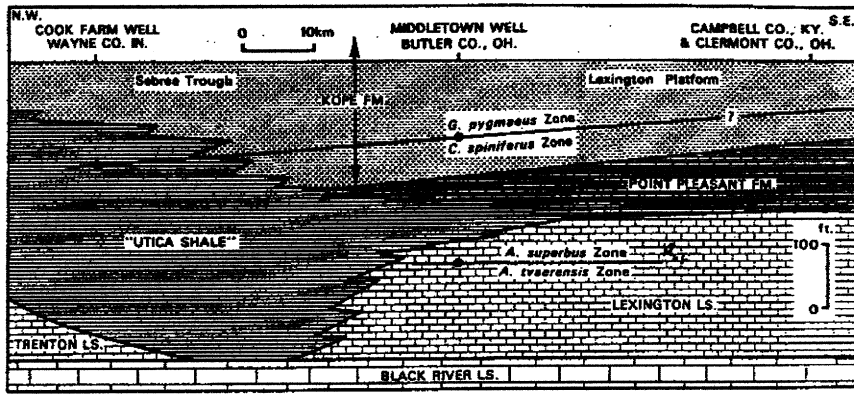
(Fig. 3). This area of active subsidence accumulated a thick wedge of siliciclastic sands, silts and muds during the Late Ordovician. These sediments commence with black shales (e.g., Utica and Antes shales) during late Mohawkian to early Cincinnati times, and progress upward through thick turbiditic flysch (Martinsburg-Reedsville formations) by the Maysvillian. During late Cincinnati (Richmondian) time sedimentation began to outstrip subsidence, resulting in upward shallowing and eventually, overflowing of the foreland basin. These shallow molasse-type facies are recorded in the upper Martinsburg, Bald Eagle-Oswego sandstones and Juniata-Queenston redbeds. The Queenston clastic wedge prograded westward with reddish marginal marine sediments reaching east-central Kentucky and Ohio by late Richmondian times.

During early Late Ordovician (Edenian) time, the Cincinnati Arch *per se* was not present in the Tristate region, rather a shallow carbonate platform (the Lexington Platform) existed to the southeast of Cincinnati, and a gentle ramp sloped to the northwest into a narrow elongated NE-SW-oriented basinal area, the Sebree Trough (Mitchell and Bergström, 1991; Etensohn, 1992c; Figs. 2-3). Hence, depositional strike in northern Kentucky-southern Ohio was also approximately NE-SW and regional dip was to the north. However, the more recent reconstructions of Etensohn (1999) indicate the existence of an embayment in the trough, with a southeastern boundary that ran NW-SE roughly coincident with the present Ohio River valley between Cincinnati and

Maysville. The Sebree Trough is of uncertain origin but is under close study by Mitchell et al. (1997) and Etensohn (1999; in review). However, its abrupt appearance during early Edenian time coincided with a major pulse of Taconic orogenic activity and subsidence of the northern foreland basin in Pennsylvania and central New York. One possible interpretation is that the Lexington Platform represents a forebulge and the Sebree Trough as a backbulge basin (terminology of Quinlan and Beaumont, 1984; Beaumont et al., 1988). Alternatively, the trough may represent a branch of the Taconic foreland basin. Etensohn (1992c, 1999, in review), in particular, has argued that Ordovician tectonic activity represents far-field tectonics. Stresses produced by Taconic thrust loading may have propagated long distances onto the Laurentian craton and produced renewed activity on old, deep-seated basement faults (Fig. 4). Subsurface study of the slightly older Black River and Trenton carbonates indicates that there are no major offsets as would be expected if basement faulting had been responsible for subsidence of the Sebree Trough. However, gentle flexural deformation may have occurred in association with these far-field stresses (Etensohn, 1999, in review). The Sebree Trough was largely infilled with sediments by mid-Maysvillian time, but a slightly deeper area appears to have persisted until the end of Late Ordovician time (Fig. 5; Mitchell and Bergstrom, 1991; Etensohn, 1999). The orientations of the carbonate ramp and adjacent trough seem to have migrated somewhat through the remainder of Cincinnati time from NE-SW to more nearly east-west (Hay, 1998).



**Figure 4.** Major unconformities and Silurian sequences in the Ordovician and Silurian of the Cincinnati Arch. Note basement faults that may have reactivated during Ordovician Taconian Orogeny. Modified from Potter (1996).

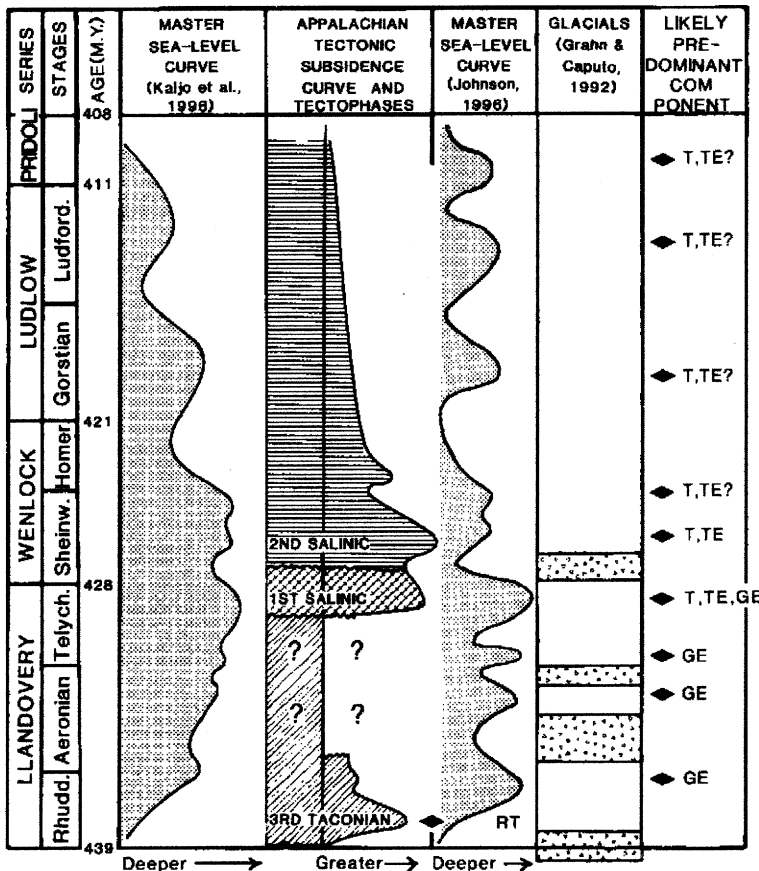


**Figure 5.** Regional cross-section of Middle-Upper Ordovician strata through south-central Ohio. Note Sebree Trough shale basin. From Mitchell and Bergstrom (1991).

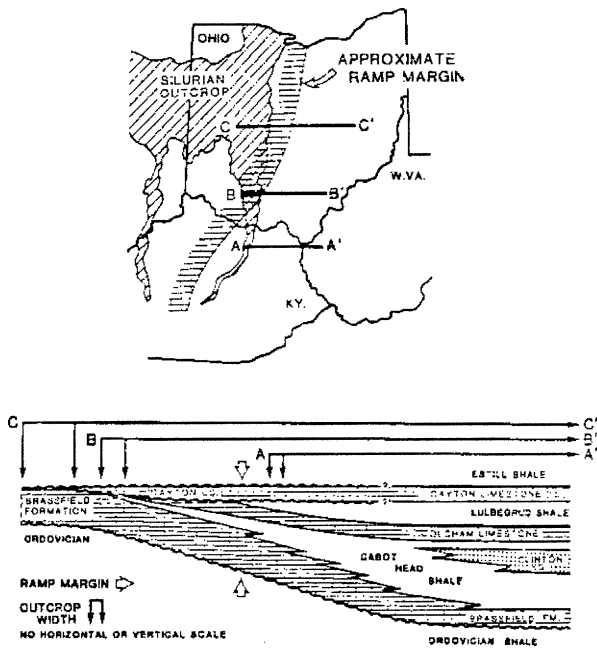
During the latest Ordovician to early Silurian, a major sea-level lowstand, probably related to continental glaciation in North Africa, created the widespread withdrawal of seas from the Cincinnati area and created a major erosion surface. Transgression in the Early Silurian enabled deposition of marine siliciclastics and carbonates over the unconformity. During this interval, the region is typically considered to have been tectonically quiescent. However, a recent study (Ettensohn and Brett, 1998; Fig. 6) indicates that a late tectophase of the Taconic Orogeny

may have taken place at this time. This spread a clastic wedge over much of the Appalachian Basin but appears to have had rather little influence in the study area in which Brassfield carbonates were deposited contemporaneously. During medial Silurian (latest Llandovery) time, there is some evidence for renewed tectonism, which produced renewed subsidence and a pulse of siliciclastics into the Appalachian basin. Locally, evidence for this is provided not only by thick shales and siltstones of the Crab Orchard-Estill formations, but also by development of regional

angular unconformities (Fig. 7; Lukasik, 1988; Goodman and Brett, 1994; Ettensohn and Brett, 1998). Regional truncation of lower Silurian units in central Ohio and northward into the Hamilton, Ontario, area suggests that the Findlay-Algonquin Arch was uplifted during late Llandovery time. The affected area cuts obliquely across the position of the former Sebree Trough. This could be viewed as evidence of reactivation of older deep-seated structures related to basement faults, but it has also been interpreted as development



**Figure 6.** Taconian tectophases of Silurian Period. From Ettensohn and Brett (1998).



**Figure 7.** Correlation of Lower Silurian sequences from New York into Ohio. From Brett et al. (1990).

of a forebulge related to thrust loading and subsidence in the adjacent Appalachian foreland basin. In a sense, this could be viewed as the origin of the Cincinnati Arch, although, in fact, the area of uplift was offset from the center of the present structural arch.

## SEQUENCE STRATIGRAPHY OF UPPER ORDOVICIAN AND SILURIAN STRATA OF THE EASTERN CINCINNATI ARCH

### Supersequences

At the largest scale, the rocks of the Cincinnati Arch region are subdivisible into great unconformity-bounded packages of the scale recognized long ago by Sloss (1963). These large-scale “supersequences” are bounded by major unconformities that are traceable widely over the North American craton and perhaps globally. The first such large-scale or “second-order” sequence embraces the entire Mohawkian (late Middle Ordovician) and Cincinnati (Late Ordovician) series of rocks, totaling approximately 450-470 meters

in thickness and encompassing deposits of about 15-20 million years (Holland and Patzkowski, 1997; Kolata et al., 1996; Potter, 1996). The lower boundary of this supersequence is the Knox Unconformity, a very widespread Middle Ordovician erosion surface that, in places, represents a hiatus of as much as 30 to 40 million years of non-deposition and erosion (Dennison and Head, 1975). This surface is nowhere exposed within the Cincinnati Arch region, although it is known in the subsurface from drill cores (Potter, 1996; Fig. 4).

At their top, the Upper Ordovician rocks are bounded by a second great unconformity, the Cherokee Unconformity (Dennison and Head, 1975). This unconformity is of global extent but of shorter duration (3-4 million years) than the Knox Unconformity, having removed only the uppermost Ordovician Gamachian Stage over most of North America. The Cherokee Unconformity is typically attributed to a major lowstand or drop in global sea level, probably of glacio-eustatic origin and related to coeval continental glaciation in North Africa. This unconformity is typically nearly planar in outcrop but may display minor relief. In southern Ohio and northern Kentucky, the unconformity is in places very sharply delineated at the top of Upper Ordovician shales of the Drakes Formation, a greenish to red mottled mudstone with abundant thin siltstone layers that appears to represent the distal feather edge of the Queenston clastic wedge. These variegated mudstones are sharply overlain by the Silurian Brassfield Dolostone, a massive orange weathering, cherty carbonate unit (Gordon and Ettensohn, 1984). Although the Cherokee Unconformity is typically nearly flat and featureless, it clearly truncates different units in various localities and is a regionally angular beveled surface.

Together the Knox and Cherokee unconformities bound a very large sequence set or “holostrome” commonly referred to as the Creek Megasequence of the Tippecanoe Supersequence (Fig. 4). The Silurian strata are typically assigned to the Tutelo Supersequence (formerly combined with Creek as the Tippecanoe Megasequence of Sloss, 1963). The top of the Silurian in eastern Kentucky and southern Ohio is defined by a second major “second-order” sequence boundary comprising actually a combination

of two or more unconformities. The lower, or Wallbridge Unconformity, separates upper Lower to Middle Devonian (Emsian-Eifelian) deposits of the Kaskaskia Supersequence (Sloss, 1963; Dennison and Head, 1975) from Upper Silurian to Lower Devonian deposits. In most areas of the Midcontinent, a higher Taghanic unconformity that occurred during a late Middle Devonian sea-level drawdown oversteps the Wallbridge Unconformity, and Middle Devonian deposits are absent. Both unconformities appear to have a combination of tectonic and eustatic signatures in their formation.

### **Third-Order Sequence Stratigraphy of Upper Ordovician-Silurian Strata of Cincinnati Arch Region**

Somewhat smaller scale, unconformity-bounded depositional sequences are present within Upper Ordovician and Silurian strata of the Cincinnati Arch region as well. These are comparable in duration (1 to 5 million years) to the “third-order” sequences recognized by seismic stratigraphers in many aspects. In particular, they are subdivisible into smaller sequences, parasequences, and systems tracts. Before discussing these stratigraphic packages in detail, the basic concepts of sequence stratigraphy will be reviewed briefly (Fig. 8).

**Sequence Stratigraphic Concepts:** Sequences are relatively conformable packages of strata bounded by unconformities formed during sea-level lowstands. Depending upon their topographic situation, sequence boundaries may be strongly erosional and display substantial erosional relief or nearly planar. It has been recognized for some time that larger scale sequences typically are overgeneralized and that most such sequences are composite sequences (Milton and Meyers, 1996). Such composite sequences can be subdivided into smaller scale sequences. Some of these are unconformity-bounded units that exhibit a pattern of relative deepening followed by shallowing (“sequences”), whereas others are bounded not by unconformities but by flooding surfaces and are distinctly asymmetrical units that mainly record shallowing (“parasequences,” Vail et al., 1991).

Based partly upon the stacking patterns of parasequences or architecture of portions of sedimentary sequences, stratigraphers have been able to recognize distinct groupings of facies within sequences, referred to as systems tracts (Fig. 8). Briefly, these include lowstand (LST; or “shelf margin”), transgressive (TST), and highstand (HST) systems tracts. In some instances, sequence stratigraphers also recognize early highstand and regressive divisions of the HST. LSTs comprise a suite of facies that typically shallow (or prograde) and include non-marine channel fillings that may occur locally immediately above a sequence boundary or erosion surface. In deeper water areas turbidite fans are another potential expression of lowstand accumulation during times when sediments are flushed from shallow water areas into deeper water regions (Fig. 8).

The transgressive systems tract (TST) may show a sharply incised transgressive erosion surface at its base, a type of ravinement surface, when it overlies more marginal marine deposits of the lowstand systems tract. This transgressive surface reflects a rapid relative rise of sea level. In many cases, including most sequences discussed herein, the sequence boundary and transgressive surfaces are combined into a single erosion surface. The transgressive systems tract itself shows a deepening upward, retrogradational stacking pattern of smaller scale cycles or parasequences, and is bounded at its top by a surface of maximum flooding (Fig. 8). This surface, which may be very distinct in some sequences, represents a time of minimal sedimentation in offshore marine settings associated with rapid sea-level rise, drowning of coastlines, and sequestering of clastic sediments in nearshore estuarine and lagoonal depositional settings. Maximum flooding surfaces are typically marked by distinct but thin lag accumulations, phosphatic nodules, conodonts, or bones. Immediately underlying and overlying the maximum flooding surface is a thin, time-rich section referred to as a condensed section that represents strongly sediment-starved conditions at times of maximum deepening.

The highstand systems (HST) tract typi-

cally commences with deeper water deposits, such as dark shales, that sharply overlie the maximum flooding surface (Fig. 8). The highstand systems tract may show a progradational succession of smaller parasequences, i.e., an overall shallowing upward pattern. Sometimes the HST can be subdivided into an early aggradational phase, in which little change in relative sea-level

elevation is evident, and a late highstand or regressive phase, in which progradational stacking of parasequences reflects an overall upward shallowing. In some cases, a thin condensed lag bed may occur at the base of the boundary between these two HST phases. The highstand systems tract ultimately exhibits an overall shallowing and may be truncated at its top by the next major sequence boundary.

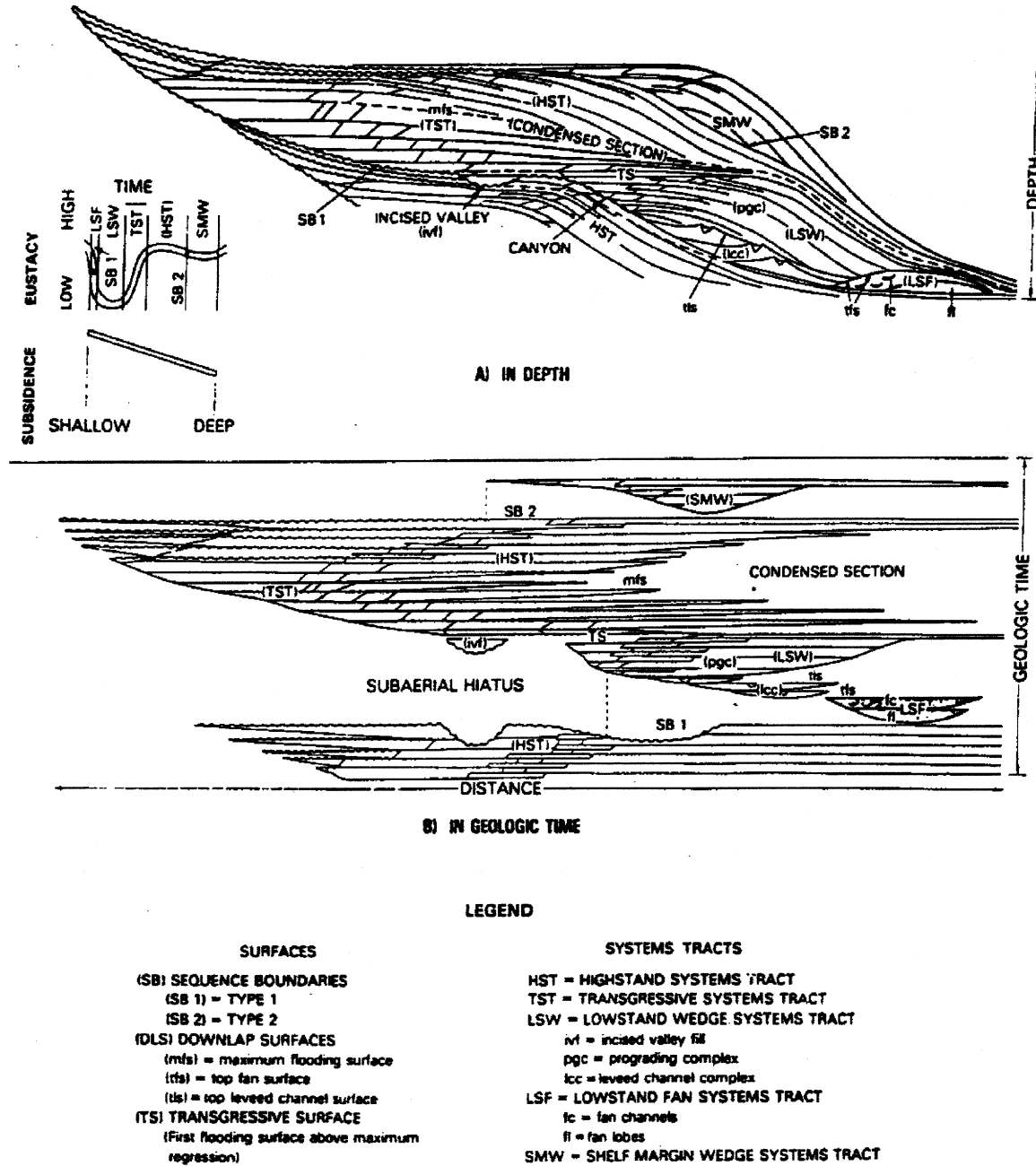


Figure 8. SLUG diagram of sequence stratigraphy. Upper figure shows actual thicknesses of units; lower figure gives time stratigraphic section. From Haq et al. (1987).

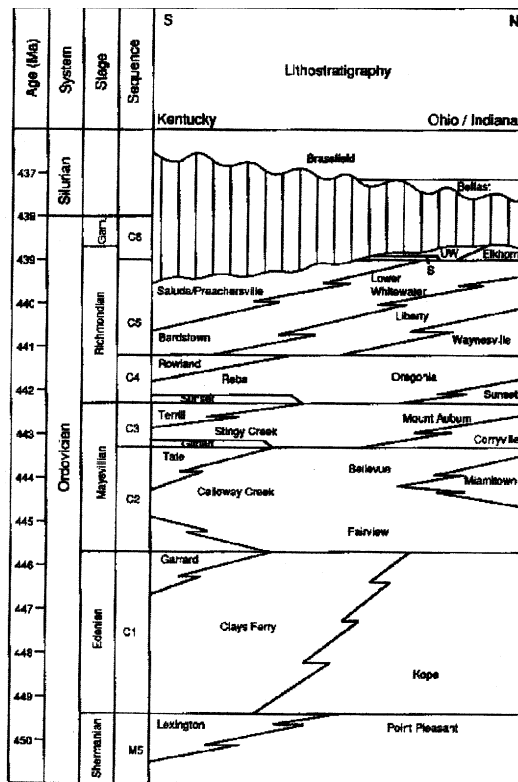
**Third-Order Sequences of the Upper Ordovician:** Holland (1993, 1998) and Holland and Patzkowsky (1966) have defined a series of six sequences in the Upper Ordovician (Cincinnatian Series), comprising the Edenian, Maysvillian, and Richmondian stages (Fig. 9). Sequence boundaries for these units are relatively subtle and occur at the bases of thin phosphatic, skeletal-rich limestones that are interpreted to be transgressive systems tracts. The majority of these sequences comprise thick coarsening/shallowing-upward successions of mudstone and calcisiltite and, toward the top, closely bundled skeletal packstones or grainstones, wavy-bedded packstones and wackestones and, in some cases, bioturbated to laminated peritidal facies. These represent late highstand or regressive systems tracts separated by relatively planar and subtle unconformities. No lowstand deposits were identified and, as such, sequence boundaries and transgressive surfaces appear to be combined.

Five of the six sequences identified by Holland are exposed in the eastern Cincinnati

Arch region. The sixth has been removed by pre-Silurian erosion at the Cherokee Unconformity. The lowest two of the six Cincinnatian sequences, the Edenian-age Kope Formation (sequence C1) and the lower Maysvillian-age Fairview Formation (sequence C2) were originally combined in a single very long-ranging sequence (Holland, 1993); however, with subsequent study these were subdivided (Holland and Patzkowski, 1996). Units equivalent to Sequence C1 and the base of Sequence C2 will be discussed in detail in this paper and will be a primary focus of the present field excursion.

Sequence C1 is the thickest and longest of Holland's Cincinnatian sequences (Fig. 9), comprising some 70-75 m of section and representing the entire Edenian Stage (ca. 4 million years in duration). This sequence commenced with an abrupt flooding surface near the base of the Kope Shale. This abrupt deepening above Point Pleasant grainstones apparently occurred within the *Climacograptus spiniferus* Zone (Mitchell and Bergstrom, 1991); as such it coincided with a major pulse of deepening in the Taconic Basin, i.e., the lower part of the Indian Castle Shale or the Utica Shale proper. Dark Utica-type shales were deposited coevally in the Sebree Trough also, where they overstep the latest Shermanian Point Pleasant limestones and intrude locally upon the Lexington Platform as a dark graptolitic shale tongue (the Fulton beds) at the base of the Kope Formation. This highstand event may reflect a eustatic sea-level rise, a pulse of widespread subsidence, or both. The major Edenian C1 deepening has been recognized by Holland and Patzkowsky (1996) throughout the southern and central Appalachians.

Despite complexities, the Kope Formation shows a general shallowing upward trend, at least to the level of the Grand Avenue beds, a bundle of closely spaced fossiliferous limestones about 10-11 m below the Fairview contact (Brett and Algeo, this volume). The Upper Kope, above the Grand Avenue beds, is shale rich and shows some faunal evidence for deeper water conditions. This abrupt deepening could be considered as a higher-order deepening superimposed



**Figure 9.** Third-order sequences in the Upper Ordovician Cincinnatian Series (from Holland et al., 1997).

upon a “third-order” shallowing trend but it should be noted that the occurrence of deeper water facies near the very top of sequence C1 is problematical.

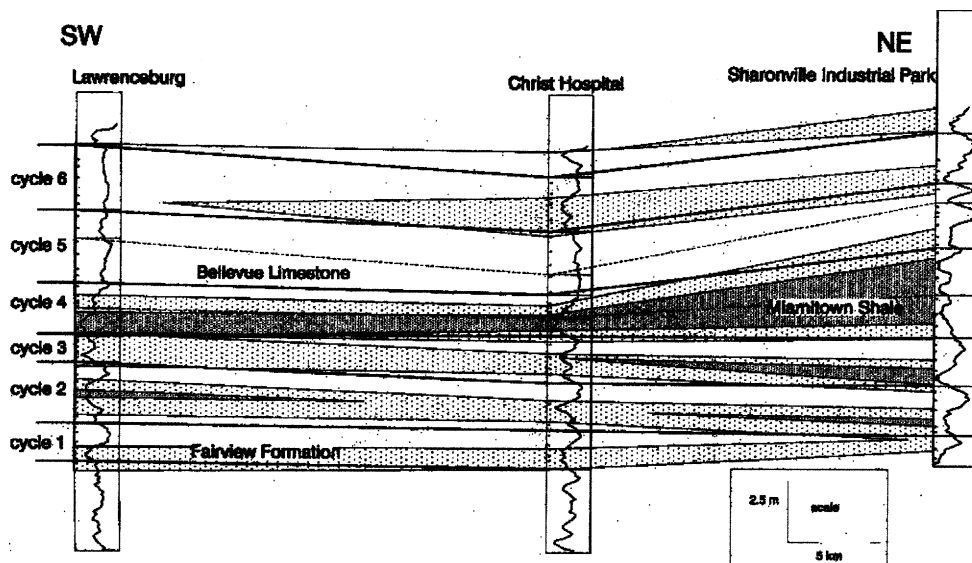
Holland et al. (this volume) discuss in some detail the placement of the C1/C2 sequence boundary. This was formerly placed at the base of the Fairview Formation, the lowermost portion of which is composed of a relatively compact noncyclic bundle of limestone beds containing abundant *Strophomena* (see Schumacher, 1992). However, Holland et al. suggest on the basis of faunal data that the shallowest level is actually present several meters higher near the base of the shaly Wesselman submember of the Fairview Formation.

The second Cincinnati sequence (C2) comprises the lower Fairview Formation through the Bellevue limestone tongue of the Grant Lake Formation (Fig. 9), which together represent the bulk of the Maysvillian Stage with an estimated duration of about 2 million years. Again, this succession shows a gross shallowing upward trend from shaly packstones through thin-bedded bryozoan-rich limestones and shales, and finally to rubbly, wavy-bedded and closely stacked limestones of the Bellevue. However, the Fairview exhibits some retrogradation and the maximum flooding may be represented in the Miamitown Shale, a tongue of presumably deeper water facies that lies between Fairview and Bellevue limestones north of the Cincinnati region (S. Holland, pers. comm., 1999).

This shale thins dramatically into northern Kentucky and is only barely recognizable in outcrops near Alexandria. The Miamitown carries a distinctive fauna, typically dominated by molluscs, including the gastropod *Loxoplocus*, and bivalves such as *Modiolopsis*, *Ambonychia*, and *Caritodens*. The Miamitown and its subdivisions recently have been studied and correlated in detail by Datillo (Fig. 10; 1996; 1998). The unit thickens and merges with the Kope Formation north of the outcrop belt in the subsurface. We consider the Miamitown to Bellevue succession to record another, as yet unrecognized sequence.

In Kentucky, the beds above the Fairview Formation consist predominantly of wavy-bedded packstones and grainstones with thinner intervals of shale and thin-bedded packstones and grainstones. This interval is assigned by the Kentucky Geological Survey to the Grant Lake Formation; however, some differentiated intervals, originally recognized as separate formations in the Cincinnati area, can still be recognized in northern Kentucky and are now considered to be members of the Grant Lake Formation. These are, in ascending order, the Bellevue, Corryville, and Mt. Auburn/Straight Creek members.

The Bellevue Limestone, as recently defined, consists of 6 to 21.3 meters of closely spaced thin- to medium-bedded shell-rich packstones and grainstones. It thickens to the southeast at the expense of the Corryville Shale; conversely, a tongue of Corryville-like



**Figure 10.** Stratigraphic cross-section of Fairview-Miamitown-Bellevue interval, corresponding to Holland's C2 sequence, from north to south through the Greater Cincinnati area. From Datillo (1996).

lithology divides the Bellevue north of Cincinnati. Otherwise, shale forms a very minor constituent of the Bellevue, and limestone beds of this unit typically are amalgamated with only minor shaly partings, giving the Bellevue a ribbed appearance in outcrops. The Bellevue contains a fauna rich in robust brachiopods, especially large specimens of *Platystrophia ponderosa*, that are considered to represent shallow-water, near-wavebase conditions associated with a late highstand phase.

Holland's third depositional sequence (C3; Fig. 9), dated as late Maysvillian in age, is substantially thinner than the first two and may represent less than a million years. It commences with shaly beds of the Corryville Member of the Grant Lake Formation, which yield upward to rubbly, wavy-bedded packstones and grainstones of the Mt. Auburn Member.

In classic exposures in the city of Cincinnati, Bassler (1906) originally recognized a shale-rich interval overlying the Bellevue which he named Corryville. In this area, near the present-day University of Cincinnati, the Corryville was about 20 m thick and consists of medium gray fossiliferous mudstone with thin brachiopod-rich packstones. The unit contains a rich, diverse fauna including exceptionally well-preserved trilobites and crinoids (Goldman, 1998). The lower portion of the Corryville becomes more limestone rich and is considered to merge with the upper Bellevue Member toward the southeast, accounting for the decrease in thickness of the Corryville to only about 6 m in the Maysville area. Hence, this thickness change is facies dependent rather than a reflection of laterally variable sedimentation rates. In any case, the Corryville appears to record another deepening event and a return to Fairview or even Kope-like facies, with a maximum flooding surface probably in the upper half of the unit. Overlying the Corryville, the Mt. Auburn-Straight Creek members of the Grant Lake Formation record shallowing into an environment very similar to the Bellevue.

Holland's fourth depositional sequence (C4) is also short and consists of the Sunset and Oregonia members of the Arnheim Formation (Fig. 9; n.b., these members were each given formational status by Holland). Once again, this succession commences with shales

and nodular limestones and progresses upward into wavy-bedded packstones and grainstones. The base of the Richmond Group (Richmondian Stage) is presently set at the base of the Arnheim Formation (base of C4).

Holland's fifth depositional sequence (C5; Fig. 9) is well developed and shows well-defined transgressive and early highstand systems tracts. It falls within the middle Richmondian and comprises the Waynesville, Liberty, and lower Whitewater formations, a shallowing upward succession. Its base is marked locally by about 1.5 m of phosphatic grainstone. This bed is abruptly overlain by gray shales of the Waynesville Formation, which contains a fauna dominated by bivalves, trilobites, and the brachiopods *Onniella* and *Sowerbyella* (or *Thaerodonta*) that strongly suggests a return to deeper water Kope-like conditions. Facies of the Waynesville, representing transgressive to highstand conditions, may correspond to a major early Richmondian deepening event seen elsewhere in the Frankfort and Blue Mountain formations (dark gray to black shales) of New York and Ontario, respectively, and the Maquoketa Shales of the upper Mississippi Valley region. Along the western flank of the Cincinnati Arch, the shaly Waynesville grades upward into packstones and grainstones of the Liberty Formation, and the latter, in turn, grades upward into wavy-bedded limestones of the Whitewater Formation. Overlying the last-named unit are bioturbated, coral-rich "lagoonal" mudstones and laminated peritidal dolostones of the Saluda Formation.

On the eastern flank of the Cincinnati Arch, the correlative section is composed of shallowing upward facies of the Bull Fork Formation. A Waynesville equivalent is recognized in the base of this sequence and shallows through variably shaly carbonates into variegated greenish gray to reddish mudstones of the Preachersville Member of the Drakes Formation. These sediments reflect westward progradation of the Queenston clastic wedge and are apparently coeval with the muddy dolostones of the Saluda Formation to the west. Sequence C5 also shows an incursion of a number of taxa such as corals, stromatoporoids, and the brachiopod *Lepidocyclus* that was referred to as the

“Richmondian invasion” by Holland and Patzkowsky (1994) and Holland (1997). Holland and Patzkowsky (1994) attributed this faunal change to a general warming of the Cincinnati seas, possibly accompanied by changes in seawater chemistry.

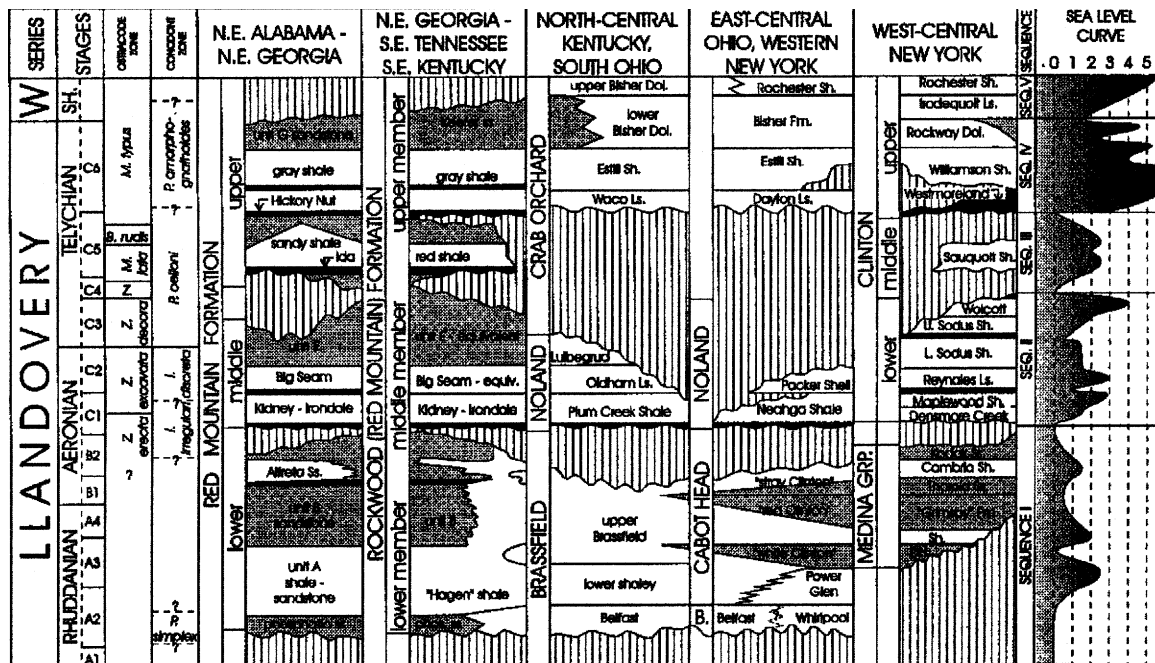
Finally, Holland (1998) recognized remnants of a sixth and highest Cincinnati sequence (C6). This sequence has apparently been completely removed at the major sub-Silurian Cherokee Unconformity on the east flank of the Cincinnati Arch (Fig. 4). However, on the west flank of the arch it is reflected in a return to packstones and shales assigned to the Upper Whitewater or Elkhorn Formation, above the Saluda dolostones.

**Third-Order Sequences of the Silurian:**

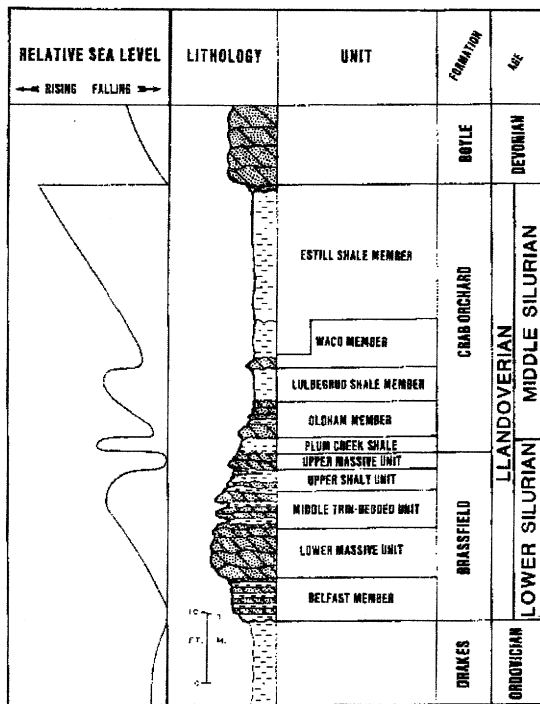
Research on the sequence stratigraphy of Silurian rocks in the northern Appalachian Basin (Brett et al., 1990, 1994, 1998) has resulted in recognition of about eight widespread, unconformity-bounded packages that may be assigned “third-order” status, as well as a large number of smaller (“fourth-order”) sequences (Fig. 11). Recently, sequence analysis of correlative units in Ohio and Kentucky has led to recognition of about six, possibly correlative “third-order” sequences in

the Cincinnati Arch region. Interregional correlation of these sequences is facilitated by the conodont biostratigraphic studies of Kleffner (1989) as well as the detailed sub-surface study of Lukasik (1988).

The first Silurian sequence (S1) is the Medina or Tuscarora sandstone succession of the Appalachian Basin, which is recorded by the Lower Silurian (lower Llandovery) Brassfield Formation in Ohio and Kentucky (Fig. 11). It is bounded at its base by the Cherokee Unconformity and at its top by a more subtle and previously unrecognized sequence boundary marked by a hematitic bed near the top of the Brassfield (Fig. 12). The sequence consists of the lower portion of the Clinton Group, comprising mixed shales, carbonates and ironstones in the Appalachian Basin. In the Cincinnati Arch region, its basal unit is the Belfast Member of the Brassfield Formation, an argillaceous dolostone that may resemble the underlying Drakes dolomitic shales. This interval apparently represents lowstand or initial transgressive conditions, and over the sequence boundary the Belfast locally features a phosphatic, glauconitic lag. The bulk of the Brassfield Formation is a massive orange buff-weathering dolostone



**Figure 11.** Correlation of medial Silurian units in New York State, Ontario, and central Ohio. From Brett et al. (1990).



**Figure 12.** Composite column of Silurian stratigraphic units of the eastern Cincinnati Arch area. Modified from Ettensohn (1992).

with layers of light gray chert. This unit contains some fossils in common with the Manitoulin Dolostone of Ontario, its probable lateral equivalent. Like the Manitoulin, the cherty Brassfield is interpreted as the TST of sequence S1. An upper division of the Brassfield in Kentucky consists of gray shale with thin-bedded dolomitic siltstones (Fig. 12). This interval probably constitutes the HST of sequence S1 and corresponds to the Cabot Head Formation of northern Ohio, Michigan and Ontario. A minor sequence may be represented by an upper Brassfield dolostone unit that is capped by a hematitic bed rich in cystoid columnals, the so-called “bead bed.”

The second Silurian sequence (S2) is represented by a thin, poorly exposed succession assigned to the Noland or Crab Orchard formations (or groups) in southern Ohio and northern Kentucky, respectively (Fig. 11). The basal Plum Creek Shale represents a TST; its base is marked by a thin, hematitic phosphatic nodule bed. Also included within sequence S2 in Ohio are the overlying Oldham Limestone and Lulbegrud Shale, which have been tentatively correlated with the Reynales Lime-

stone and Sodus Shale of the classic New York section (Brett et al., 1990, 1998). In Ohio these units are truncated to the northwest and overstepped by the Dayton Limestone, a distinctive, thin glauconitic carbonate (Lukasik, 1988). The Dayton has been dated as late Llandovery (mid-Telychian) on the basis of conodonts (Kleffner, 1990). The Dayton is thus approximately coeval with the Merritton Limestone and upper Fossil Hill Dolostone, which similarly overstep strata of sequence S2 in the Bruce Peninsula area of southern Ontario, Canada. Brett et al. (1990) inferred that the sub-Dayton unconformity of central Ohio and the sub-Merritton-Fossil Hill unconformity in Ontario are local manifestations of the same regional unconformity. It probably represents a minor episode of uplift and erosion along the Alonquin-Findlay Arch, which was evidently active during the medial Silurian. Goodman and Brett (1994) suggested that this activity may reflect an isostatic response to thrust loading during early phases of the Salinic Orogeny.

The third and fourth Silurian sequences (S3 and S4) are represented by the Estill Shale (a member of the Crab Orchard Formation in Kentucky terminology), which overlies the Dayton Limestone (Fig. 11). These units are separated by a subtle but possibly regionally angular unconformity. The lower Estill Shale consists of purplish shales and contains an ostracode and conodont fauna suggestive of a late Telychian age; this would correlate with sequence S2 (Sauquoit Shale) in the New York succession (Brett et al., 1990, 1998). At the Charters roadcut on the AA Highway, a subtle but slightly angular discordance appears between the lower purplish shales and the overlying greenish-grey shales and siltstones of the upper Estill. At most, a thin transgressive lag deposit occurs at the base of sequence S4.

The upper Estill Shale is assigned a latest Llandovery (late Telychian) age on the basis of graptolites of the *Monograptus clintonensis* Zone and conodonts of the *Pterospiriferus amorphognathoides* Zone (Kleffner, 1987). The lower five meters of shale and thin, fossiliferous siltstones appear to correlate directly with the uppermost Rose Hill Shale of the Appalachian Basin and with the Williamson-Willowvale shales (sequence

S4-A) of the standard New York section. This represents the highest stand of relative sea level during the Silurian in eastern North America and may be a global eustatic highstand (Johnson et al., 1998).

The uppermost Estill dolomitic siltstone unit (previously assigned to the overlying Bisher Formation; Potter et al., 1991; Mason et al., 1991), which is regionally removed under the S5 unconformity, comprises thin- to medium-bedded dolomitic and somewhat fossiliferous carbonates and greenish-grey shales. This dolomitic siltstone appears to correlate directly with the Rockway Formation of Ontario and New York State and with the lower Keefer Sandstone or sandy uppermost Rose Hill Formation in Pennsylvania (late highstand of sequence S4; subsequence S4-B). Also, probable K-bentonites have been found in this interval, which may correlate with beds in the Osgood Shale on the western flank of the Cincinnati Arch (Ray and Brett, 1999). These ash beds may also correlate with K-bentonites found in the upper Llandovery of the southern Appalachians (Kolata et al., 1996).

A very distinct sequence boundary at the base of the Bisher Dolostone separates overlying Sequence S5 from the underlying Estill Shales (Fig. 11). At this surface, the uppermost Estill dolomitic siltstones and shales are regionally truncated in a series of outcrops near Vanceburg, Kentucky (Stop 8 of field trip, p. 21). Sequence S5 shows a well-defined transgressive systems tract, recorded in crinoid-rich dolomitic packstones and grainstones of the lower unit of the undifferentiated Bisher Formation. This is sharply overlain by a thin shaly HST interval, apparently correlative with the Rochester Shale in the Appalachian Basin. No more than a half meter of shales and thin calcisiltites occurs at this level in Kentucky; however, to the north near Hillsboro, Ohio, a succession of nearly four meters of typical Rochester Shale occurs overlying the basal grainstones of the Bisher Dolostone. The top of the lower Bisher unit is thus interpreted as a major flooding surface.

A cryptic, but important, sequence boundary occurs above the overlying calcisiltite and shale interval. This sequence boundary appears to correlate with the base of the

Lockport Group and the base of the McKenzie Formation in Pennsylvania and Maryland and represents the base of sequence S6. This interval is represented by hummocky to herringbone cross-stratified crinoidal dolostones, assigned to the upper Bisher Formation in Kentucky and to the Bisher or lower Lilly Formation in Adams County, Ohio (Kleffner and Ausich, 1988; Kleffner, 1990). The top of this succession contains a distinctive, poorly bedded interval consisting of mounds or blocks of dolomicrite surrounded by poorly bedded dolomitic mudstones. This interval has been interpreted as a collapse breccia associated with karstification during the Devonian because it lies just below the Kaskaskia unconformity. However, its association with poorly preserved corals and stromatoporoids and the occurrence of in-situ crinoid holdfasts on the surfaces of the dolomicrite mounds indicate that, instead, these structures may represent bioherms or mud mounds. If so, they are associated with the early highstand/maximum flooding surface of sequence S6. As such, they would correlate with a widespread zone of coral-stromatoporoid reefs in the lower Lockport Group in New York State and thrombolitic mounds in the McKenzie Formation of Pennsylvania and West Virginia (Crowley, 1973; Brett et al., 1990). The overlying Lilly-Peebles dolostone succession of southern Ohio has been largely removed by Devonian erosion in northern Kentucky.

In the study area gray to black pyritic shales of the Upper Devonian (Famennian) are juxtaposed directly upon eroded Silurian carbonates (see Over et al., this volume). The unconformity typically displays a small amount of relief and may be overlain by a thin lag deposit of dark bone and conodont-rich pyritic to phosphatic limestone. Corrosion and some dissolution of the underlying Silurian carbonates is common and in places minor sandstone dikes may intrude downward into Silurian dolostones.

This field trip will provide an opportunity to examine both the Cherokee and Wallbridge unconformities, as well as a number of the less profound but widespread surfaces discussed above. In the context of sequence stratigraphy, these represent sequence boundaries or, in some cases, maximum flooding surfaces.

**STRATIGRAPHY OF THE UPPER ORDOVICIAN KOPE  
FORMATION  
IN ITS TYPE AREA (NORTHERN KENTUCKY),  
INCLUDING A REVISED NOMENCLATURE**

Carlton E. Brett and Thomas J. Algeo

Department of Geology  
University of Cincinnati  
Cincinnati, Ohio 45221-0013

## INTRODUCTION

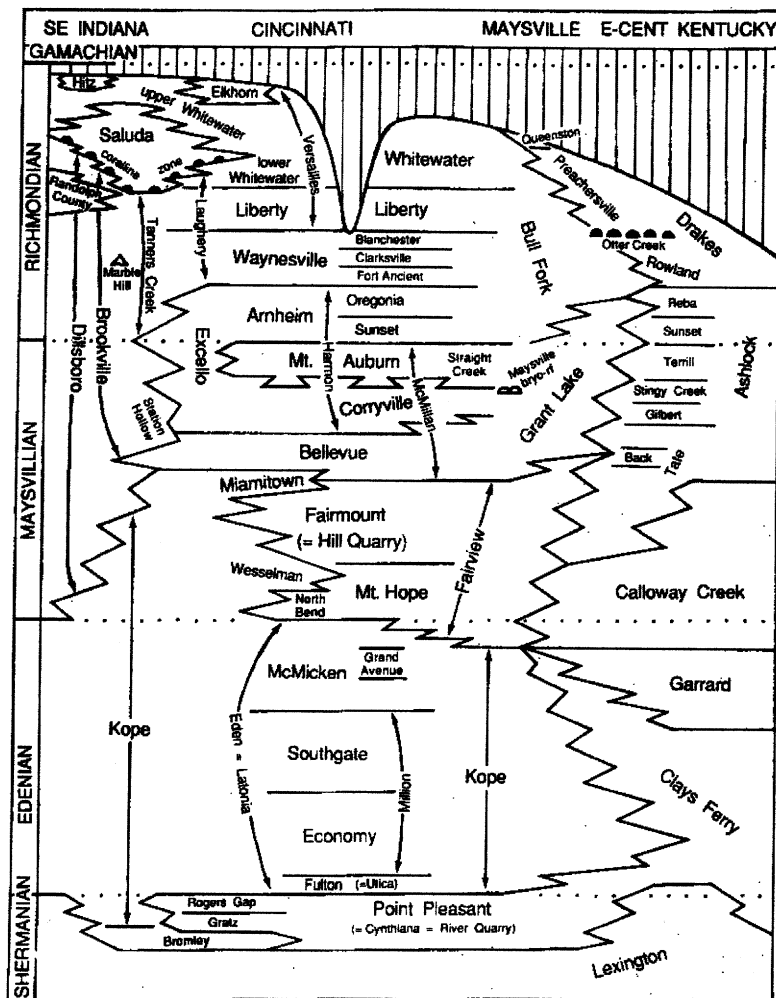
A well-developed stratigraphic framework is a necessary condition for detailed analysis of sedimentary processes in ancient rock units. Although the stratigraphy of Upper Ordovician strata of the Greater Cincinnati region has been studied for many years, studies of process sedimentology are still limited by a less-than-thorough understanding of the fine-scale stratigraphy of these units. Early on, the rocks of the classic Cincinnati Series were subdivided using a mixed biostratigraphic and lithostratigraphic approach (Bassler, 1906; Ulrich and Bassler, 1914). These early workers were interested in establishing a regional time framework within which to examine primarily faunal changes. Although these workers clearly recognized the existence of local facies changes, their views on the lateral continuity of lithofacies and biofacies in some cases led to correlation errors.

In recent decades, the application of a facies model approach has contributed to a paradigmatic view of the stratigraphic record as a mosaic of local lenticular sedimentary bodies with little lateral continuity and little or no relationship to similar appearing beds in other sections. Earlier attempts to link together marker horizons in the Cincinnati Series into a regional framework were viewed with suspicion and commonly were castigated as antiquated "layer-cake stratigraphy," although in many cases such efforts were based on strong empirical evidence. Many of the classic named units of the Greater Cincinnati area were subsequently abandoned as stratigraphers in adjoining regions developed a plethora of local terms based on a perhaps

overly zealous attempt to make stratigraphy strictly "lithostratigraphic." A complex mosaic of terms came to be applied to the same set of rocks (e.g., Cuffey, 1998; Fig. 1). Even today the states of Ohio, Kentucky, and Indiana have distinct sets of names for strata that are arguably the same. In the process, the interest in temporal relationships and depositional processes recorded in the stratigraphic record were sometimes eclipsed (see Holland, 1993, for discussion).

With its renewed emphasis on through-going discontinuities and condensed beds, sequence analysis has encouraged a broader, more regional view of stratigraphy and an attempt to understand the genetic significance of particular beds and surfaces. To some degree it vindicates the earlier view of the Cincinnati Series as exemplifying "layer-cake stratigraphy." Sequence stratigraphy, originally developed from remote seismic studies of passive margin sediment wedges, is now being applied at an outcrop scale to diverse depositional systems including foreland basins such as the Appalachian (or Taconic) basin of the Ordovician and Silurian periods (Brett et al., 1990a, b; Witzke et al., 1996; Brett et al., 1998).

Although a number of authors have recently attempted to recognize small-scale cycles within the Kope Formation in its type area, there has been little attempt to correlate these beyond the immediate area of Cincinnati (i.e., the area circumscribed by the I-275 ring highway). However, early efforts at correlation of event horizons within this core area have led to promising results. For example, Jennette and Pryor (1993) were able to recognize event beds, such as a distinctive gutter cast horizon and a band of siltstone beds



**Figure 1.** Correlation chart of Upper Ordovician Cincinnatian Series for the Ohio-Kentucky-Indiana area. From Cuffey (1998).

containing a distinctive morphotype of *Diplocraterion* burrows, widely across this area (see Fig. 8, p. 70, this volume). In a similar vein, Datillo (1994) recognized a distinctive set of marker beds and faunal cycles that permitted detailed correlation of the somewhat younger Miamitown Shale in outcrops and drill cores from this area (Fig. 10, p. 42, this volume). However, there have been few attempts at fine-scale correlation (i.e., at the level of bundles of beds or even single-event beds) over an area extending beyond the core region of Cincinnati. This, however, represents the next challenge: to trace individual beds and sets of beds from the Cincinnati core area outward in directions both parallel to and perpendicular to depositional strike.

The AA Highway in northern Kentucky provides a cross-section of a mixed siliciclastic-carbonate ramp, from slightly

deeper, more distal, shale-dominated facies to the north-west (i.e., near Cincinnati) to shallower, somewhat more proximal, carbonate-dominated facies to the south-east (i.e., near Maysville; Fig. 2, p. 35, this volume). The roughly NW-SE orientation of the AA Highway was previously thought to be normal to the NE-SW-oriented Sebree Trough located north and west of the Cincinnati area and, hence, approximately perpendicular to inferred depositional strike (e.g., Mitchell and Bergström, 1991; Ettensohn, 1992a; Fig. 3, p. 35, this volume). However, recent paleogeographic refinements suggest that the Sebree Trough had an embayment to the south-east of Cincinnati (Ettensohn, in press). The southern boundary of this embayment was aligned along a NW-SE-oriented lineament, approximately parallel to a deep-seated fault and subparallel to the Ohio River (Ohio-Kentucky border) from Cincinnati to slightly south-east of Maysville. The local depositional dip along this portion of the ramp would have been to the north-east and depositional strike would have been north-west-south-east. With this reconstruction, the Ohio-Maysville axis of the AA Highway would be oriented more nearly parallel to facies strike.

Detailed stratigraphic analysis of the Kope Formation may provide a test of these alternative paleogeographic models. If the older, simpler model of NE-SW-oriented depositional strike is correct, major across-strike facies and thickness changes would be anticipated in the Cincinnatian Series along the AA Highway transect. Conversely, if the

embayment model is correct, then Cincinnati Series facies and thicknesses should be relatively uniform along the AA Highway, facilitating stratigraphic correlation. We have utilized the large number of relatively fresh exposures along the AA Highway and adjacent regions to refine the stratigraphy of the lower Cincinnati Series, especially that of the Kope Formation, and to test these alternative paleogeographic models. In this paper, we review and update aspects of the stratigraphy of the Kope Formation and associated units, establish a more detailed framework for future depositional process studies, and consider implications of our stratigraphic work for an understanding of the paleogeographic setting of the Cincinnati Series.

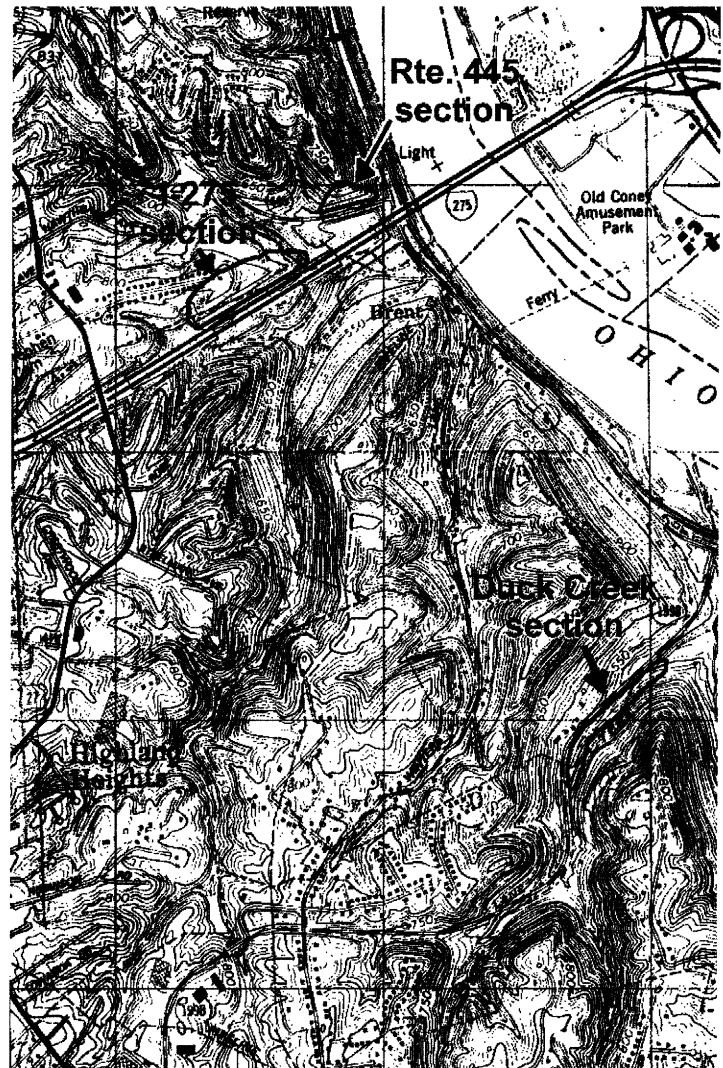
## DETAILED SUBDIVISION OF THE KOPE FORMATION

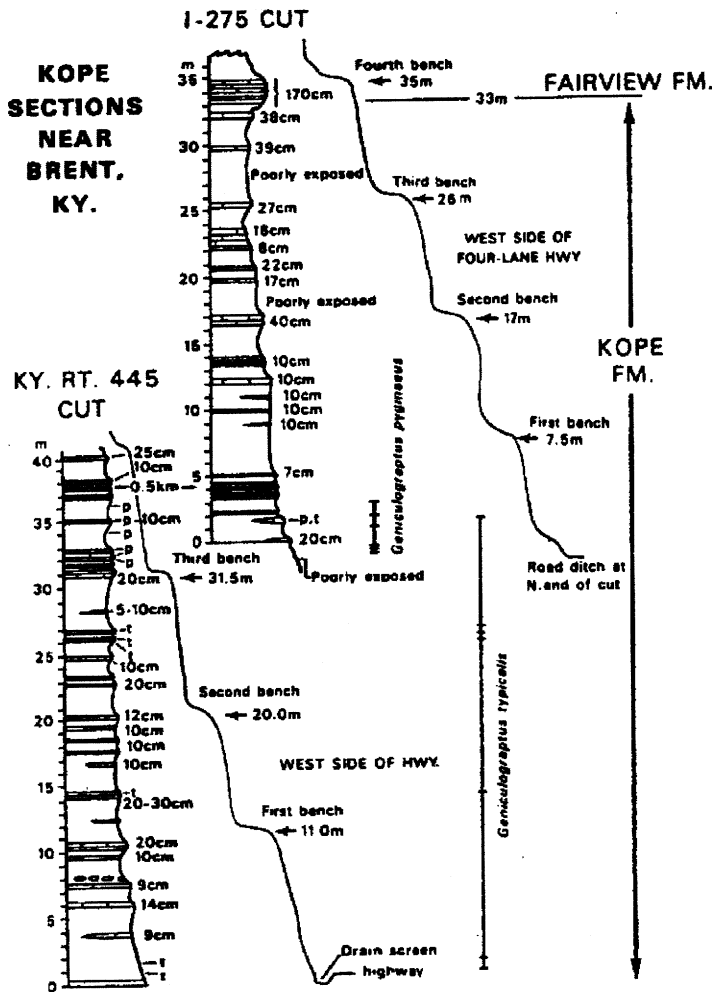
In our recent studies, we have undertaken a detailed subdivision of the Kope Formation, starting from a well-studied 60-m-thick reference section, a composite of outcrops at KY Rte. 445 and along I-275 near the Ohio River (Holland et al., 1997; Fig. 5, Holland et al., this volume). The Kope Fm. is well-exposed in these sections, although the lowermost ten or so meters of the formation is missing here. We will visit the KY Rte. 445 section, which near its junction with Kentucky Rte. 8 (Stop 1 on Sunday; Fig. 23, p. 29, this volume). These sections were previously studied in detail from the standpoint of biostratigraphy by Mitchell and Bergström (1991), who obtained numerous graptolite

samples and recognized the *Climacograptus spiniferus* (*Geniculograptus typcalis*)-*Geniculograptus pygmaeus* zonal boundary about 40 m above the base of the Rte. 445 roadcut (Figs. 3-4). Subsequently, Holland et al. (1997) made detailed measurements and faunal censuses and defined a series of 40 meter-scale cycles within this 60-m-thick composite section. Despite different approaches and minor discrepancies, these two groups of researchers produced generally similar measured sections.

We independently examined the composite reference section and identified a series of potentially traceable beds and intervals, the stratigraphic positions of which were determined in relation to the numbered cycles of Holland et al. (1997) and to prominent beds shown in the outcrop profile diagram of Mitchell and Bergström (1991). Beds were

**Figure 2.** Area of new Composite Reference Section (CRS) for the Kope Fm., established herein. The CRS includes sections at Duck Creek, KY Rte. 445, and I-275. This area is just SE of Cincinnati, along I-275 as it approaches the Ohio River from the west. Portion of U.S.G.S. Newport, Ky. Quadrangle sheet (scale 1:24,000); area shown is about 1.5x2.5 miles.





numbered in accordance with the numbering scheme of Holland et al.'s (1997) cycles, and, in most cases, the prominent marker limestone beds that we recognized correspond to the tops of Holland et al.'s cycles. Regardless of whether or not sedimentary cyclicity is present in this reference section, these prominent marker beds do display distinctive features and stacking patterns that together can be used as a template for regional correlation studies. In addition, we located a section of the upper Point Pleasant Fm. and the basal 15 m of the Kope Fm. in Duck Creek, about 1.5 km south of the Rte. 445 section (Fig. 2). Beds near the upper end of this section overlap with those at the base of the Rte. 445 roadcut. Splicing this new section with the existing Rte. 445 section has yielded a new Composite Reference Section (CRS) for the entire Kope Formation, presented herein (Fig. 5).

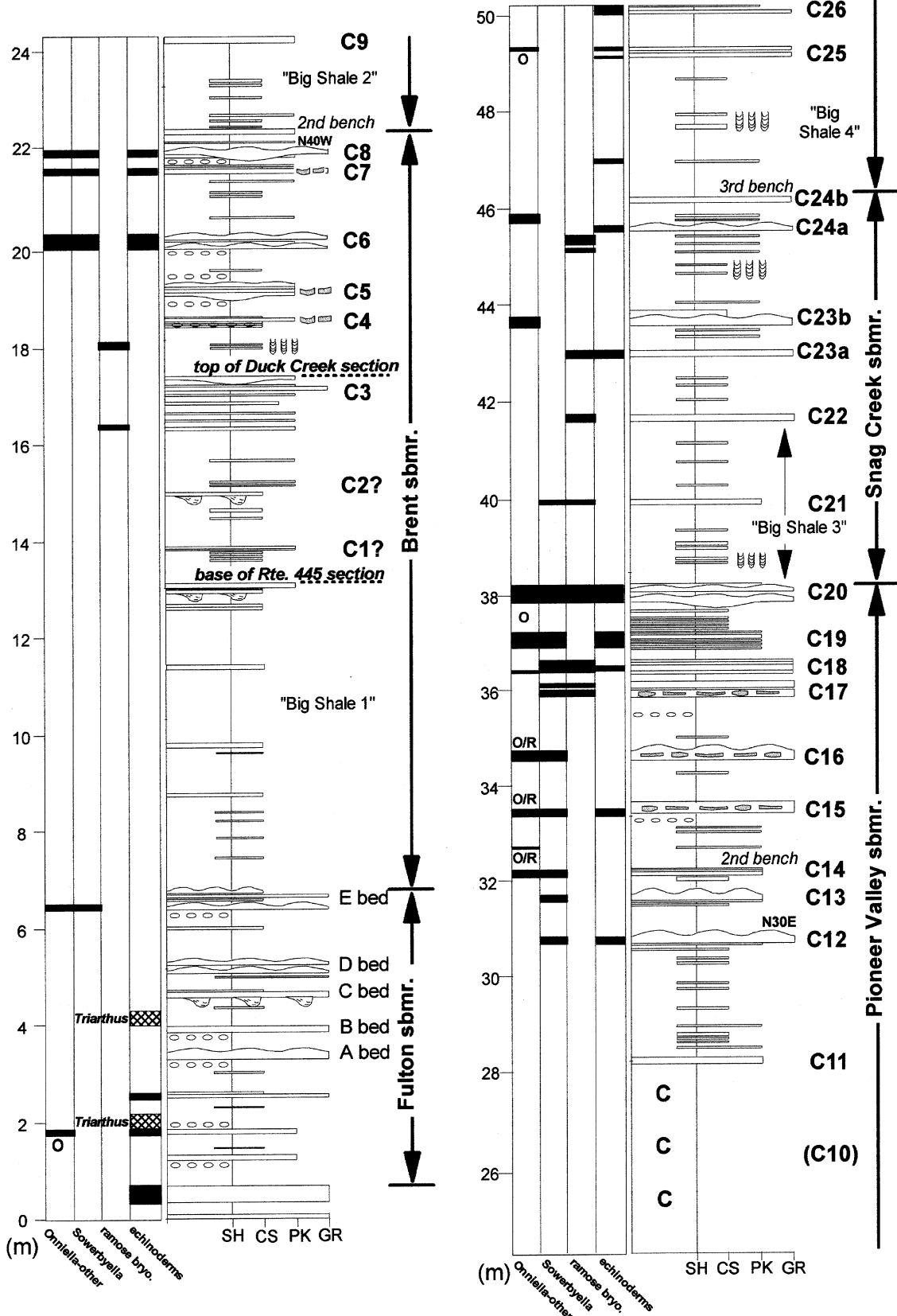
**Figure 3.** Vertical ranges of graptolite species at the Rte. 445 and I-275 composite section at Brent, Kentucky. Modified from Mitchell and Bergström (1991). This is the same as the Kope reference section of Holland et al. (1997; Fig. 5, p. 100, this volume).



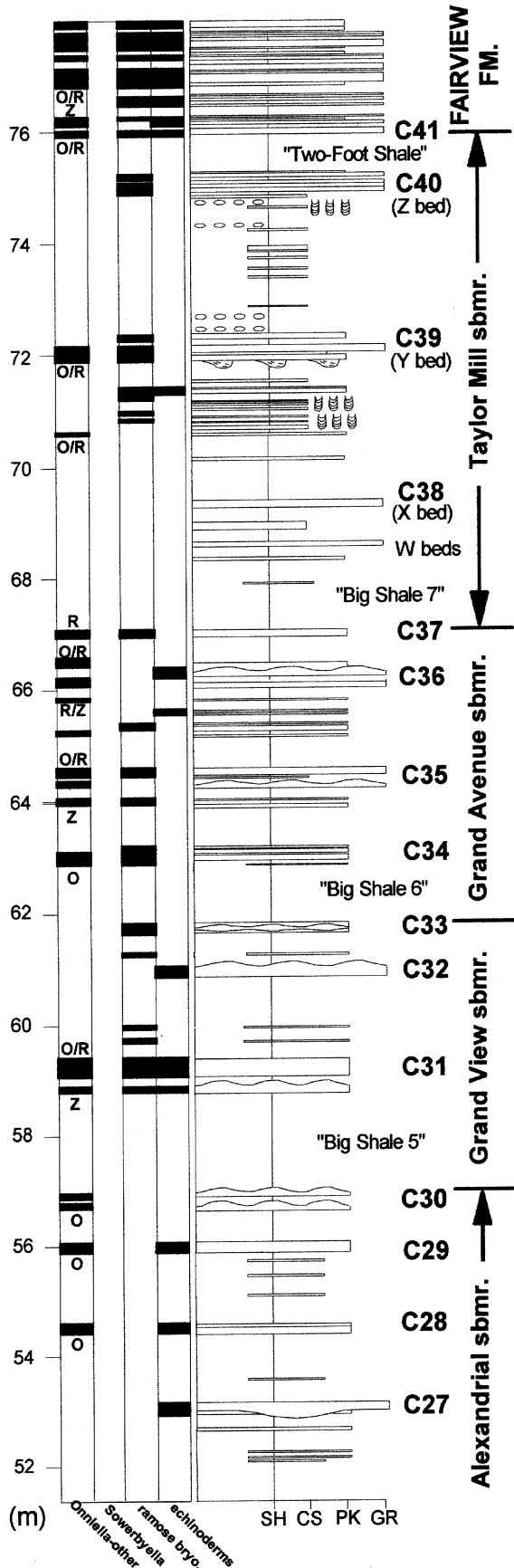
**Figure 4.** Graptolites (*Genticulograptus* cf. *G. typicalis*) in calcareous shale from Snag Creek submember (Southgate Member of Kope Fm.); outcrop behind Kentucky emissions check station off Rte. 17 ("White Castle site"), Covington, KY. Field of view ca. 5x8 cm.

Recognition of specific marker horizons is facilitated by features such as unusual or distinctive faunal elements, trace fossil horizons, taphonomic features, and sedimentary structures. Certain trace fossil horizons are very useful at a regional scale, e.g., Jennette and Pryor's *Diplocraterion* bed (see discussion in 3rd Brett and Algeo paper, this volume). With respect to the utility of taphonomic features, an example is a bed within the middle Kope Fm. (bed 25) containing abundant, highly abraded fragments

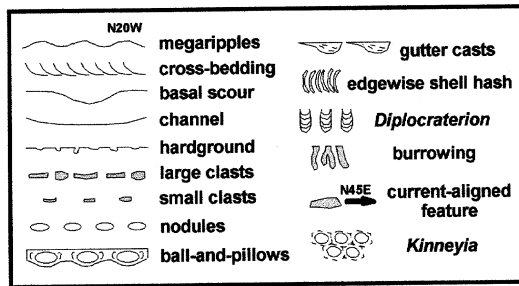
# Composite Reference Section (lower) (middle)



(upper)



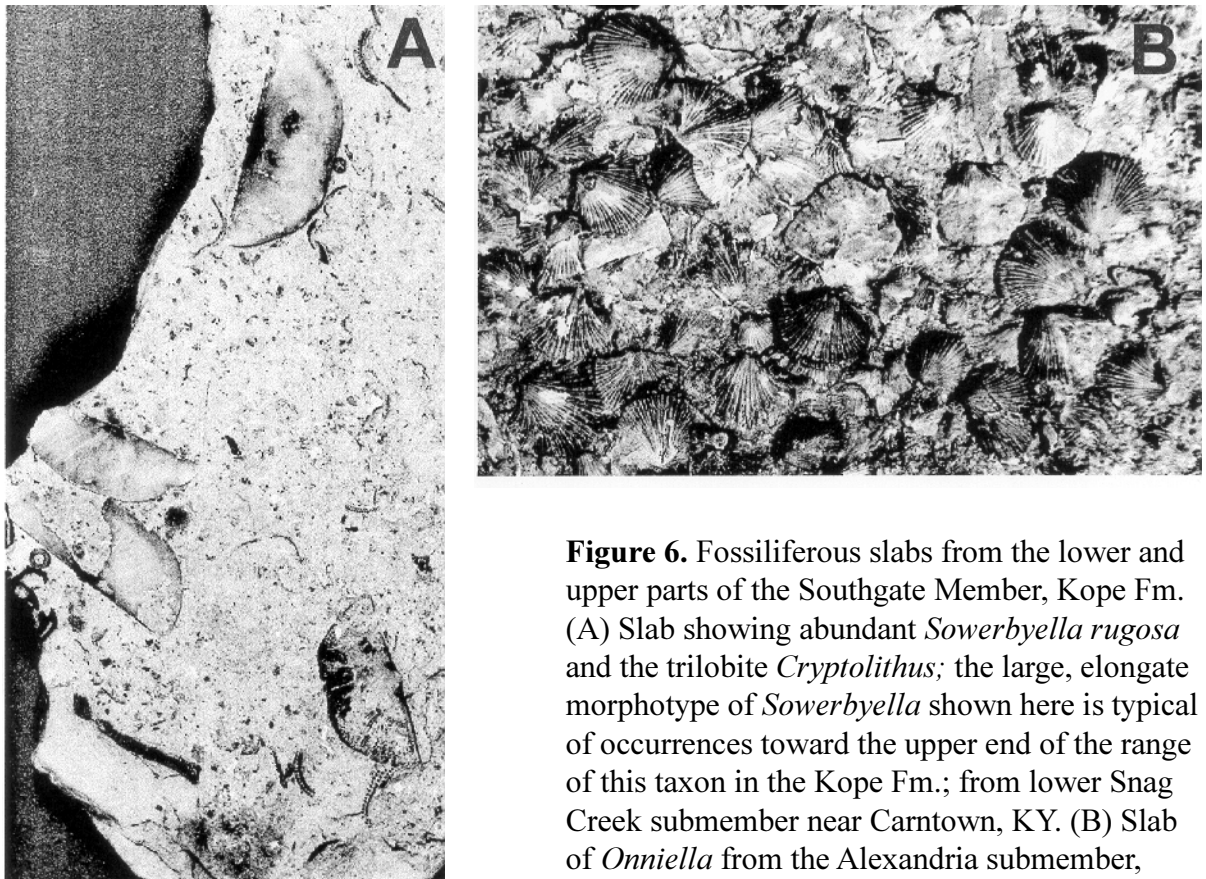
**Figure 5.** New Composite Reference Section (CRS) for the Kope Formation in the Greater Cincinnati area. This section combines (1) the existing Rte. 445 reference section of Holland et al. (1997; their fig. 5, p. 100, this volume), itself a composite based on outcrops along KY Rte. 445 and I-275 near the Ohio River, and (2) a newly measured section of the upper Point Pleasant Limestone and basal Kope Formation along Duck Creek, about 1.5 km south of the Rte. 445 section. (Fig. 2). We tied these sections at the top of a set of thin limestone ledges (cycle 3 of Holland et al.) that are underlain by three meters of shale, calcisiltites, and very thin packstones. This results in about four meters of overlap between sections (at 13-17 m in the CRS) and suggests that ca. 13 m of basal Kope are missing in the Rte. 445 reference section. Note that we have redrawn the Rte. 445 portion of our new CRS based on the original field sections and notes of S. Holland, A. Miller, and D. Meyer in conformance with the style of the other measured sections presented in this field guide. As for all measured sections herein, the four-part column at left shows dominant components of skeletal grainstones and packstones: O = *Onniella*, R = *Rafinesquina*, Z = *Zygospira* (col. 1), *Sowerbyella* (col. 2), ramose bryozoans (col. 3), and echinoderms (col. 4). In the main stratigraphic column, column width represents lithology: SH = shale, CS = calcisiltite, PK = packstone, and GR = grainstone. Beds are labeled per the stratigraphic nomenclature of Brett and Algeo (Table 1, p. 55, this volume). Beds inferred to be correlative with capping beds of cycles in the Holland et al. Rte. 445 reference section are designated by "C" followed by the cycle number; uncertain cycle assignments are indicated by "?", and missing or covered cycle cap beds are enclosed in parentheses.



of the brachiopod *Onniella* that are typically blackened and set into a dark grey matrix; these features are uncommon in the Kope, and the bed itself is widely traceable on this basis. Certain stratigraphic intervals can be distinguished by “taphonomic” features, e.g., a series of beds in the upper middle Kope Fm. (beds 26-30) is characterized by red-weathering *Onniella* brachiopod valves which are relatively complete and only show minor fragmentation; although this discoloration may be of post-depositional rather than taphonomic origin, it nonetheless represents a characteristic useful in correlation. Further, horizons of small carbonate nodules or concretions that show a distinctive pattern of occurrence provide useful fingerprints for particular parts of the section. Sedimentary structures or features such as megaripples, gutter casts, rip-up clast layers, or beds of reworked concretions also provide distinctive marker horizons.

Distinctive features of faunal distribution could also be related to the framework of marker units, and to earlier defined (but now

sometimes disregarded) three members of the Kope Formation: the Economy, Southgate, and McMicken members (Bassler, 1906; Davis, 1994). For example, the brachiopod *Sowerbyella rugosa* (Fig. 6A) was found to be exceedingly abundant in a series of limestones up to about 25 m above the base of Kope (up to about bed 18) at the Rte. 445 reference section; this approximates Bassler's (1906) Economy-Southgate boundary. This species shows an abrupt decrease in abundance above this level, although it reappears as scattered abnormally large and broad-hinged specimens in a few thin beds of the Southgate Member. *Onniella* (Fig. 6B) and, to a somewhat lesser degree, *Rafinesquina* are the dominant brachiopods in limestones of the Southgate and McMicken members. Also present in these units are distinctive mollusc-rich shale horizons that had been used in earlier definition of the Southgate Member. Because the faunal changes can be related to objectively defined lithostratigraphic boundaries, we chose to retain the older member names in essentially their original meanings



**Figure 6.** Fossiliferous slabs from the lower and upper parts of the Southgate Member, Kope Fm. (A) Slab showing abundant *Sowerbyella rugosa* and the trilobite *Cryptolithus*; the large, elongate morphotype of *Sowerbyella* shown here is typical of occurrences toward the upper end of the range of this taxon in the Kope Fm.; from lower Snag Creek submember near Carntown, KY. (B) Slab of *Onniella* from the Alexandria submember, along I-275 near Brent, KY. Both figures X1.5.

but with more tightly defined lithostratigraphic boundaries. Inevitably, our research also pointed up some discrepancies, most notably relating to reported thicknesses of the members of the Kope Fm., that have seemingly been carried on in the literature for many years.

We also recognized a series of eight thick (1-7 m) shale-rich intervals (“Big Shales”) that were subsequently found to be very useful in establishing broad stratigraphic correlations between outcrops (Fig. 5; Fig. 23, p. 29, this volume). Ultimately, we used the decameter-scale shale-limestone packages defined by these shales to define a series of informally named submembers within the Kope Formation (Fig. 5; Table 1). Our submembers, which are each on the order of 10-20 m thick, commence with the bases of these “Big Shale” intervals. As such, they might be interpreted as shallowing upward cycles or parasequences. But, regardless of their interpretation, we believe that they are objectively defined and useful lithostratigraphic and sequence stratigraphic units. We also found it useful to name a few of the more distinctive beds (Table 1), and other beds were numbered following the scheme of Holland et al. (1997). While some workers will surely object to the proliferation of names, we found it useful for purposes of communication to have this shorthand method of denoting particular intervals in the Kope. Also, the use of names for beds, or bundles of beds, obviates problems of numerical order that may arise, for example, when additional beds are found to exist in laterally correlative sections between previously numbered units.

#### **DETAILED CORRELATION OF THE KOPE FM. ALONG THE AA HWY.**

Once a series of marker beds and intervals was established in the Rte. 445 reference section, we began studying nearby outcrops and extending detailed bed-by-bed correlations outward (Figs. 7 and 8). Our strategy was to critically examine adjacent sections moving progressively from northwest to southeast, approximately normal to inferred depositional strike, from the vicinity of Cincinnati to the region of Maysville. More than

50 outcrops were examined along the relatively new Kentucky Rte. 9 (Alexandria to Ashland, or AA Highway) over a distance of about 100 km from Alexandria to new exposures on Route 3071, just northwest of Maysville, Kentucky. Major sections were measured to the nearest centimeter with a steel tape and hand level, and a digital altimeter was used to establish the relative elevations of prominent marker horizons in most outcrops. Representative samples of certain marker beds were collected and slabbed to examine lithology and to make within- and between-bed comparisons of fabrics and faunas. Work on correlation proceeded from large-scale features (e.g., the Kope/Fairview contact, the Grand Avenue beds) to intermediate-scale features (e.g., the six “Big Shales” and the submembers that they define) to, finally, fine-scale features (e.g., individual limestone bundles and event beds). Work at the finest level of correlation is still in progress.

A complicating factor in regional correlation is the commonly observed phenomenon of lateral variation of bedding patterns within a single outcrop. Many amalgamated beds show substantial variation in overall thickness, number of component beds, and degree of homogenization at the outcrop scale, e.g., variations in thickness on the order of 10-15 cm are not uncommon over lateral distances of a few meters or tens of meters. Clearly, many of these beds have complex histories and their final appearance is the net result of multiple episodes of reworking including, in some cases, particularly severe events that occurred toward the end of their depositional history. Although some beds, even thicker amalgamated units, are visibly discontinuous within a given outcrop, we observed that these beds are commonly present at the same stratigraphic level in the next outcrop a few kilometers distant. From this, we concluded that, while beds or bed sets may be missing locally, they are commonly persistent over a broader area *as a series of lenses at the same stratigraphic level*. Further, many beds and bed sets show distinctive stacking patterns that can be identified in a succession of outcrops. Hence, the stacking pattern of limestone beds separated by shales of various thicknesses provide a “bar code” for recognition of particular stratigraphic intervals.

Table 1. Informal Terminology for Divisions and Beds of the Kope and Lower Fairview Fms.

**FAIRVIEW FORMATION**

FAIRMOUNT MEMBER (Upper Fairview)

MT. HOPE MEMBER (Lower Fairview)

Wesselman Submember

"A. Miller shell bed"

North Bend Submember

*Strophomena* beds

~2.5 m; ="non-cyclic interval"

**KOPE FORMATION**

McMICKEN MEMBER (Upper Kope)

1) Taylor Mill submember

a) upper Taylor Mill shale ("Two-Foot Shale")

b) *Onniella* limestone (or "Z bed")c) *Diplocraterion* beds  
(or "Reidlin Road beds")

d) Jennette's gutter cast bed

e) "Y bed"

f) "X bed"

g) graded *Diplocraterion* beds ("W beds")

h) basal Taylor Mill shale ("Big Shale #7")

2) Grand Avenue submember

a) upper Grand Avenue beds

b) lower Grand Avenue beds

c) basal Grand Avenue shale ("Big Shale #6")

~9-10 m; with basal Fairview, equiv. to  
Holland's C1-4 parasequence

cycle 40

cycle 39

cycle 38

~2.5 m

~5 m; equiv. to upper part of Holland's C1-3  
parasequence

cycle 37

cycles 35-36

~1.5 m

**SOUTHGATE MEMBER**

1) Grand View submember

a) "I-471 beds"

b) "Grand View big bed"

c) basal Grand View shale ("Big Shale #5",  
contains upper *Triarthrus* beds)2) Alexandria submember (or "red *Onniella* zone")

a) "Alexandria Pike twin beds"

b) "River Road triplet beds"

c) "black *Onniella* beds"d) basal Alexandria shale ("Big Shale #4",  
contains Carrolltown gastropod beds)

3) Snag Creek submember

a) "Snag Creek twin beds"

b) "Snag Creek triplet beds"

c) lower Snag Creek shale ("Big Shale #3")

4) Pioneer Valley submember (or "*Sowerbyella* zone")

a) "upper White Castle bed"

b) "middle White Castle bed"

c) Nigel Hughes' "trilobite beds"

d) "lower White Castle bed"

e) Newport Plaza hiatus concretion bed

f) lower limestone beds

g) basal shale/calcsiltite beds ("Big Shale #2")

~4.5 m; equiv. to lower part of Holland's C1-3  
4 regularly spaced beds; cycles 32-35

cycle 31

~2 m

~8 m; with Snag Creek sbmr., equiv. to  
Holland's C1-2 parasequence

cycles 29-30

cycles 26-28

cycle 25

~2.5 m

~7 m

cycles 24a-24b

cycles 21-23

~4 m

~17-18 m; named for Pioneer Valley Industrial  
Park, also known as "White  
Castle site"

cycle 20

cycle 18

cycle 16

cycle 15

cycles 12-14

~4 m; cycles 9-11

**ECONOMY MEMBER**

1) Brent Submember

a) "3rd Brent twins"

b) "2nd Brent twins"

c) "1st Brent twins"

d) lower Brent limestones

e) basal Brent shale ("Big Shale #1")

2) Fulton Submember

a) A through G limestone beds

b) lower *Triarthrus* shalesc) "*Glyptocystites fultonensis*" beds

~14 m; equiv. to Holland's C1-1 parasequence

cycles 7-8

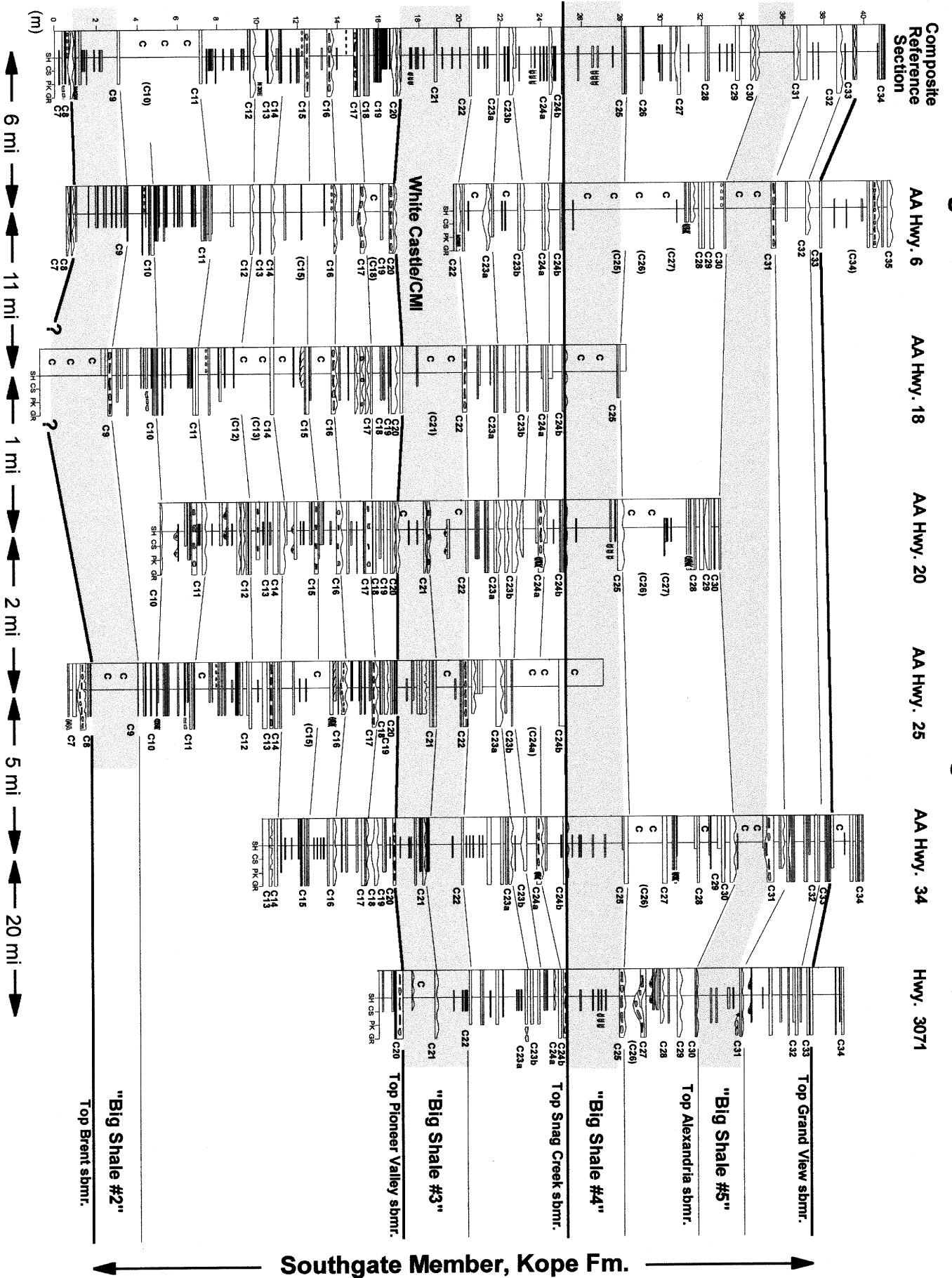
cycles 6a-6b

cycles 5a-5b

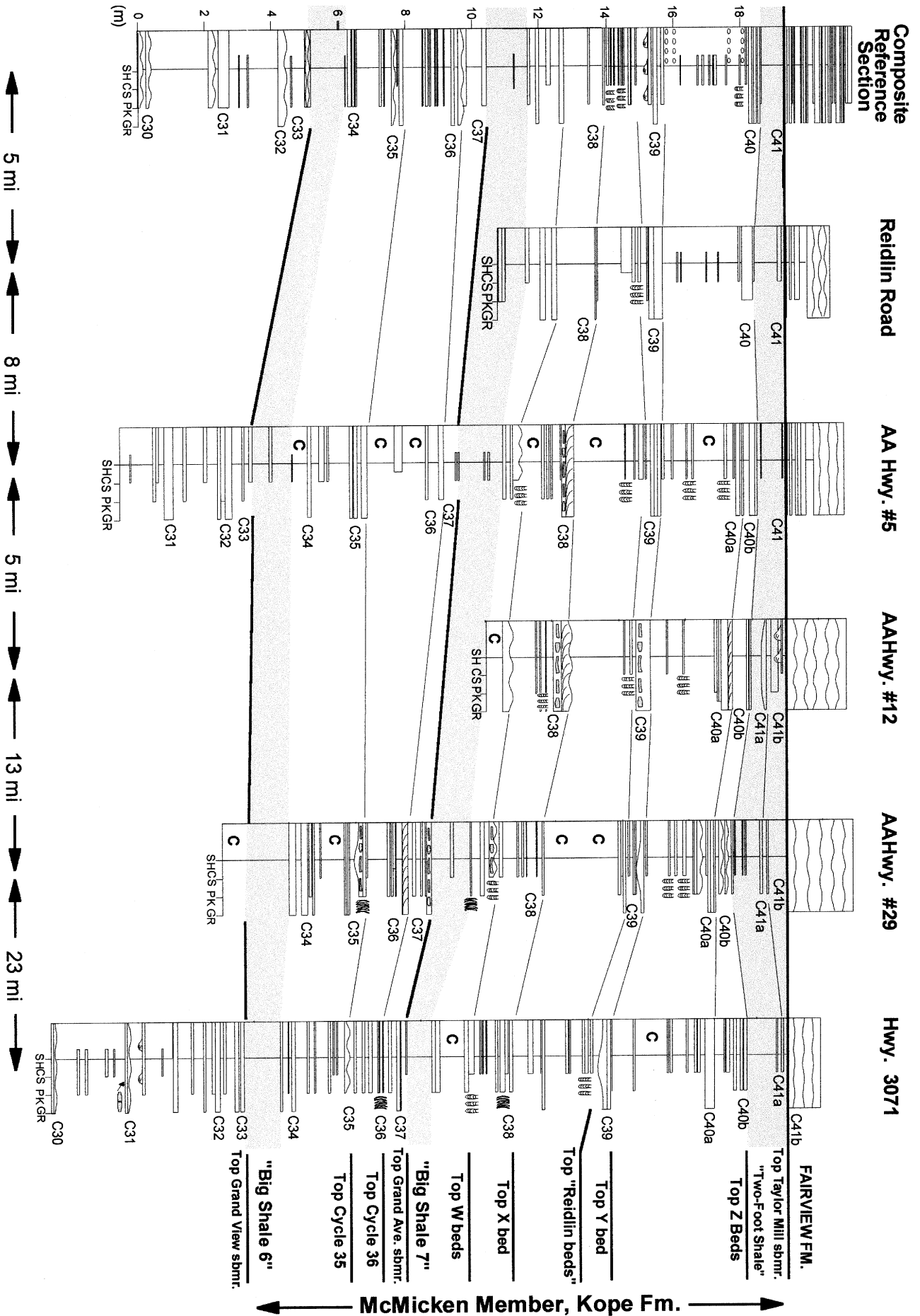
cycles 3-4

~4-5 m; cycles 1-2

**Figure 7. Correlated cross-section of Southgate Member, Kope Fm.**



**Figure 8. Correlated cross-section of McMicken Member, Kope Fm.**



## STRATIGRAPHY OF EDENIAN TO LOWER MAYSVILLIAN STRATA OF THE CINCINNATI ARCH REGION

Although the classic Edenian and Maysvillian strata of the Cincinnati Arch region have been studied since the time of James Hall, many aspects of their detailed stratigraphy require further study on a regional basis. In the following sections, we provide a survey of the existing stratigraphic nomenclature of the Point Pleasant, Kope, and Fairview formations, and a discussion of proposed or modified stratigraphic units and subunits, particularly within the Kope Formation (Table 1).

### Point Pleasant Formation (or Point Pleasant Tongue of Clays Ferry Formation)

The oldest strata exposed in the area of Cincinnati are thin fossiliferous limestones of the upper Point Pleasant Formation (uppermost Shermanian or Mohawkian; Trenton or Lexington Group) at the top of the Middle Ordovician as typically defined (Figs. 12 and 19, p. 12, this volume). The strata are exposed at low elevations along the Ohio River and on the AA Highway in a small region around Brooksville, Kentucky, apparently as a result of development of a very gentle arch, the Moscow-Carntown Anticline (see Potter, 1996). The Point Pleasant beds are partially exposed along the banks of Duck and Holst creeks, where they comprise a series of thin-bedded, crinoid and brachiopod shell fragmental limestones with thin dark gray shale partings. A number of surfaces display well-defined megaripples oriented mostly at N35E to N45E. Irregular, darkly stained hardgrounds occur at several levels, and some of these are encrusted by holdfasts of crinoids,

**Figures 7-8 (previous pages).** Detailed correlations of the Southgate Member of the Kope Fm. (Pioneer Valley, Snag Creek, Alexandria, and Grand View submembers (Fig. 7) and of the McMicken Member (Grand Avenue and Taylor Mill submembers) of the Kope Fm. (Fig. 8) between Cincinnati, Ohio, and Maysville, Kentucky.

such as *Anomalocrinus* and *Lichenocrinus*. A one-meter thick zone of synsedimentary folding and minor faulting occurs about 7 m below the top of the Point Pleasant Fm. near Brooksville, Kentucky (see DeJong et al., this volume). A distinct angular discordance exists between these deformed beds and an overlying coarse crinoidal grainstone.

Biostratigraphic studies of the Point Pleasant Fm. indicate that it belongs to the *superbus* conodont Zone, suggesting a latest Shermanian Age (Sweet and Bergström, 1984). The Point Pleasant Fm. is overlain by Kope Formation shales that have yielded early Edenian graptolites (*Climacograptus spiniferus* Zone; Mitchell and Bergström, 1991). By general agreement, the base of the Kope Fm. near Cincinnati is the stratotype of the base of the Edenian Stage and, therefore, also marks the base of the Cincinnati Series.

### Kope Formation

The Kope Formation is a major package of shale-dominated strata between the limestone-dominated Point Pleasant and Fairview intervals (see CRS, Fig. 5). The Kope consists predominantly of soft, pale to medium gray, readily weathering mudstones or shales with very minor black or dark gray tongues, thin (generally one to five cm) beds of light gray laminated siltstone and/or calcisiltite, and thin to (rarely) medium (5 to 60 cm) beds of skeletal (brachiopod, bryozoan, and crinoid debris) packstones and grainstones (e.g., Fig. 6). The latter typically form the caps of small bundles and may in some cases be abruptly overlain by mudstone. The mudstone itself varies from nearly barren to highly fossiliferous, locally containing intact colonies of branching bryozoans, articulated crinoids, trilobites, and other fossils (e.g., Fig. 4). Our measurements indicate that the Kope Formation is approximately 70-75 m (230-246 ft) in thickness in the Cincinnati region, which agrees well with measurements of Ulrich (1888) and Davis and Cuffey (1998).

The Kope Formation was named by Weiss and Sweet (1964) for exposures at Kope Hollow, at Levanna in southern Ohio, and the term was used in substitution for the biostratigraphically based Eden or Latonia Formation (see Diekmeyer, 1998, for review).

The Kope Formation coincides approximately with the Edenian local stage; the base of the Kope is generally placed at or near the base of the Edenian and, therefore, by most definitions also at the base of the Upper Ordovician Cincinnati Series. The absolute age of the Edenian Stage has recently been estimated to be about 445.5 to 449.5 million years.

Bassler (1906) recognized three members in the “Eden Shales”: (a) the lower Kope, or *Aspidopora newberryi* beds, was designated the Economy Member (originally reported as 28 m but subsequently as little as 16 m in thickness; Davis, 1994); (b) the middle Kope, typified by *Batostoma jamesi*, was assigned to the Southgate Member (ca. 36-37 m); and (c) the upper Kope, a limestone-rich interval with abundant *Dekayella ulrich*, was designated the McMicken Member (ca. 16-21 m; Table 1). These members were based in part upon unique bryozoan assemblages, but also partially on lithologic criteria. The term “Fulton beds” was introduced by Foerste (1905) for the basal dark shale tongues containing the trilobite *Triarthrus*, and, subsequently, the term Grand Avenue Member was introduced by Ford (1967) for a distinct 2.5- to 3-m-thick bundle of limestones and thinner shales about 10 m below the top of the Kope Fm. Weiss and Sweet also advocated abandoning the older member names because they felt that these were local, biostratigraphically based units and could not be traced laterally for any great distance beyond Cincinnati. However, because much of the older literature as well as some more recent reports (e.g., Davis, 1992) refer to Bassler’s divisions, we have chosen to retain these names but to redefine them to aid in their recognition. We conclude that, as redefined, these divisions are traceable well beyond the Cincinnati area. In addition, we recognize a series of finer divisions within the Kope that are also widely traceable and that herein will be named as informal submembers, for purposes of detailed stratigraphic correlation (Table 1).

**Economy Member (Lower Kope):** The lower division of the Kope Shale, designated as the Economy Member by Bassler (1906), carries a distinctive fauna that includes the

small eyeless trinucleid trilobite *Cryptolithus*, an abundance of the small brachiopod *Sowerbyella* and the bryozoan *Aspidopora* (especially in the upper part of this member). The thickness of the Economy Member has been variably reported as 16 to 28 m (Caster et al., 1961; Davis and Cuffey, 1998; Diekmeyer, 1998, based on Bassler, 1906). This discrepancy probably reflects both poor exposure of the lower Kope interval and confusion as to where to draw its upper boundary. Measurements by Holland et al. (1997) and the present authors suggest that a thickness of about 20-22 m is typical for the Economy Member in the Cincinnati region. This places the upper contact of the Economy Member at the base of “Big Shale #2” in our nomenclature (Fig. 5; Table 1) and at the top of Holland’s sequence C1-1 (located at about 9 m in the Rte. 445 reference section; Fig. 5, p. 100, Holland et al., this volume); we also designate this level as the top of the Brent submember of the Kope Fm.

**Fulton submember:** Where observed, the upper contact of the Point Pleasant Formation with the Economy Member of the Kope Formation ranges from a lithologically abrupt transition from limestone to shale to a gradationally interbedded succession of beds (Fig. 12 and 19, p. 12, this volume). The basal Kope near Cincinnati has been referred to as the “Fulton beds” (Foerste, 1905); we consider the Fulton beds to be the first submember of the Economy Shale (Table 1). The Fulton interval contains an unusual fauna that Ulrich and Bassler (1914) considered to be a recurrence of the older Bromley Shale assemblage (below the Point Pleasant Fm.); it includes the inarticulate *Leptolobus*, a small form of *Leptaena*, and the crinoid *Merocrinus*. Many of the darker shales yield graptolites and the trilobite *Triarthrus*, which is normally restricted to dysoxic facies such as the Utica Shale of New York State. Such beds are intercalated with crinoidal grainstones and small carbonate concretions in the lower 2 m of the Kope Fm. at Duck Creek near the Rte. 445 reference section. The top of the Fulton submember is herein defined as the contact between a bundle of limestone beds about 4 above the base of the unit and an overlying ca. 6-m-thick shale (Big Shale #1) assigned to the Brent submember (see CRS; Fig. 5).

Near Brooksville, Kentucky, the contact between the upper Point Pleasant and Kope formations appears gradational and the basal beds lack the dark shaly tongues typical of the Fulton beds near Cincinnati. Here, the basal few meters of the Economy Member contain several unique faunal elements, notably the rhombiferan "*Glyptocystites fultonensis*" (presently being revised by C. Sumrall) and the large crinoid *Merocrinus*. At Holst Creek near Fosters, Kentucky, the lower 4.5 meters of the Kope Fm., representing the Fulton beds, include a suite of about five fairly regularly-spaced, 20-30 cm-thick limestone beds, primarily crinoid grainstones (Fig. 12, p. 12, this volume).

**Brent submember:** The Fulton beds are followed by a ca. 6- to 7-m-thick interval dominated by sparsely fossiliferous shale with thin (< 5 cm), hummocky, laminated calcisiltites and minor packstones ("Big Shale #1"; see CRS, Fig. 5). This interval culminates in a series of three twinned packstone or grainstone beds with associated carbonate nodules or concretions, totaling about three members in thickness; we term these the "Brent beds" for exposures along the Rte. 445 reference section at Brent, Kentucky (Fig. 23, p. 29, this volume). These fossil fragmental limestone beds are typically megaripped and weather a rusty color due to the presence of pyrite. They contain abundant fragments of *Sowerbyella*, *Onniella*, and slender ramose bryozoans as well as some sheetlike bryozoans and *Rafinesquina* (Fig. 6B). The top of this interval displays an abrupt shift back to shales and calcisiltites; faunal studies of Holland et al. (1999; this volume) also show a significant faunal shift above these beds (at about 9 m in the Rte. 445 reference section). Holland et al. used this shift to demarcate the top of Kope sequence C1-1. The base of their C1-1 sequence is not clearly defined, because the Rte. 445 reference section does not reach the lower Economy Member beds. The upper contact of sequence C1-1 is correlative with the boundary of the Economy and Southgate Members.

**Southgate Member (Middle Kope):** The middle portion of the Kope (approximately coinciding with the Southgate Member of earlier authors (e.g., Caster et al., 1955) is

widely reported to comprise about 35 to 37 m of shale and thin siltstones/calcisiltites. It corresponds to all of Holland et al.'s (1997) C1-2 sequence and the lower 3/4 of their C1-3 sequence (the top of C1-3 being comprised of the Grand Avenue submember of the overlying McMicken Member of the Kope). The Southgate carries a somewhat less diverse fauna than the Economy but includes bivalve and gastropod assemblages, the trilobite *Flexicalymene granulosa*, and the bryozoan *Batostoma jamesi*. An important faunal change is the distinct shift from *Sowerbyella*-dominated assemblages to *Onniella*-dominated assemblages in the middle of the Southgate Member, at the contact between the Pioneer Valley and Snag Creek submembers (Fig. 5; Table 1). This faunal change coincides approximately with a graptolite zonal boundary, marked by a shift from abundant *Geniculograptus typicalis* (probably indicative of the *C. spiniferus* Zone) to *Geniculograptus pygmaeus*, indicative of the *G. pygmaeus* Zone (Figs. 3-4; Mitchell and Bergström, 1991).

The Southgate Member is divisible into four easily identifiable stratal packages herein assigned submember status (Fig. 7; Table 1). Each interval has a lower portion dominated by shale and an upper interval with numerous closely spaced thin limestone beds, including both calcisiltites and fossiliferous packstones/grainstones. We have termed these intervals the Pioneer Valley, Snag Creek, Alexandria, and Grand View submembers

**Pioneer Valley submember:** This submember is equivalent to sequence C1-2 of Holland et al. (1997). The unit is named for good exposures near the Pioneer Valley Industrial Park, adjacent to KY Rte. 17 and about 0.5 mi. south of I-275 (called the "White Castle site" by Holland et al., 1997). It commences with a thick (ca. 11 m) sparsely fossiliferous shale-calcisiltite interval ("Big Shale #2"; see CRS, Fig. 5). A rather poorly known bed that is rich in molluscs occurs near the base of this shale (S. Felton, pers. comm. 1999). At the Rte. 445 reference section, this 11-m interval contains only three limestone beds thicker than 10 cm; these beds are located at about 2.2 m, 6 m, and 10 m above the base of the unit. Each of these intervals

shows a minor spike of thin ramose bryozoans, suggestive of minor shallowing and/or less turbid conditions. Near Carntown, the lower Pioneer Valley submember becomes much more carbonate rich, with up to half of this lower 11-m interval consisting of limestone beds (Fig. 9, p. 9, this volume).

A number of probable deeper water faunal elements make their first appearance in these shales; these include the delicate inadunate crinoids *Cincinnatiocrinus* and *Iocrinus*. The crinoid *Ectenocrinus* is also abundant, sometimes occurring in dense masses or “log jams” of columns (Fig. 7, p. 69, this volume). The trilobite *Cryptolithus* is also relatively common in these beds. Two important horizons were recognized and traced in this interval: (a) a “worm bed” (rich in *Sphenothallus*) about 6.7 m above the base of the unit; and (b) a starfish bed, rich in *Taeniaster*, about a meter higher. The “worm bed” contains unique elements such as *Sphenothallus*, *Protoscolex*, and a bivalve fauna including *Rhytmya*.

The uppermost 3 m of the Pioneer Valley submember carries a distinctive suite of thick, megaripped beds (Fig. 3, p. 67, this volume) and shows an abrupt increase in ramose and cryptostome bryozoans (“Pioneer Valley beds”; see CRS, Fig. 5). These thick limestones are characterized by near-total dominance of the brachiopod *Sowerbyella* (Fig. 6A), which becomes uncommon above this level in the Cincinnati area. The three upper limestones form distinctive, thick, commonly limonite-stained ledges. The lowest is a megaripped crinoidal bed that contains reworked clasts encrusted by fossil bryozoans and crinoid holdfasts, probably deposited on a hiatal surface (Fig. 9, p. 70, this volume); it is informally called the “Newport Plaza bed” for occurrences behind a shopping plaza off Grand Avenue in Newport, Kentucky. This bed has been traced from near Batavia, Ohio, to near Big Bone Lick State Park, in Kentucky (M. Wilson, 1998; S. Felton, pers. comm. 1999). A shale bed containing well-preserved *Flexicalymene* and other trilobites occurs slightly above the hiatal concretion bed and was described recently by Hughes and Cooper (1999) from the Pioneer Valley (“White Castle”) site. As yet this bed has not been traced to other outcrops. About 1.5 m

above the Newport Plaza bed is a thick crinoidal grainstone (“White Castle bed”) and a meter higher is the uppermost bed of the Pioneer Valley submember. This last bed is up to 30 cm thick and is an amalgamated crinoidal and *Sowerbyella* shell grainstone with large orange-buff mudstone clasts. It is distinctive in being the last major bed below a thick shaly interval at the base of the overlying submember.

*Snag Creek Submember:* The thick *Sowerbyella*-rich limestones of the Pioneer Valley submember are abruptly overlain by a shaly zone which culminates in distinctive orange-weathering siltstones and packstone beds (Fig. 7). The interval is about 8 to 8.5 m thick near Cincinnati. A siltstone about 0.5 m above the base is notable for exceptionally well-preserved trilobite traces; a second, higher siltstone bed is typified by millimeter ripples. These beds are well-exposed along the AA Highway just southeast of Snag Creek valley, for which they are named (Figs. 15-18, pp. 15-17, this volume).

The lower shale-rich interval (“Big Shale #3”) is characteristically rich in graptolites and passes upward into a distinctive series of closely spaced, bryozoan-rich limestone ledges that weather a rusty yellow. An interval rich in calcareous nodules, some containing oriented graptolites (Fig. 4), occurs about 1.5-2 m below the top of this package. The uppermost pair of limestone ledges (beds 24a and 24b), stands out especially well because it is overlain by a thick, relatively pure shale (“Big Shale #4”) at the base of the overlying Alexandria submember (Fig. 16, p. 15, this volume). Below bed 24a at several localities are one or more lenticular beds consisting of coarse ramose bryozoan packstones and representing possible channel fills. Just west of the Snag Creek valley, a zone of ball-and-pillow deformation occurs about 2 m below the top of this submember (cycle 23; Fig. 16, p. 15, this volume). This deformed zone appears to be very local in extent.

*Alexandria Submember:* This distinctive interval is named for exposures along both sides of the AA Highway just west of East Alexandria Pike, near the town of Alexandria, Kentucky (Fig. 3, p. 5, this volume). Its base is a 2.5- to 3-m-thick, pure shale interval (“Big Shale #4”) that is easily recognized

in outcrops between Carrollton and Maysville, Kentucky. The base of this shale is notable in containing a horizon that is exceptionally rich in well-preserved uncrushed mollusc shells (“Carrollton gastropod bed”; Table 1). The fossil assemblage includes the gastropods *Lophospira*, *Sinuities*, *Ruedemania*, and *Cyrtolites*, the bivalves *Modiolopsis*, *Cycloconcha*, and *Lyrodesma*, and the nautiloids *Gomphoceas*, *Technoceras*, and *Cameroceras* (Ulrich and Bassler, 1914). Isolated specimens of an unusually large, long-hinged morphotype of *Sowerbyella* as well as *Cryptolithus* also recur at this level. This fauna was noted by Ulrich as typical of the lower Southgate Member. The first appearance of the zonal graptolite *Geniculograptus pygmaeus* occurs at approximately this level (ca. 33 m above the base of the Rte. 445 reference section; Mitchell and Bergstrom, 1991).

The upper portion of the Alexandria submember shows a distinctive pattern of compact limestone ledges separated by intervals of rather pure shale (Fig. 7). The first ledge-forming limestone (bed 25) is typically tabular and contains blackened fragments of *Onniella* and other fossil debris (“black *Onniella* bed”). The overlying series of ledges (beds 26-30) are sharp-based 15- to 3-cm-thick buff-weathering packstones to grainstones containing shale clasts that are especially typified by a reddish discoloration of *Onniella* valves (“red *Onniella* beds”; Fig. 6B); this discoloration is possibly due to limonite impregnation. The upper two ledges (beds 29 and 30) are subequal in thickness and separated by about 60-70 cm of shale (n.b., these can be confused with beds 24a and 24b at the top of the Snag Creek submember). The upper bed is typically an amalgam of two limestones; the lower of which displays reworked encrusted concretions at several localities near Cincinnati.

*Grand View Submember*: This unit, named for exposures along the AA Highway near Grand View Road, is relatively thin (ca. 4.5-5 m) and includes a basal 1.3- to 2-m-thick pure dark gray shale (“Big Shale #5”) that has been reported to contain a recurrence of the trilobite *Triarthrus*, otherwise known primarily from the basal Fulton beds. Hol-

land et al. found *Cryptolithus* to be common immediately below this level. The base of this shale displays yet another bed rich in molluscs, especially the bivalves *Rhitimya*, *Cymatonota*, and *Psiloconcha*, typically preserved as molds; this bed also shows the recurrence of certain faunal elements found in the “Worm bed” of the lower Southgate Member. This thick shale is overlain sharply by a 40- to 60-cm-thick amalgamated bundle of packstone to grainstone beds, and that bundle, in turn, by three evenly spaced thick limestone ledges (Fig. 7). These beds also possess reddish weathering brachiopods, including both *Onniella* and *Rafinesquina*.

**McMicken Member (Upper Kope):** Approximately  $\frac{3}{4}$  of the way through the thickness of the Kope Formation, a somewhat more compact bundle of limestone beds forms the previously named “Grand Avenue Member” (GAM) of the Kope Fm. It is composed of about 60-70% limestone beds and is more carbonate rich than the remainder of the Kope Fm. (Figs. 4-5, p. 6, this volume). It is overlain in turn by the shaly upper portion of the Kope, herein designated the “Taylor Mill submember” that finally grades upward into the Fairview Formation (Figs. 5 and 7, p. 6-7, this volume). Together, the Grand Avenue and overlying uppermost Kope were previously referred to as the McMicken Member. This interval has an approximate thickness of 15 to 16 m (Fig. 5; Bassler, 1906, Caster et al., 1951; Diekmeyer, 1998).

*Grand Avenue Submember*: This interval was named as a member by Ford (1967) for exposures along Grand Avenue just northwest of Bald Knob in Cincinnati. It is herein reclassified as a submember of the McMicken Member. As defined herein (and in nearly the original sense), the Grand Avenue submember begins with a relatively thick (90-100 cm) shale band (“Big Shale #6”; Fig. 8). This is overlain by an interval about 30 cm of closely spaced, thin packstone and grainstone beds, 45-50 cm of shale with thin lenses of limestone, and then the main body of “Grand Avenue beds,” about 2.5 to 3 m composed of numerous closely spaced, thin and laterally discontinuous packstones and fossiliferous shales, resembling the upper Fairview Formation. In most outcrops, this interval is di-

visible into two or three bundles of limestone beds by somewhat more shaly zones. A highest compact limestone (bed 37) occurs about 0.5 m above the main mass of Grand Avenue beds but is included in the Grand Avenue submember. The Grand Avenue is very rich in bryozoans, especially *Dekayella* and *Batostoma* and contains abundant *Rafinesquina*, sometimes as edgewise coquinas. In outcrops near Maysville, the unit has yielded *Constellaria*, a bryozoan generally associated with the Fairview Formation.

*Taylor Mill submember:* The highest division of the Kope Fm. is very distinct from both the Grand Avenue beds and the overlying Fairview Formation; together with the North Bend submember of the overlying Fairview Formation, it corresponds to the C1-4 sequence of Holland et al. (1997). This interval is generally 9.5 to 10 m thick and contains a very distinct succession of beds (Fig. 8). It is excellently exposed along Taylor Mill Road at its junction with Mason/Reidlin Road, where it has been well studied by Diekmeyer (1998), Jennette and Pryor (1993), and others. It is much more shaly than the Grand Avenue submember and commences with a pure shale (“Big Shale #7”) about 1.5 m thick. Above this interval at most localities is a distinctive two-part graded bed with a packstone base overlain by thick hummocky-laminated calcisiltite with large *Diplocraterion* burrows (“W beds”). A second calcisiltite-packstone bundle occurs about 2 m higher (“X bed”). These beds are rich in bryozoans and *Onniella* and are separated by thick shales containing numerous burrowed calcisiltites.

Toward the top of the interval, several beds form outstanding markers. A 50-cm-thick limestone bundle (“Y-bed”) has at its base a prominent 10-15 cm siltstone bed with distinctive *Diplocraterion* and penetrative millimeter ripples (“Reidlin Road bed”) and a gutter cast bed; both have been found in many localities around Cincinnati (Fig. 8; Jennette and Pryor, 1993). This is overlain by about 2.5 m of shale containing numerous calcisiltites. At the top of the Taylor Mill submember is a distinctive compact bundle (up to six beds) of *Onniella*-rich packstone and grainstone (“*Dalmanella* bed” of older literature) followed by a final 60- to 80-cm-

thick shale interval (the so-called “Two-Foot Shale bed”), and then densely stacked grainstones of the basal Fairview. All of these beds are laterally persistent and have been observed in virtually all outcrops of the uppermost Kope (Fig. 8).

### Fairview Formation

The Fairview Formation ranges from about 28 to 32 meters thick, thickening slightly from Maysville to the Cincinnati area, and consists predominantly of limestones. The interval is locally subdivisible into bundles of limestone and thinner intervals of shale. In contrast to the Kope Fm., limestone predominates in most intervals of the Fairview (averaging about 60% of total thickness), at least in the Cincinnati to Maysville area. Tongues of more shaly material have been detected to the north in Ohio. The most prominent of these is a shaly wedge (the Wesselman tongue of the “Kope Formation”) that separates compact limestones of the lower third of the Fairview (North Bend tongue) from compact limestones of the upper third of the Fairview in northern Hamilton, Butler, and Adams counties (Schumacher, 1998). The lower compact (“non-cyclic”) interval contains a distinct epibole of the brachiopod *Strophomena planumbona*. This compact limestone interval is an important marker bed in outcrop and in the subsurface (Schumacher, 1992). Minor thin shale shaly tongues are also recognized in the Alexandria to Maysville exposures of the Fairview Formation. The Fairview constitutes the lower part, or approximately 2/3 of the thickness, of the type Maysvillian Stage. The Fairview Fm. is dominated by shell-rich beds composed primarily of the brachiopod *Rafinesquina*. Diverse other brachiopods, including *Platystrophia laticosta* (s.l.), *Hebertella*, *Zygospira modesta*, are common at many levels. Certain beds within the Fairview Fm. display sharply burrowed tops and may represent firmgrounds or hardgrounds. Also, the upper Fairview contains distinctive horizons of strongly deformed limestone that have been interpreted as seismites.

## IMPLICATIONS OF DETAILED CORRELATION OF THE KOPE FORMATION

We have attempted detailed correlations for two intervals of the Kope Formation: (1) the Southgate Member, the 35- to 40-m-thick middle third of the Kope (Fig. 7), and (2) the McMicken Member, the 15-m-thick upper third of the Kope, immediately below the well-defined contact with the overlying Fairview Formation (Fig. 8). These intervals were chosen because they are easily recognizable and identifiable based on criteria independent of the lithology of the strata. Our correlations provide unequivocal evidence for the persistence of certain distinctive decimeter- to meter-scale limestone beds and bed bundles as well as certain shaly intervals throughout the Cincinnati-Maysville region. In some cases, even single event beds such as distinctive calcisiltite with gutter casts or with other types of sedimentologic features can be traced over this distance.

Comparison of the Kope Fm. near Cincinnati (Rte. 445 reference section) with the Rte. 3071 roadcut in Maysville shows that all submembers in the upper 40 m of the formation are easily discernible across this distance of ca. 80 km (n.b., the lower 30 meters of the Kope is not exposed at Maysville). This strong correlatability reflects the persistence of the "Big Shale" intervals, as well as the major bundles of limestones separating them (Figs. 7-8). The thicknesses of both of these major components show only minor changes over this distance, being slightly thicker at Maysville. Moreover, facies in the Kope Fm. in both areas are quite similar. Relative to the Cincinnati area, the Kope Fm. at Maysville exhibits somewhat thicker limestone bundles, and calcisiltites that are both thicker and somewhat more numerous.

In contrast to the apparent uniformity of facies and unit thicknesses along the Cincinnati-to-Maysville transect, much more significant facies and thickness changes are apparent over comparable distances along transects in other directions (e.g., southward along I-75 toward Lexington, Kentucky). This strongly suggests that the Cincinnati-Maysville transect exposed along the AA Highway is closer to being parallel to depo-

sitional strike than normal to it. The slight changes in lithofacies and biofacies of the Kope Fm. observed along this transect suggest that the Maysville area represents a slightly more proximal facies than the Cincinnati area. Evidence for shallower ramp conditions in moving southeastward from the Cincinnati area is even stronger in the overlying Fairview and Grant Lake formations (see Schumacher, 1992). In any case, our observations suggest that local depositional strike is closely coincident with the NW-directed, Maysville-to-Cincinnati segment of the Ohio River (and thus also parallel to the AA Highway). This provides empirical support for Ettensohn's (1999, in review) reconstruction of a NW-SE-oriented embayment in the Sebree Trough just north of the Greater Cincinnati area.

A further implication of this work is that the processes responsible for producing the pattern of thicker shales and limestone bundles (putative cycles) and even individual thicker beds were pervasive over wide tracts of the ramp, at least parallel to and, to a limited extent, across depositional strike. At least in this portion of the Cincinnati Series, the empirical evidence suggests a stratigraphic pattern closer to a layer cake than the local facies mosaic that has been depicted in recent stratigraphic charts (e.g., Fig. 1; Cuffey, 1998). This result strongly supports the inference that these stratigraphic patterns were generated by allocyclic processes (e.g., eustatic sea level or climatic changes) as opposed to strictly local autogenic phenomena.

One significant departure from lateral facies uniformity is observed along the AA Highway. The Pioneer Valley submember appears distinctly more limestone rich and coarser grained in the region around Carntown to Brooksville, midway between Cincinnati and Maysville. Also, Upper Kope limestone beds are slightly thicker and more prominent in this area. This may reflect the existence of a gentle paleo-swell in this area, resulting in slightly shallower water depths there than to either the north or south. It is intriguing that this is also the area of the gentle "Moscow-Carntown anticline" recognized by Potter (1996). These are preliminary observations but they suggest the need for additional study.

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

Carlton E. Brett and Thomas J. Algeo

Department of Geology  
University of Cincinnati  
Cincinnati, Ohio 45221-0013

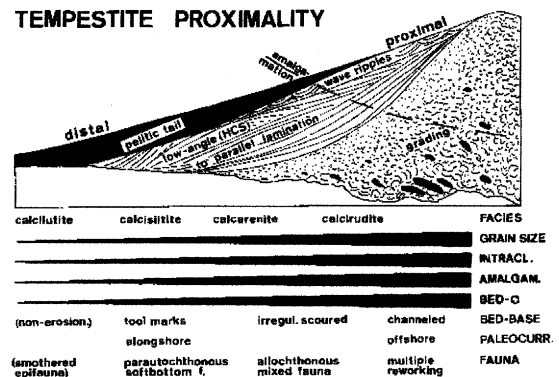
## INTRODUCTION

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

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

A second major advance in sedimentary geology is the recognition, or more correctly, the resurgence of interest in cyclicity of many scales within the sedimentary record. In particular, geologists have begun to recognize that a number of recurring, possibly periodic, processes may be recorded in certain sedimentary facies. The renewal of interest in the Milankovitch-band perturbations in the Earth's orbit and their effects upon climates has triggered a re-examination of many sedimentary sections for the possible presence of

periodic cycles (DeBoer and Wonders, 1984; Gale and House, 1995). If small- and intermediate-scale Milankovitch-driven cycles can be recognized consistently in sedimentary rocks, it will have a revolutionary impact on stratigraphic correlation as well as the ability to determine the relative amounts of geologic time recorded in particular sedimentary packages. However, the Milankovitch cycles studies have had their cogent critics (e.g., Wilkinson et al., 1996, 1997).



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

The Edenian-Maysvillian strata in the area of Cincinnati contain many limestone beds exhibiting features inferred to reflect rapid (i.e., event) sedimentation, and the ubiquitous rhythmicity of shale-limestone couplets has been interpreted to represent some type of cyclic sedimentation process. A number of authors have investigated event beds

and small-scale cycles within the Kope and lower Fairview formations and associated units (e.g., Tobin 1982; Jennette and Pryor 1993; Holland et al., 1997; Miller et al., 1998). In this contribution, we will review the conclusions of these workers regarding the nature and significance of event beds and cycles in the Kope and lower Fairview formations and add observations and interpretations based on our own field studies. Our work along the AA Highway between Alexandria and Maysville has also permitted us to correlate many of these event beds and small-scale cycles over distances of ca. 80 km, and, hence, we are able to report on their lateral continuity and proximality characteristics for the first time.

## EVENT BEDS

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

Event beds that exhibit distinctive characteristics are highly useful in correlating strata within the Cincinnati Series. This utility derives from the fact that event beds represent single, unique episodes of sediment

deposition and/or deformation and, hence, are timelines. In the Kope Formation, these range from small episodes of deposition of silt and mud to large-scale, possibly catastrophic, seismic deformation horizons. In the following paragraphs, we describe some of the various types of event beds and their importance for correlation of Edenian and lower Maysvillian strata of northern Kentucky.

## Tempestites

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



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

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

Many skeletal debris layers show evidence of intense reworking in the form of megaripples, graded bedding, and caps of fine laminated silt (Fig. 3). Such episodes of intense reworking are likely to have been brief, e.g., the duration of a major storm, although the sediments themselves may have accumulated over a much longer period of time. Such

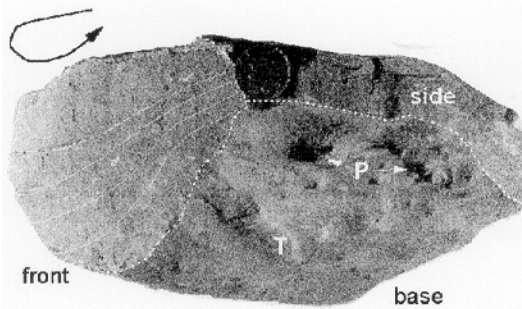


**Figure 3.** Megaripples in the “Z bed” of the Taylor Mill submember. Wavelength about 0.5–0.8 m. From Jennette and Pryor (1993).

graded beds may be persistent through outcrops over a wide area. A particularly notable example of such a complexly graded shell bed was documented by Miller (1997) and is presently under detailed study by S. Barbour (see contribution this volume).

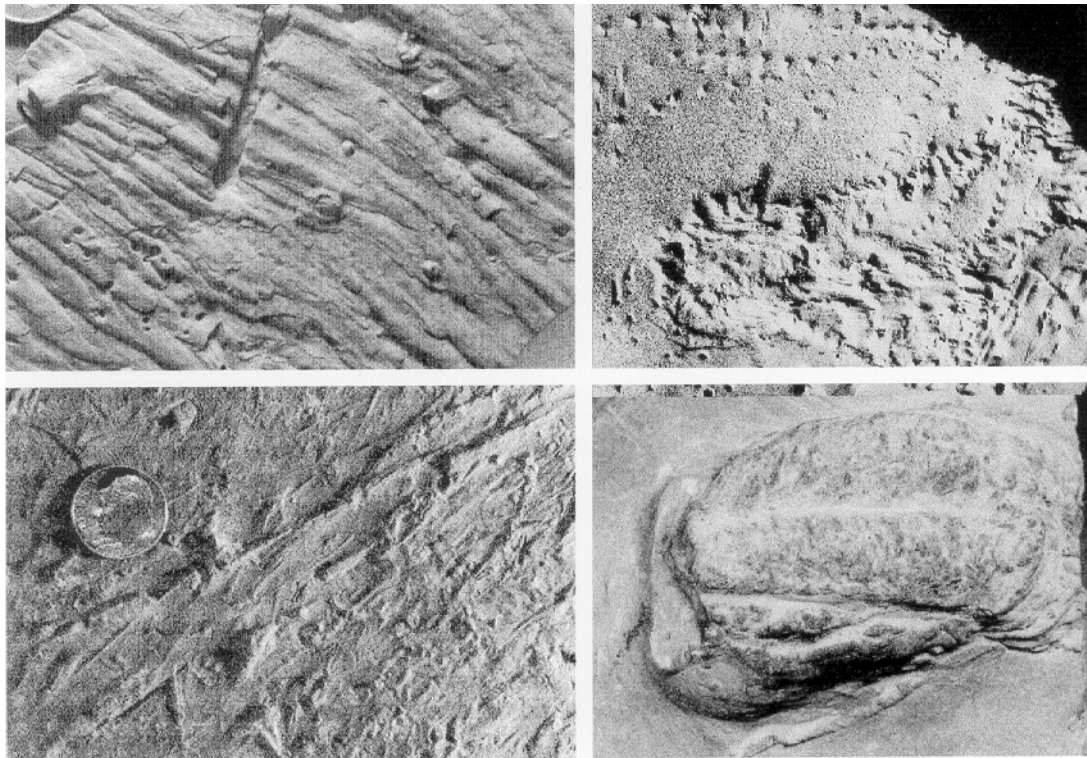
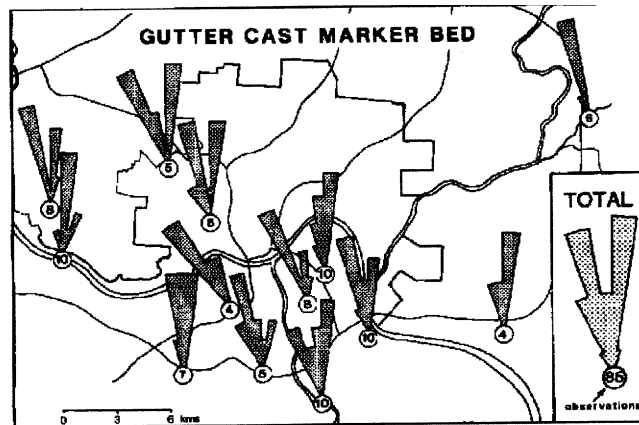
Several types of more distal tempestites have proven to be regionally extensive and traceable (Jennette and Pryor, 1993). These include (1) distinctive graded beds (e.g., one such layer in the upper Kope Formation that grades upward from shell hash to a thick hummocky laminated calcisiltite has been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

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



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

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



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

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

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

### Trace Fossil Horizons

Likewise, certain horizons carry particularly well-preserved trace fossils, such as *Rusophycus*. These also can be found in more than one outcrop and indicate conditions particularly favorable to formation and/or preservation and of such traces. Rapid removal of surficial sediments during storm erosion might expose infaunal organisms such as



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

worms providing a potential food source for predators such as trilobites. Traces showing interception of a horizontal burrow (*Planolites*) intercepted by a *Rusophycus* suggest hunting behavior on the part of the trilobites (see Brandt et al., 1995). Such foraging might have gone on particularly intensely following a storm unroofing of worm burrows.

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

### Shell Pavements/Hardgrounds

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



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

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

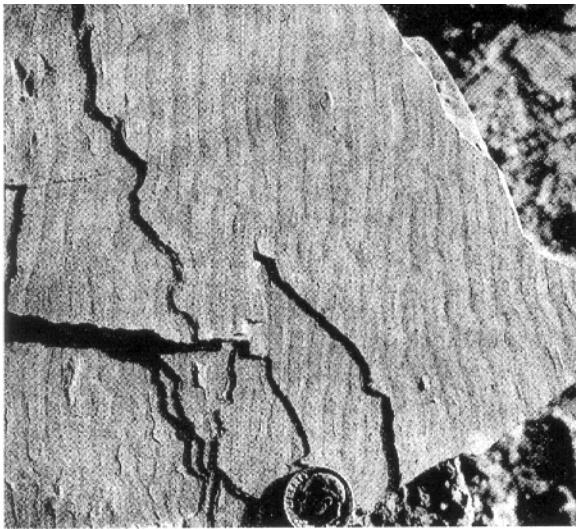
### **Beds Containing Unusual Sedimentary Structures**

Beds containing unusual sedimentary structures have also proven to be traceable, at least within closely spaced outcrops. An example of this is distinctive millimeter

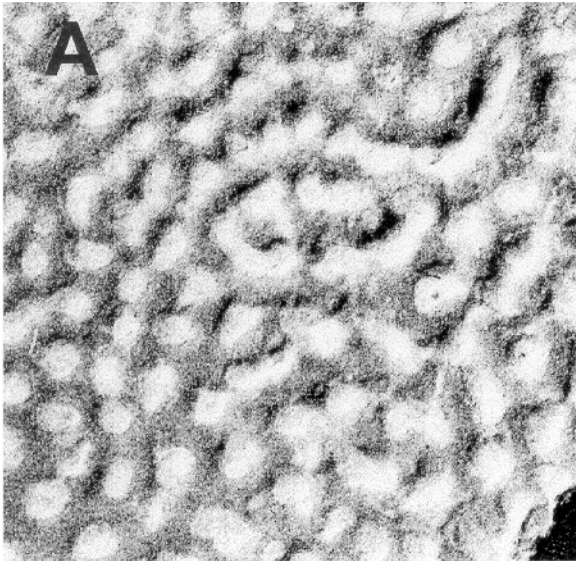


**Figure 9.** Hardground surface on limestone from upper Kope Formation; note encrusting crinoid holdfasts and bryozoans; Montana Avenue exit of I-74; Cincinnati, Ohio, X1.

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



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



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

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

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

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



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

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

### Seismites

Recently, a number of authors have begun to recognize zones of widespread deformation that may be attributable to seismic shocking (Pope et al., 1997; Ettensohn, in review). These intervals are typified by beds of ball-and-pillow deformation that extend for tens to hundreds of square kilometers (Schumacher, 1992 and this volume; Pope et al., 1997). Careful observation of these deformed intervals demonstrates that they resemble beds known to have been deformed seismically, e.g., by liquefaction of muds and foundering of overlying coarser sediments (“seismites,” *sensu* Seilacher, 1982). The larger deformed masses show overturned

folds and flame structures, but most deformed zones do not show consistent orientation of fold axes (Pope et al. 1997; DeJong et al., this volume). Such evidence is consistent with deformation induced by liquefaction rather than by slumping. Basal surfaces of the pillows display small load casts, striations, deformed burrows and load casts, indicating deformation of semi-plastic muds by loading. Commonly, the deformation appears to have been concentrated in thickened portions of siltstone beds, which may represent submarine channel fills. A deformed channel-fill like feature that cuts some 2 m down into underlying strata is found locally along one of the ball-and-pillow horizons on the Rte. 3071 roadcut near Maysville (Stop 4 on Saturday).

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

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

More dramatic evidence for deformation, probably associated with some lateral sliding, occurs in a thin interval (ca. 1.0-1.5 m) in the upper Point Pleasant Ls. near Brooksville, KY (DeJong et al., this volume). Here, the presence of rotated blocks, brecciation, and small-scale thrusts indicates more

severe deformation of indurated sediment, possibly accompanied by slumping. Angular discordance between the deformed and broken strata and the overlying limestones indicates that slumping was syndimentary and occurred on the seafloor (rather than intrastratally). The lateral extent of this zone is presently unknown.

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

#### **CYCLES IN THE KOPE AND FAIRVIEW FORMATIONS**

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

These patterns hold remarkably well through most of the Cincinnati Series, although cycles at the formation scale do not correspond exactly to formational contacts, and, hence, are probably best viewed as "subformational" in scale (see 2nd Brett and Algeo paper, this volume). For example, the Kope-Fairview interval consists of three broad shale-limestone cycles, the first from

the Fulton submember (base of Kope Fm.) to the top of the Grand Avenue submember (Kope Fm.), the second from the base of the Taylor Mill submember (Kope Fm.) to the top of the North Bend submember (Fairview Fm.), and the third taking in the Wesselman submember and Fairmount Member of the Fairview Formation. Each subformational cycle grades upward from a shaly base to a more carbonate-rich cap, reflecting a shallowing upward trend.

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

#### **Decameter-Scale Cycles**

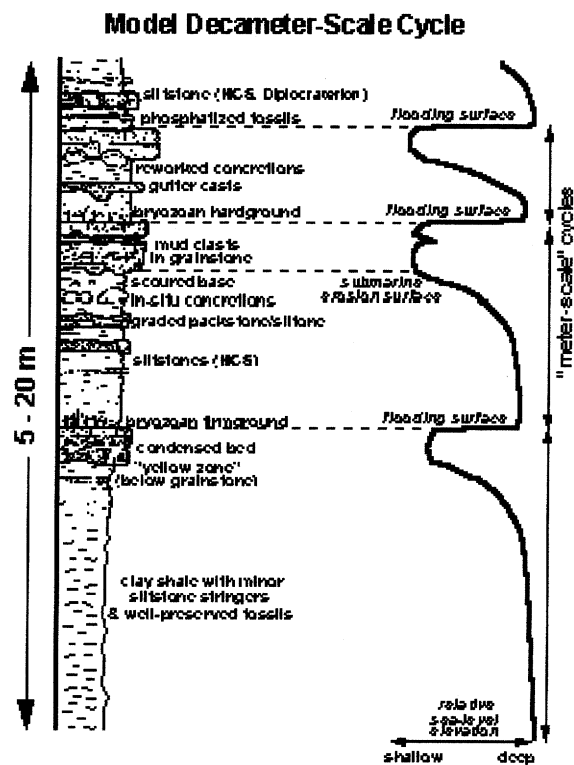
We recognize eight large (5-20 m) or "decameter-scale" cycles within the Kope Formation (Fig. 13; see also CRS, Fig. 5, p. 51-52, this volume); these are equivalent to the informal stratigraphic submembers that we defined herein (see 2nd Brett and Algeo paper, this volume). Holland et al. (1997) used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

Defining cycle boundaries is somewhat subjective, depending upon the degree of symmetry in the sedimentary pattern. For completely symmetrical cycles the choice of cycle base would be arbitrary, whereas for highly asymmetrical successions the boundaries may be more clear. Thus, for proximal depositional sequences, the basal sequence boundary is a sharp lowstand erosion surface and a transgressive-regressive pattern is evident, whereas for shallowing-upward parasequences, flooding surfaces provide objective cycle (or hemicycle) boundaries. Decameter-scale cycles in the Kope Fm. actually show some aspects of both sequence and parasequence motifs (Fig. 14). For example, some of these cycles, e.g., the Grand View submember of the Kope, show the abrupt superposition of a bundle of amalgamated limestones with sharp facies dislocation



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

(i.e., evidence for abrupt shallowing) over more distal shaly facies. In such cases, one might place a lowstand sequence boundary at this juncture. Others, however, seem to show a more gradual upward increase in the thickness and coarseness of “capping” limestone beds, and therefore, more resemble parasequences. These, too, are not completely asymmetrical and may show a minor retrogradational (upward-deepening) component. In this respect, decameter-scale cycles in the Kope Fm. closely resemble classic Klupfel cycles described by Bayer and McGhee (1985). However, all of the successions that we recognize as submembers of the Kope Fm. share the feature of an abrupt (gen-



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

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

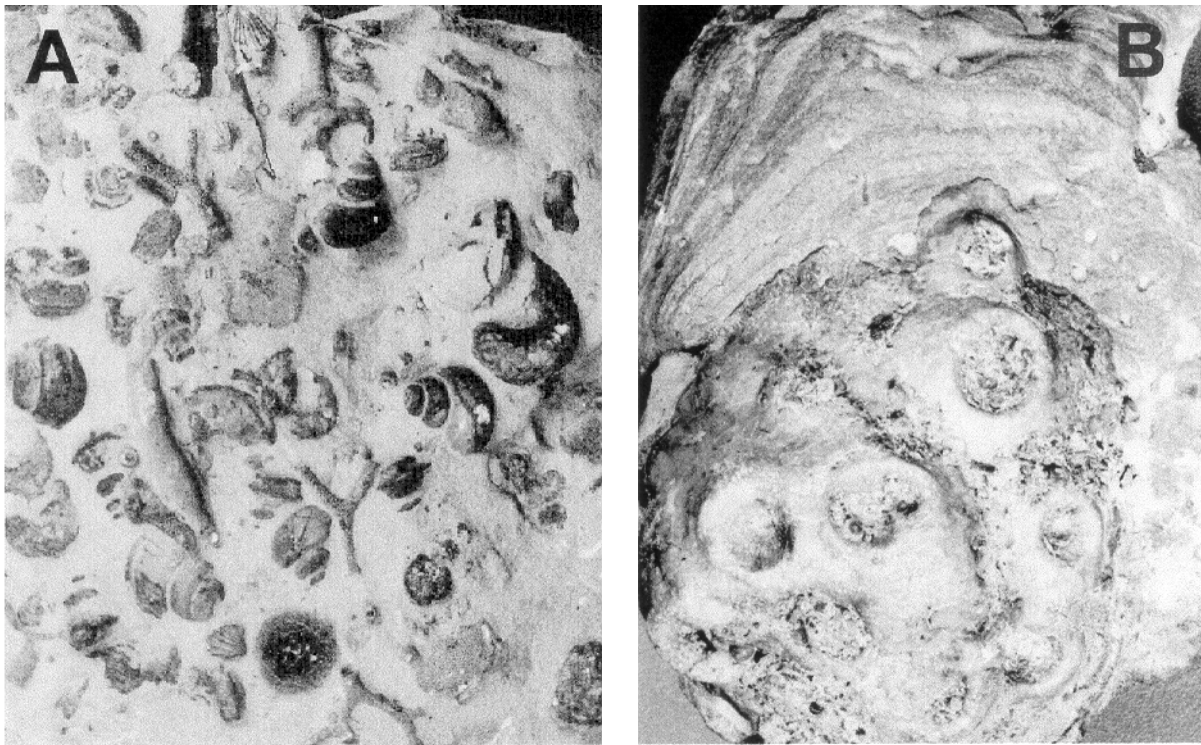
As thus defined, each decameter-scale cycle has a relatively sharp lower boundary at the base of a thick shale typically exceeding a meter in thickness (Figs. 13-14). The upper contact of the last thick limestone bed (packstone or grainstone) may be sharp and feature phosphatic staining, corroded fossil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

Such thin, transitional facies tend to be abruptly overlain by 1 to 3 meters of medium to dark gray claystone with few interbeds except for very thin beds or laminae of siltstone/calcisiltite. This clay shale interval typically forms approximately half of the thickness of the overall cycle. It is generally sparsely fossiliferous, but the occurrence of minor, pyritic thread-like burrows and a diminutive fauna of a few species of brachiopods, small bivalves, crinoids, and trilobites suggests dysoxic, stressed environmental con-

ditions. Presence of graptolites and nautiloids in some of the mudrocks indicates an input of pelagic organism remains (Fig. 4, p. 50, this volume). The preservation of fossils tends to be very good, with at least partially articulated crinoids, rolled-up small trilobites, and intact graptolites. Such taphonomic evidence tends to support an interpretation of rapid and episodic accumulation of muds. Slight thinning or “ghosting” of some calcitic shells and plastic deformation of aragonitic mollusc shells indicates some early dissolution of carbonates. The upper portion of the thick, mudstone-dominated interval becomes increasingly silty and displays increased frequency and thickness of thin-laminated siltstones/calcisiltites and fossil-rich packstones (Fig. 14). Thicker (7 to 10 cm) lenticular, typically bryozoan-rich packstones occur near the tops of the decameter cycles.

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

Upward within each decameter-scale cycle, the proportion of shale decreases and limestone becomes increasingly dominant (to about 30-40% of section; Figs. 13-14). The upper carbonate-rich portion of each decameter-scale cycle is 2-3 m thick and commonly represents several (up to as many as ten) limestone-shale rhythms equivalent to the “meter-scale” cycles of previous workers (Tobin and Pryor, 1981; Jennette and Pryor, 1993; Holland et al., 1997; see below). Carbonate beds toward the tops of bundles, in particular, tend to show irregularly hummocky, stained tops that represent minor diastems. These are characterized by distinctly sculptured surfaces and commonly darkened phosphatic- or pyrite-rich crusts as well as minor borings and encrusting organisms (Fig. 8). The upper lime-



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

stones may have associated concretionary “underbeds” or even reworked concretions (Fig. 15; see discussion below). Fossils in the thicker beds are typically small rounded fragments or whole valves of brachiopods, many of which are darkened or appear reddish in weathered outcrops, probably due to shell impregnation by limonite or pyrite (Fig. 6B, p. 53, this volume). Taphonomic features suggest that fossil hash in many beds has been subject to longer term reworking.

**Temporal Constraints on Decameter Scale Cycles:** The approximate duration of the decameter-scale cycles is difficult to estimate. At present, we recognize eight such cycles in the Kope Formation, but the second and third cycles (Brent and Pioneer Valley submembers) require further study; each could perhaps be further subdivided. The Edenian Stage, which comprises the Kope and lower Fairview formations, has a duration of some 3 to 4 million years. Thus, the eight

decameter-scale cycles in the Kope Fm. have an average duration of ca. 400-500 ky. Obviously, there is no reason to assume *a priori* that the cycles are of equal duration; these numbers simply are meant to give an order-of-magnitude estimate for the time represented by these units. These calculations also assume that the lower sequence boundary, a subtle discontinuity within the Point Pleasant Ls., does not occupy a large fraction of the total time span of the C1 sequence (see Holland and Patzkowsky, 1996).

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

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

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

“precursor beds” of Brett, 1995, 1998). The tops of these 10-20 m cycles show minor evidence for progradation of coarser sediments and are interpreted as the late highstand or regressive phase of these “fourth-order” sequences.

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

### **Meter-Scale Cycles**

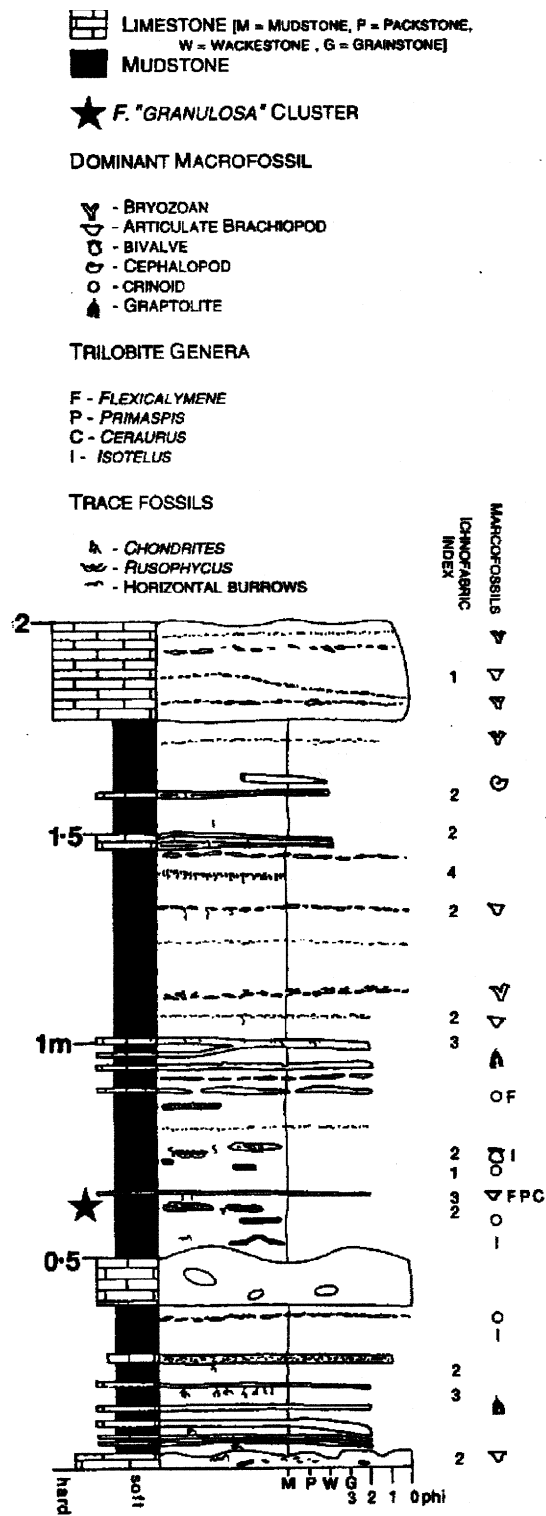
The Kope Formation is characterized by a large number (> 45) of small-scale (typically 0.5 m to 1.5 m thick) alternations of recessive weathering shales (mudstones) and ledge-forming, medium- to thick-bedded skeletal packstones and grainstones (Figs. 16-17). These smaller scale bundles in some way

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

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



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



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

(1981), Jennette and Pryor (1993) and Holland et al. (1997), as well as our own observations.

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

etal material, e.g., crinoid ossicles, brachiopod fragments, and bryozoan debris (e.g., Fig. 6, p. 53, this volume). The tops of calcisiltite beds are normally gradational into the overlying mudstones. In some cases, however, the tops are sharp and may show oscillation or interference ripple marks (Fig. 10). Dewatering “runzel marks” or *Kinneyia*-type structures may be present on the tops of rippled silty beds (Fig. 11).

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

**Limestone Hemicycle:** The upper part of meter-scale cycles is carbonate rich, consisting of compact single beds, or closely spaced bundles of beds, of skeletal packstones and grainstones (Figs. 14, 18). Evidence of amalgamation is abundant, with amalgamated beds most commonly consisting of two to six discrete layers separated by thin (often < 1 mm) shaly partings. These skeletal carbonates typically weather to slightly to strongly rust-stained ledges (probably owing to oxidation of pyrite) that project up to several tens of centimeters outward from the outcrop surface. Bases of the beds or bed bundles are characteristically sharp and may be undulatory with a relief of 5 to 10 centimeters (rarely more; Fig. 18). Irregular lumps or mounds of mudstone may project upward into concavities on

the bases of the beds. The bed bases may show gutter casts, tool marks, or other sole features indicative of scouring and loading (Fig. 6). The beds themselves are composed of skeletal debris, particularly of whole and broken valves of brachiopods, bryozoan fragments, and crinoid ossicles. This fossil material may appear crudely, normally graded with a decrease in the average grain size upward through the thickness of the bed. Capping beds or bed bundles range from 5 to over 30 centimeters.

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

Internally, the capping limestones com-

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



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

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

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

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

The basal portion of the shaly hemicycle of most meter-scale cycles consists of fossiliferous mudstones with a few thin skeletal limestones. Small, refractory phosphatic and organic fossils such as scolecodonts and con-

odonts are abundant in these basal shales, while thin interbedded packstones commonly contain a "microhash" of finely comminuted, blackened (phosphatized?) shell fragments and ostracodes. Such evidence suggests that this portion of the cycle represents a relatively condensed interval.

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

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

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

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

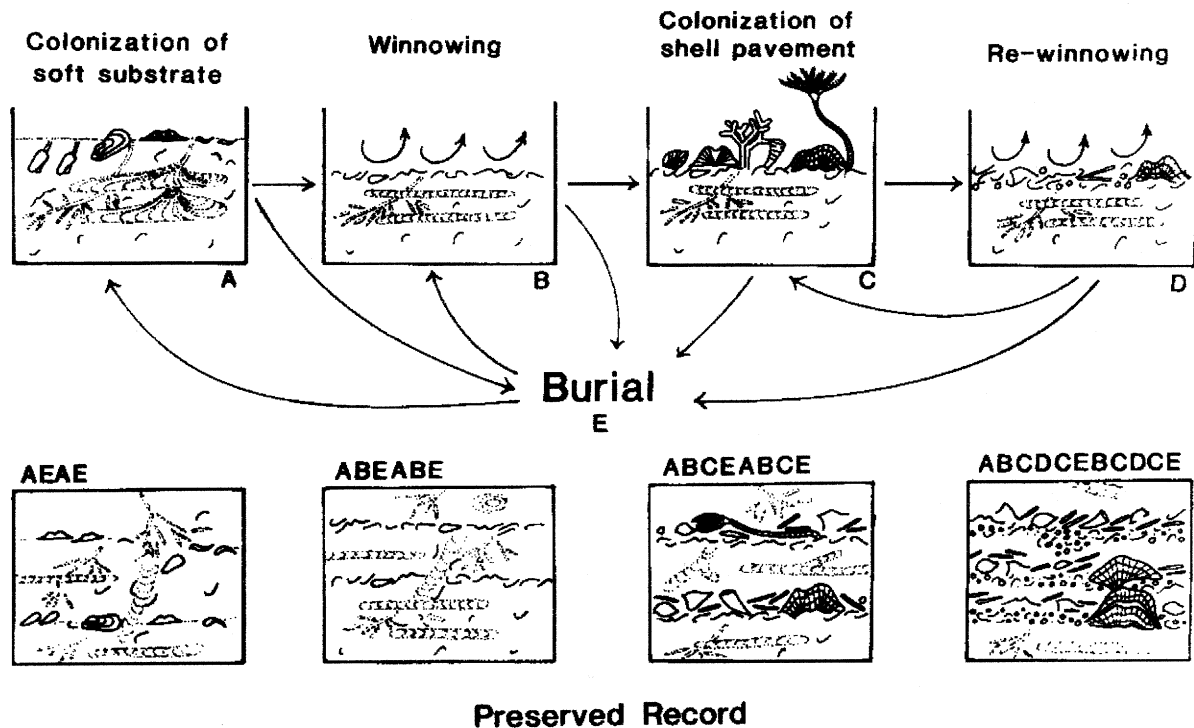
Third, if tempestite fossil assemblages are indeed parautochthonous, then the relative density of fossils in these beds versus in the underlying shales becomes an important consideration. Specifically, limestone beds exhibit a fossil density that is typically several hundred-fold greater than subjacent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

tation, and symsedimentary mineralization characteristic of many of these beds.

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

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

## Shell Bed Genesis



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

term sediment starvation and/or erosion, which may have maintained particular increments of sediment within the zone of sulfate reduction for a sufficient period to allow growth of small nodules or semi-continuous concretionary limestone beds. Although the precise timing of such phenomena is difficult to judge, there is reason to believe that carbonate nodules require a substantial time period for formation. Mass balance calculations of Raiswell (1976) suggest that the radial growth of small concretions requires a period of time on the order of one to five thousand years. This implies a stable sediment-water interface well above, but spatially related to the concretionary horizons. Excellent candidates for just such a position are the sharp basal contacts of complex limestone beds that lie small distances above the concretionary horizons. In some instances, erosion later cut down through mud layers, exhumed pre-lithified carbonate nodules onto the seafloor, and incorporated them into shell-

rich lag beds. Again, this is further evidence that shell-rich limestones may represent substantial amounts of time. Not only may the first of the shelly deposits have begun accumulating during times of slow sedimentation when concretions were forming in the underlying sediment, but later generations of shell debris came to incorporate the reworked concretions. Occasionally, concretions in lag deposits show evidence of differential erosion and/or encrustation on one side (presumably the upper) that indicates prolonged exposure of the exhumed nodules on the sea floor. Thus, concretion growth and reworking would have required a substantial amount of time, at least on the order of several millennia.

Sixth, development of bored and encrusted hardgrounds at the tops of some limestone bundles indicates a hiatus in sedimentation prior to burial by overlying mudstones. These hardgrounds are commonly marked by the appearance of specialized communities of organisms, e.g., edrioasteroids, which at-

tached directly to the hardgrounds or to shells in stabilized shell pavements. In several instances, these final hard substrate communities were buried abruptly by pulses of mud, again, showing the obrutionary or rapid depositional character of some of the mudstones that overlie the tops of major shell beds.

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

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

which tractional movement of sediment was rare and out-of-equilibrium with normal conditions.

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

Tobin and Pryor (1981) were among the first researchers to specifically address the cyclic nature of meter-scale couplets. These authors interpreted them as fining (deepening) upward small-scale cycles, in which time-rich amalgamated shelly layers were overlain by fossil packstones, and these, in turn by claystones. Tobin thought that the mudstones were event beds and represented rapid deposition of muds associated with

storms that brought up mud-laden currents from deeper portions of the basin. We concur that at least some mudstones were deposited rapidly, although the immediate source of the mud remains ambiguous. We also agree that many of the limestones are amalgamated units and, hence, are "time-rich," as inferred by Tobin and Pryor.

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

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

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

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

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

proximality patterns of storm beds documented by Jennette and Pryor (1993). Additional factors seem necessary to explain these phenomena.

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

A third possibility, favored by Jennette and Pryor (1993) and suggested by Holland et al. (1997), is that meter-scale cycles represent minor oscillations in sea-level elevation. Since most such cycles exhibit a mainly shallowing-upward pattern, they would then be interpreted as parasequences. As a slight modification of this view, we would suggest that many cycles take on the aspect of "small-scale sequences": the sharp erosive bases of limestone bundles may be small-scale analogs of sequence boundaries, and the limestone bundles thus resemble small-scale transgressive systems tracts culminating in flooding surfaces at their tops. Overlying shales thus represent relative highstand to regressive conditions. In this model, the

strongly proximal nature of shell gravels in the thicker limestone bundles is explained by shallow-water conditions. Conversely, the mud- and silt-rich portions of the package reflect deeper water conditions and less frequent stirring of sediments. More importantly, the amalgamation of limestone beds and other indications of condensation may be explained as the result of low rates of sediment input associated with an initial sea-level rise following relative lowstands. This would explain the basinward thinning, rather than thickening (per the Holland et al. model above), of finer-grained carbonate bundles. In this model, limestone bundles in both proximal and distal areas would be expected to exhibit a response to basinwide intervals of sediment starvation. This model would also explain the sharp, diastemic tops of limestone bundles and the apparent abrupt transitions to mud-rich, seemingly deeper water facies, because these represent flooding surfaces followed by renewed aggradation of sediment. The increasingly silty character of the upper parts of shale hemicycles would reflect seaward movement of coarser-grained, more proximal facies. This model seems to account for most observed features of the Kope Formation, although it does not offer any specific mechanism to explain short-term sea-level oscillations. Nonetheless, the possibility of Late Ordovician glacio-eustasy cannot be dismissed, and there is strong evidence for such eustatic variation in the Hirnantian (latest Ordovician; xxxx).

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

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**SEQUENCE STRATIGRAPHY  
OF THE KOPE-FAIRVIEW INTERVAL  
(UPPER ORDOVICIAN, CINCINNATI, OHIO AREA)**

Steven M. Holland<sup>1</sup>

Arnold I. Miller<sup>2</sup>

David L. Meyer<sup>2</sup>

<sup>1</sup>Department of Geology, University of Georgia, Athens, GA 30602-2501

<sup>2</sup>Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221-0013

## INTRODUCTION

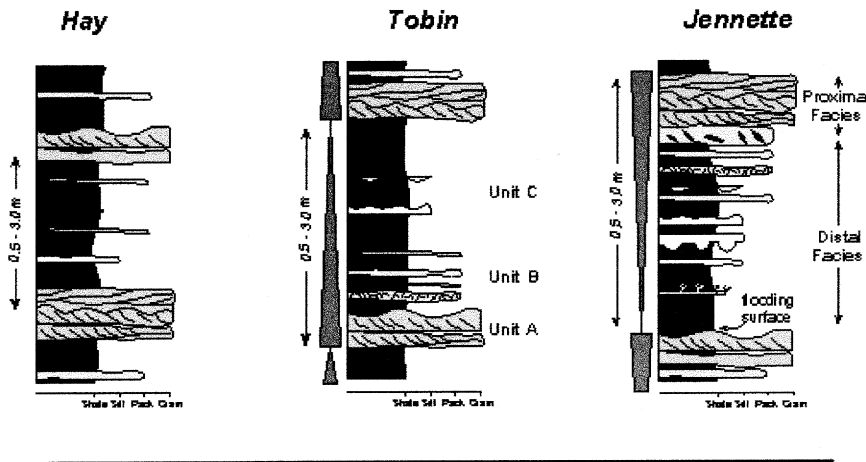
The stratigraphic interpretation of the type Cincinnati Series and particularly the Kope Formation has evolved significantly over the past two decades. Initial progress began with the interpretation of the type Cincinnati lithofacies, the recognition that these strata were deposited on a northward-dipping storm-dominated mixed carbonate-clastic ramp, and the delineation of three or four major (10-100 m) shallowing-upward sedimentary cycles within these rocks (Hay 1981; Hay et al. 1981; Tobin and Pryor 1981; Tobin 1982). Subsequent work reinterpreted these large-scale cycles in a sequence stratigraphic framework and eventually led to the recognition and regional correlation of six third-order (1-10 m.y.) depositional sequences (Holland 1993; Holland and Patzkowsky 1996). Meter-scale cycles were also recognized (Hay 1981; Tobin 1982) but their interpretation and even their basic characterization has undergone revision (Jennette and Pryor 1993; Holland et al. 1997; Miller et al. 1997). The most recent work has focussed on the correlation of meter-scale cycles (Brett, this volume, Holland et al. 1999) and faunal changes within both the meter-scale and the third-order cyclicity (Miller et al., in prep.). This paper will highlight recent advances on the interpretation of meter-scale cycles of the Kope-Fairview transition and the sequence stratigraphy of the Kope-Fairview transition, both in light of previous work.

## METER-SCALE CYCLICITY

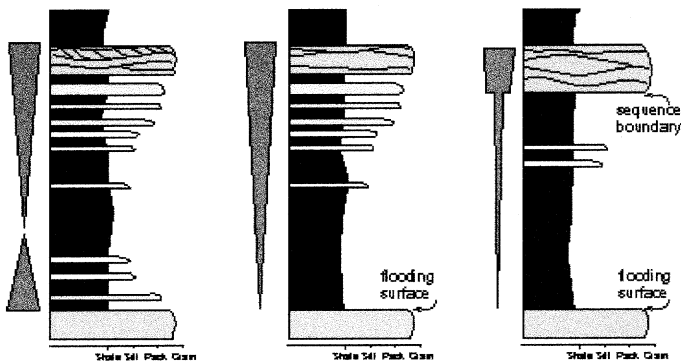
### Cycle Anatomy

Meter-scale cyclicity has been recognized in the type Cincinnati for at least the past two decades. Hay (Hay 1981; 1981) described a meter-scale alternation of intervals dominated by shale but containing a few thin limestone beds with intervals dominated by thicker bedded limestones with thin shale partings (Fig. 1). In particular, she noticed that roughly 30 cm thick rippled grainstones tended to be regularly spaced every 1.5 m. Hay made little comment on the structure of these cycles, other than noting the presence of this simple alternation of facies.

During the same period of time, Tobin also recognized meter-scale cycles. Tobin and Pryor (1981) initially characterized the cycles as consisting of a basal unit of intraclastic and bioclastic grainstones, a middle unit with bioclastic packstones and shales, and an upper unit with shales and rippled calcisiltites. They emphasized the overall fining-upward structure of the cycles as well as the sharp contacts of the basal grainstone unit on the upper shale unit of the underlying cycle. They also noted variation in cycle structure, with the middle unit commonly absent. Shortly thereafter, Tobin (1982) reappraised the meter-scale cycle structure. Because the middle unit of Tobin and Pryor was absent in most of the cycles, Tobin recharacterized the cycles as consisting of a lower carbonate hemicycle and an upper shale hemicycle. The carbonate hemicycle was dominated by thick



#### Holland, Miller & Meyer



**Figure 1.** Evolving views on the structure of meter-scale cycles in the type Cincinnati Series. Modified from Holland et al. (1997).

and closely spaced bioclastic grainstones, packstones, wackestones, and calcisiltites and contained less than 20% shale. The shale hemicycle was described as containing greater than 70% shale, but included thin siltstones, calcisiltites, and lime mudstones.

Subsequently, in the most thorough analysis to date of the sedimentology of these cycles, Jennette (1986; Jennette and Pryor 1993) described meter-scale cycles from the upper Kope and lower Fairview Formations as having a lower distal storm bed facies and an upper proximal storm bed facies. The distal storm bed facies was dominated by shale, and included graded shale layers, hummocky to laminated calcisiltites and siltstones, and thin bioclastic packstones. The proximal storm bed facies contained minor amounts of shale and was dominated by amalgamated, megarippled, bioclastic packstones and grainstones. Thus, contrary to Tobin, Jennette saw the base of the shale-rich unit or distal storm

bed facies as the sharp contact, with its contact with the overlying limestone-rich unit or proximal storm bed facies as a gradual transition. Jennette did also note that, in some cases, the base of the proximal storm bed facies was unusually abrupt.

Most recently, Holland and others (1997) were impressed by the wide variability in the anatomy of meter-scale cycles throughout the Kope and into the lower Fairview. Like Hay, Tobin, and Jennette before, Holland and others recognized the same basic facies, with a limestone-dominated unit and a shale-dominated unit. However, they also saw that storm-bed proximity concepts (Aigner 1985) could be used to recognize trends within these facies. From this, it became apparent that cycles contained both upward coarsening and upward fining intervals, and that the transitions between the two facies could be either sharp or gradational. Part of this recognition was almost certainly the result of unusually de-

tailed section measurement, in which every bed thicker than 5 mm was described. If thin beds were removed from the measured sections, then most of the cycles appeared to coarsen upwards as Jennette had argued (Miller et al. 1997). In short, although Kope meter-scale cycles can appear at first to be highly and similarly structured, closer examination reveals a lack of consistent cycle architecture.

### Cycle Correlation

Views on correlation of meter-scale cycles have also evolved over the past two decades. Tobin and Pryor (1981) seemed initially to discount the possibility of anything more than local correlation by invoking a local patch model for the formation of these cycles (see below). Later, however, Tobin (1982) demonstrated that meter-scale cycles could be correlated across 11 km by following distinctive marker beds, such as a prominent calcisiltite containing abundant *Diplocraterion* (U-tube trace fossils). Jennette (1993) showed that packages of cycles could be correlated over even greater distances of up to 40 km along depositional strike (E-W) and 18 km along depositional dip (N-S). Jennette used a combination of marker beds, such as a widespread bed of gutter casts, and changes in cycle thickness for correlation.

Both Tobin's and Jennette's correlations were based on visual pattern matching and the reliability of these correlations, although they were clear and apparently never questioned seriously, could not be evaluated quantitatively. In addition, their correlations hinged partly on the ability of recognizing distinctive marker beds. The difficulty in this approach is that the features used to identify marker beds commonly occur multiple times in a stratigraphic section. Gutter casts are known from multiple levels within the Kope, and *Diplocraterion* occurs in many beds as well. If one is attempting to correlate a short section and one of these markers occurs in it, there is the question of how one can be sure exactly which horizon of gutter casts or *Diplocraterion* has been found.

To avoid these problems, Holland and others (1999) used the technique of cross-

correlation (e.g., Anderson and Kirkland 1966) to correlate cycles in the Kope. This technique met with great success in the 1960's and 1970's when applied to correlation of varve and bed thicknesses, but produced unconvincing results when applied to correlation of well log signatures, and eventually fell into disuse. Provided that there are no great differences in accommodation, stratigraphic completeness, or the timing of sedimentation (e.g., as if clinoforms prograded across the region), then changes in cycle thickness ought to be regionally correlatable. With cross-correlation, two Kope sections separated by 7 km have been successfully correlated (Fig. 2) and the correlation checked by comparing faunal changes within the Kope (Fig. 3). Future work will attempt to determine the geographic limit to this technique. Currently, we are also attempting to quantify these faunal changes using ordination techniques such as detrended correspondence analysis and to use this as an independent means of correlation. Preliminary results suggest that these faunal patterns can be correlated across the tri-state area (Miller et al., in prep.). Carlton Brett (this volume) is currently using visual matching of distinctive event beds and cycle architectures for correlation within the Kope.

Regional correlation of these meter-scale cycles demonstrates that they are not just the random local accumulation of limestone versus shale. Regardless of which particular model of cycle structure is correct, meter-scale cycles must have formed in response to ramp-wide conditions. Although bed thicknesses within the Kope may follow an exponential distribution that suggests the importance of random processes in sediment accumulation (Wilkinson et al. 1997), the presence and correlatability of cycles at the meter-scale indicates some degree of order to deposition within the Kope.

### Cycle Origin

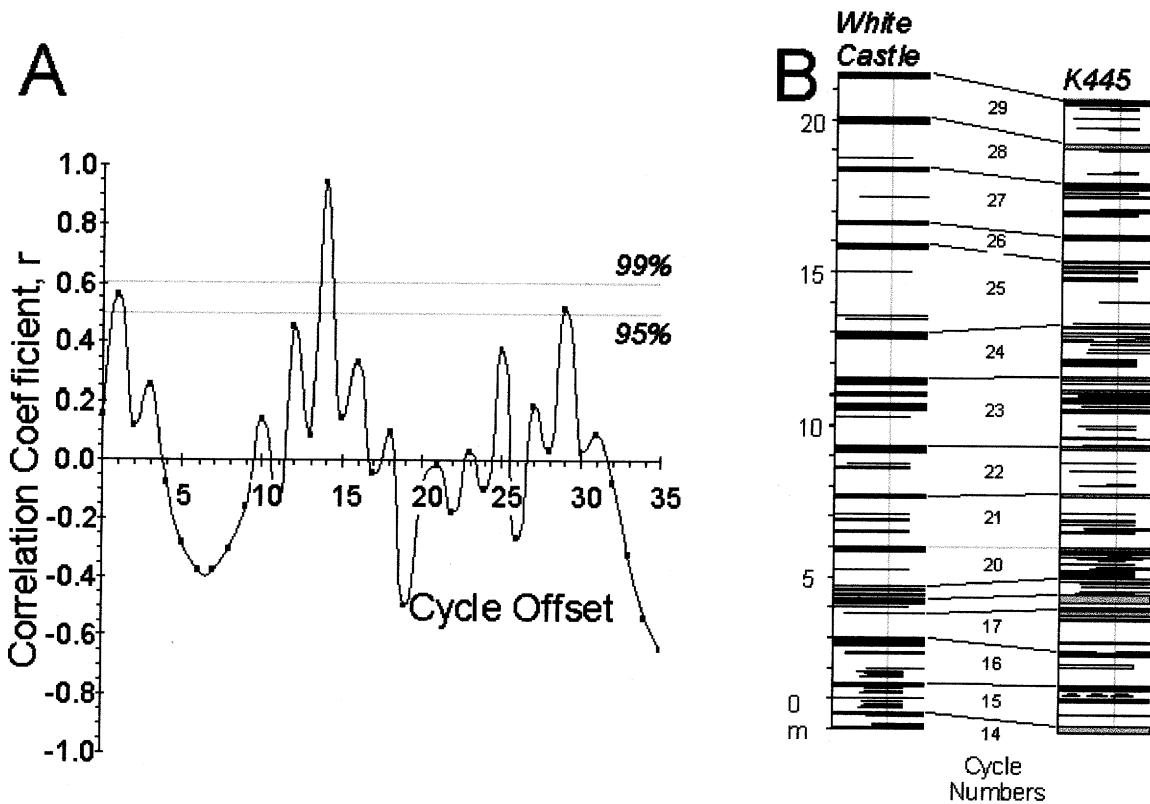
Over the past two decades, there has been little consensus on the origin of meter-scale cyclicity and little attempt to test the various hypotheses rigorously. Originally, Hay (1981; Hay et al. 1981) suggested that cycles could

reflect clustering of intense storms through time. Tobin and Pryor (1981) favored an autocyclic model involving the formation and abandonment of local highs on the seafloor, but Tobin (1982) later abandoned that model in favor of a eustatic origin for these cycles. Jennette and Pryor (1993) also attributed the cyclicity to eustatic fluctuations, specifically those driven by changes in the volume of polar ice caps.

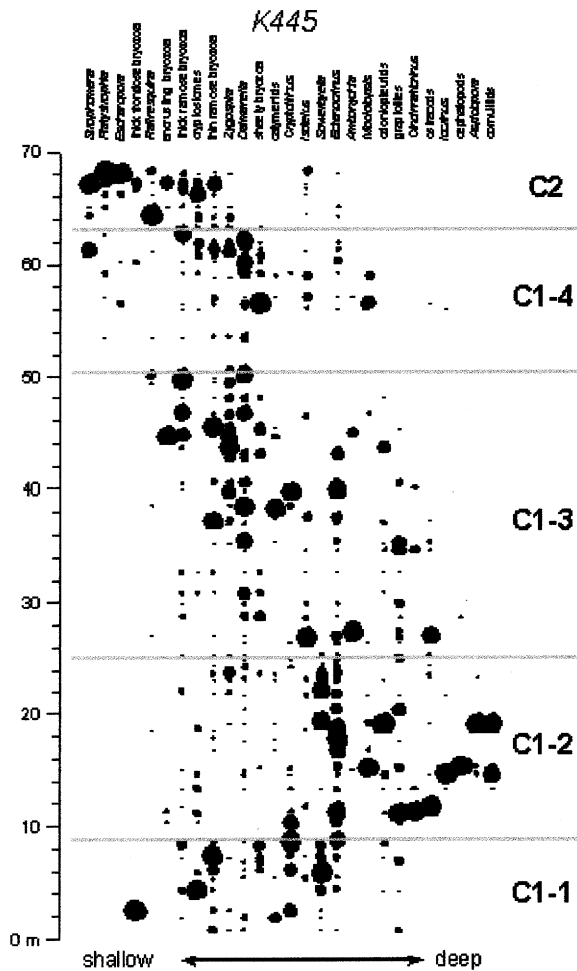
Holland and others (1997) were less certain of the cause of cyclicity, primarily because of a lack of sufficient data for testing among the possibilities. They suggested either relative changes in sea level, which would allow for the changes in subsidence rate as well as eustatic changes, or changes in the intensity or frequency of storms. A third possibility not raised by previous authors is

that meter-scale cycles are driven by changes in the supply of siliciclastic mud, perhaps in response to climatic changes in the source areas to the east. However, such a model seems unlikely given the changes in sedimentary structures and carbonate grain types and size seen within the cycles. By some mechanism, the effect of storms on the seafloor changed cyclically (but not necessarily periodically) over time.

We currently do not favor a relative sea-level origin of meter-scale cyclicity in the Cincinnati region for three reasons. First, the Cincinnati series is notable in that meter-scale cycles are consistently well-expressed in offshore and deep subtidal (= transition zone of Tobin (1982) and Holland (1993)) settings such as the Kope, Fairview, Clays Ferry, Corryville, Sunset, Waynesville, and



**Figure 2.** Correlogram of meter-scale cycles in the K445 section and the White Castle section, several kilometers away. Changes in the thickness of meter-scale cycles can be cross-correlated, allowing for confidence limits to be placed on correlation. Of the three peaks in correlation significant at the 95% level of confidence, the middle peak can be confirmed by overall faunal similarity of the two sections when they are correlated at this level.

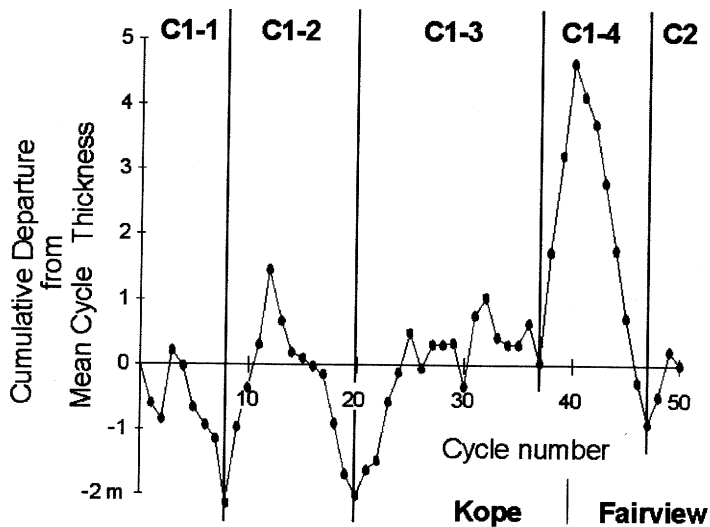


**Figure 3.** Faunal changes within the K445 section. Taxa were seriated, or ordered, using the technique of Brower (1988). Taxa on the left are interpreted as relatively shallow-water forms, while those on the right are inferred to favor deeper-water. Size of circles indicates differences in relative abundance. Stratigraphic trends in faunal composition are highlighted with gray shading. These trends map onto a 20-m scale of cyclicity (C1-1 through C1-4) defined by changes in the thickness of meter-scale cycles and suggest that the 20-m scale of cyclicity reflects changes in water depth. C1 and C2 refer to third-order depositional sequences that can be correlated regionally (Holland and Patzkowsky 1996).

Liberty Formations. Meter-scale cyclicity is poorly expressed or non-existent in shallow subtidal and particularly peritidal settings such as the Bellevue, Mt. Auburn, Oregonia, Whitewater, and Saluda Formations of the Cincinnati area and the Grant Lake, Bull Fork, and Drakes Formations of central Kentucky. If relative sea-level was the driving mechanism, then meter-scale cyclicity should be better developed in shallower-water settings than deep-water settings, if only because shallower-water facies occupy relatively narrower bathymetric ranges than deeper-water facies. Numerical models of cyclicity and field observations of cycles driven by relative sea level consistently display the reverse relationship: peritidal cycles are well-developed, but meter-scale cycles become more obscure into deeper-water settings (Markello and Read 1981; Elrick and Read 1991).

Second, meter-scale cycles fail to mirror the facies transitions seen in the third-order cyclicity, known to have a relative sea-level origin because of its wide lateral extent (Holland 1993; Holland and Patzkowsky 1996). If relative sea level drove both scales of cyclicity, then meter-scale cycles should display in miniature, the same cyclic alternations of facies that comprise larger-scale cycles. For example, as Kope meter-scale cycles are traced updip, they should display deep subtidal (i.e., Fairview-like) facies at their top and eventually shallow-subtidal facies (e.g., Bellevue-like) at their tops. However, such shallow-subtidal cycle caps are unknown, suggesting that the meter-scale cyclicity represents changes in the style of sediment accumulation, but entirely within an offshore or deep subtidal environment and not the lateral shifting of bathymetrically defined facies.

Third, although meter-scale cycles show consistent changes in thickness within larger scale 20-m cycles (Fig. 4), they do not display any consistent change in their anatomy. If two orders of cyclicity are driven by changes in relative sea level, numerical models consistently predict that the higher-order cycles should systematically change their anatomy within the lower order cycles. For example, meter-scale cycles ought to have prominent flooding surfaces and subdued sequence boundaries during times of relative sea-level rise in the 20 m cycles, and vice



**Figure 4.** Fischer plot of m-scale cycles from Kope and lower Fairview Fms. at the K445 composite section. This Fischer plot does not include triangles for each cycle, but shows only cumulative departure from mean cycle thickness. A rising trend indicates occurrence of several thicker-than-average cycles and a falling trend several thinner-than-average cycles. Several 20-m scale cycles are recognized based on changes in cycle thickness. Each 20-m cycle (C1-1 through C1-4) starts with several thicker-than-average cycles and is followed by several thinner-than-average cycles. The revised location of the C1-C2 third-order sequence boundary is shown (see text for discussion).

versa during times of relative sea level fall within 20 m cycles (Van Wagoner et al. 1990). Several attempts at discovering such order in meter-scale cycle anatomy all resulted in failure (Holland et al. 1997). This can mean either that relative sea level follows a far more irregular history than that depicted in numerical models or that meter-scale cycles have nothing to do with changes in relative sea level.

Ultimately, any hypothesis of the origin of meters-scale cycles in the Cincinnati must account for (1) cycle anatomy and its variation, (2) the presence of clear cyclicity only in deep subtidal and offshore environments, (3) the failure of meter-scale cycles to mimic the facies transitions seen in larger-scale cyclicity known to be driven by relative sea-level because of its lateral extent, (4) the lack of systematic changes in meter-scale cycles within the 20 m scale cycles, and (5) the ability to trace meter-scale cycles for up to 40 km along depositional strike and 18 km along depositional dip. A possible mechanism that could do so is climatically driven cyclicity in the intensity or frequency of storms, as Hay and others (1981) suggested in the first place! Times in which storms were either relatively weak or infrequent would allow significant mud to accumulate on the sea floor, giving rise to a shale-dominated facies containing a few single-event storm beds. Times in which

storms were either relatively intense or frequent would favor extensive and repeated scouring of the sea floor. In this way, little mud would accumulate, storm beds would be prone to amalgamation and the formation of multi-event beds as each successive storm would erode down into the deposits from a previous storm. Transitions from stormy times to quiescent times (and back) might be expected to be abrupt in some instances and gradual in others, giving rise to the variability seen in the sharpness of facies transitions. If such a model of cyclicity is correct, then trends in storm bed proximity within meter-scale cycles do not reflect changes in water depth as argued previously (Jennette and Pryor 1993; Holland et al. 1997), but changes in storm intensity. This second possibility was recognized by Aigner in the original conception of storm bed proximity (Aigner 1985).

### KOPE-FAIRVIEW TRANSITION

The stratigraphic interpretation of the Kope-Fairview contact is currently in a state of flux. The contact between these two formations was drawn originally on both faunal and lithologic grounds. In particular, the top of the Kope (McMicken Member of the Latonia Formation in older literature) was characterized by a zone of abundant *Resserella* (now *Dalmanella*) and the lowermost Fairview was characterized by the ap-

pearance or increased abundance of a species of the gastropod *Cyclonema gracile*, the brachiopods *Platystrophia* and *Plectorthis*, and the bryozoans *Constellaria* and *Escharopora* (Caster et al. 1955). The top of the McMicken was also described as a thick limestone layer bearing ripple marks. Ford (1967) subsequently redefined the Fairview Formation on strictly lithostratigraphic criteria, as was done in the 1960's through 1980's for most of the Cincinnati Series. He placed the base of the Fairview at a sharp lithologic break in which overlying rocks contained proportionately much more limestone than rocks below. The boundary was drawn at the top of a 2-foot thick shale, now known simply as the "2 foot shale" (Fig. 5). This placement of the lithostratigraphic boundary is actually several meters below the traditional boundary, based on the horizon at which several new taxa appear and the top of a prominent zone of *Dalmanella* (Fig. 3).

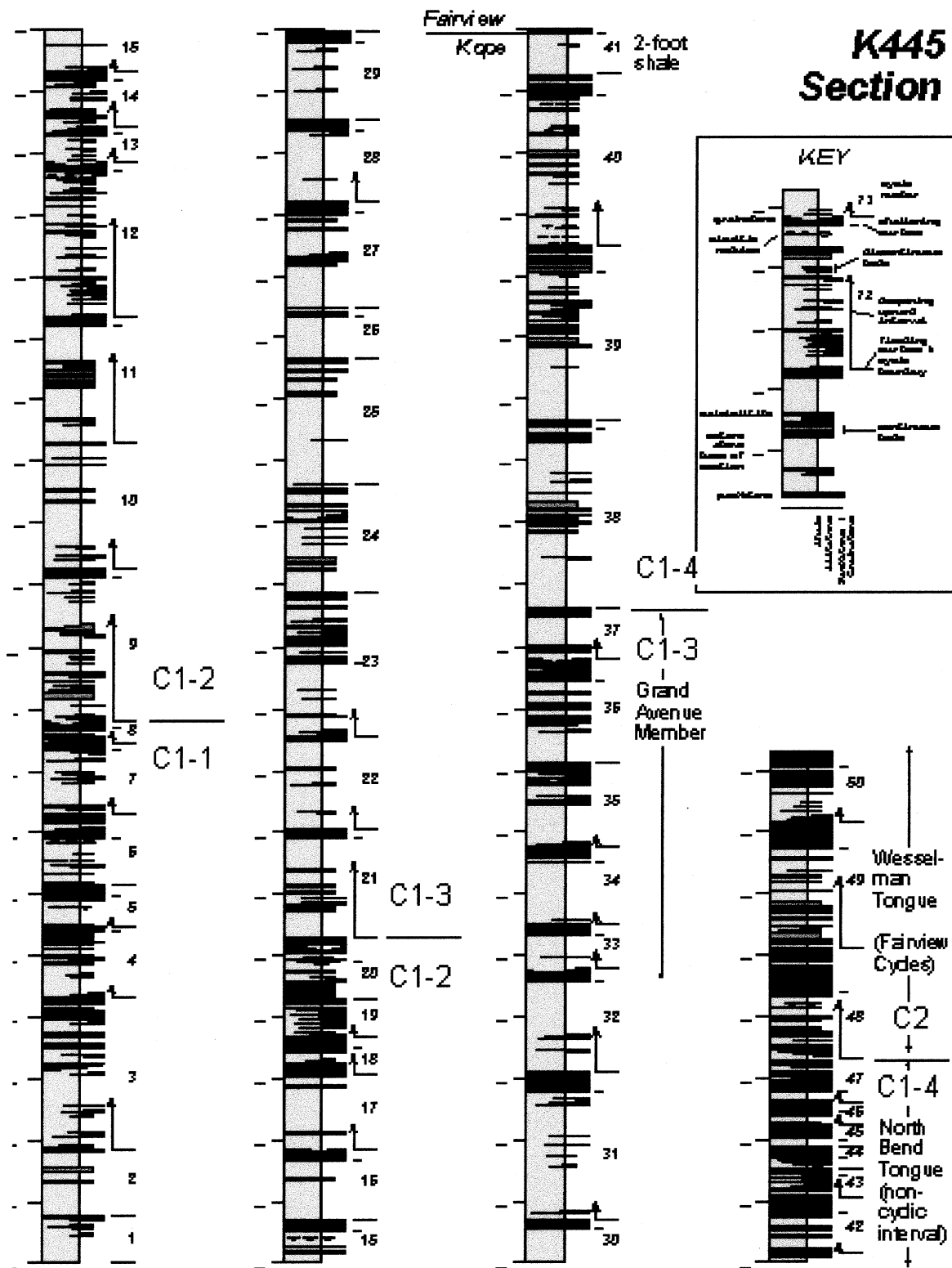
With the advent of sedimentologic interpretation of the Cincinnati Series by Hay (1981) and Tobin (1982), the contact between the Kope and Fairview formations was regarded as an entirely conformable and gradational transition within a large-scale shallowing-upward cycle. In an early sequence stratigraphic interpretation of the Cincinnati, this interpretation was maintained and placed within the C1 depositional sequence (Holland 1993; Holland 1998). Subsequent workers began to emphasize the unusual sharpness of the lithologic transition at the formational contact and placed greater weight on its meaning. Jennette and Pryor (1993) and then Holland and others (Holland and Patzkowsky 1996; Holland et al. 1997) interpreted the Kope-Fairview contact as a sequence boundary. The basal limestone-rich portion of the Fairview, known formally as the North Bend Tongue and informally as the non-cyclic interval (Fig. 5), was interpreted to be the lowstand systems tract of the C2 sequence (Holland and Patzkowsky 1996; Holland et al. 1997). Similarly, Schumacher recognized shallowing upward within the Kope through North Bend Tongue, though he did not place a sequence boundary at the contact (Schumacher 1998). He also placed a flooding surface at the contact between the North Bend Tongue and the overlying more

shale-rich unit known formally as the Wesselman Tongue and informally as the Fairview Cycles (Fig. 5).

Recent work on the relationship between the faunal changes and the sequence architecture of this interval calls into question the current interpretation of the Kope-Fairview contact as a sequence boundary and the North Bend tongue or non-cyclic interval as a lowstand systems tract. If the North Bend Tongue represents an abrupt basinward shift in facies, then the fauna should jump abruptly from a relatively deeper-water fauna to a shallow-water fauna. No such transition is observed. In fact, the shift to a shallow-water fauna dominated by the brachiopods *Strophomena*, *Platystrophia*, and *Rafinesquina*, thick ramose and encrusting bryozoans, and the bryozoan *Escharopora* occurs higher in the section, at the original base of the Fairview. In short, although meter-scale cycle thicknesses do decrease dramatically into the North Bend Tongue, there is little evidence that the major decrease in water depth occurs at this position.

Alternatively, the Kope-Fairview contact may represent a sequence boundary, complete with subaerial exposure, and the North Bend Tongue may be part of the transgressive systems tract. However, this interpretation does not fit the observed thinness of cycles in the North Bend Tongue. Meter-scale cycle thickness ought to increase in the transgressive systems tract as the rate of accommodation increases. Although it appears that this alternative explanation is not tenable, it is testable in that geochemical or petrographic evidence of subaerial exposure at this boundary could be sought.

A third interpretation, one that we currently favor, is that the C1-C2 sequence boundary lies at the traditional contact between the Kope and Fairview formations, not at Ford's lithostratigraphic contact. The North Bend Tongue would represent a cluster of thin cycles at the top of a 20-m cycle, much like the Grand Avenue Member does at the top of the C1-3 20-m cycle (Fig. 5). The Wesselman Tongue would be interpreted as a transgressive systems tract, but deposited in relatively shallower water than the underlying North Bend Tongue and implying a surface of subaerial exposure at the contact between these



**Figure 5.** Sequence stratigraphy of the Kope-Fairview contact interval, modified from the interpretation of (Holland et al., 1997). C1-1 through C1-4 represent 20-m cycles defined by changes in thickness of meter-scale cycles (numbered). For a full discussion of this section and its cyclicity, see Holland and others (1997).

two tongues. This interpretation would also account for the shift to shallow-water fauna where meter-scale cycles are actually thickening. The top of the C1-4 would represent cycles thinning as accommodation decreased prior to the sequence boundary. During initial flooding, a relatively shallow-water fauna was then introduced and meter-scale cycles are relatively thick because of increasing accommodation.

There are undoubtedly other interpretations of this interval and all of them need to be tested with an evaluation of meter-scale cycle structure, 20-m scale cycle structure, changes in depth-related biofacies, and petrographic and geochemical evaluation of the potential for surfaces of subaerial exposure. This work is ongoing and the interpretations we offer here are strictly preliminary and intended as seeds for discussion.

## CONCLUSIONS

1) Meter-scale alternations of shale-rich and limestone-rich facies are real, although these cycles show tremendous variation in their anatomy. These cycles can be correlated for long distances and so reflect ramp-wide, not local, processes. The origin of meter-scale cycles is not resolved and climatically driven cyclicity in storm intensity or frequency may better explain the characteristics of meter-scale cycles than models invoking relative sea level.

2) The interpretation of the Kope-Fairview contact interval is in flux. Currently, we interpret a third-order sequence boundary to lie at the original biostratigraphically defined contact and not the lithostratigraphic contact as we had previously. Our interpretation suggests the presence of a subaerial exposure surface at this contact because of a lack of a lowstand systems tract, and the presence of such a surface needs to be tested.

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**DEFORMED ZONES  
IN THE POINT PLEASANT FORMATION (UPPER ORDOVICIAN)  
ALONG LOCUST CREEK AND ROUTE 1159,  
NORTHERN KENTUCKY**

Kees DeJong, Craig Dietsch, Laura Gilpin, Todd Roberts, and Jane Stormer

Dept. of Geology, University of Cincinnati, Cincinnati, OH 45221-0013

**ABSTRACT**

A deformed zone in the Upper Ordovician Pt. Pleasant Formation, exquisitely exposed in Locust Creek (40 miles or 65 km southeast of Cincinnati, Ohio), contains two deformed grainstone beds, a chaotic layer, a nodular mudstone, and two conglomerate beds interpreted as debris flows. The deformed grainstone beds, massive at the bottom and laminated at the top, may have been the product of turbidity currents, sandy debris flows, or storm events. The chaotic layer can be explained as a debris flow on which one of the grainstone beds had been deposited. It is also possible that the chaotic layer resulted from sliding of the (at least partially lithified) grainstone layer over an unlithified sequence of argillaceous and calcareous mud layers. The two conglomerates interpreted as debris flows contain clasts up to 3 ft. (90 cm) across, as well as one exceptionally large clast of 15 ft. (4.5 m) diameter. The deformed grainstone beds fractured shortly after deposition. Slabs of the upper deformed grainstone bed moved at least a few feet and overrode each other along "thrust faults," suggesting southeastward transport. The slabs are also folded disharmonically: gently in their lower massive parts, but tightly and overturned in their laminated upper parts. This disharmony may reflect the presence and absence of layering, respectively, or the effect of progressive induration of the grainstone beginning at the bottom of the layer. The Locust Creek Deformed Zone could not have been formed without the presence of a submarine slope. Whether earthquake(s) triggered the sediment flows and the deformation is unknown.

**INTRODUCTION**

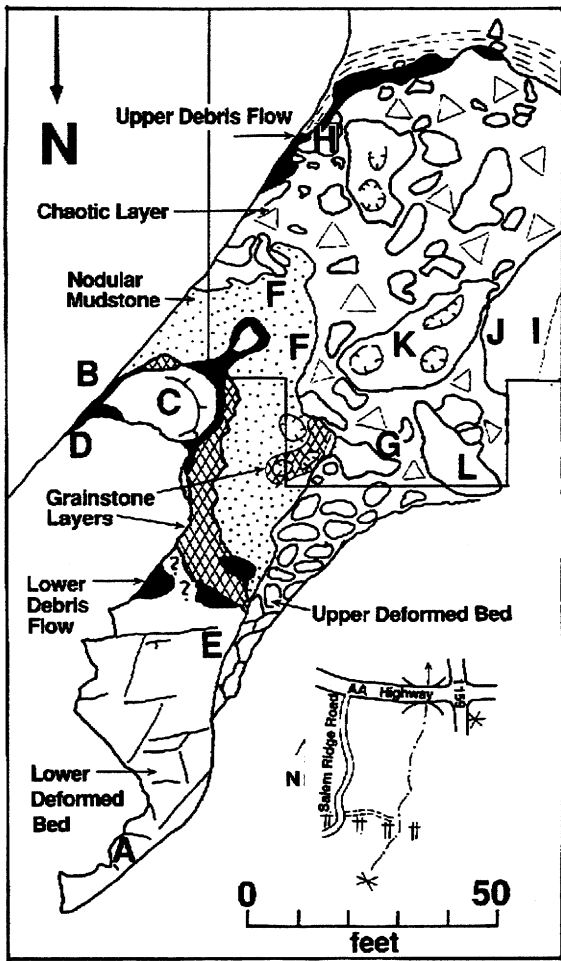
About 40 miles (65 km) southeast of Cincinnati are two exposures of large synsedimentary deformation features: (1) along Locust Creek, and (2) along KY Rte. 1159. These are similar to structures in Kentucky, SW Ohio, and Virginia that have been described as seismites by Pope et al. (1997). The purpose of this paper is to describe and make inferences regarding the origin of the deformation structures at both locales above; the superb quality of the outcrop along Locust Creek, in particular, allows a detailed description that may shed new light on the origin of these deformed zones and possible links to synsedimentary seismic activity.

**LOCUST CREEK DEFORMED ZONE**

The major outcrop is a stream bed exposure along Locust Creek, located near the intersection of the AA Highway and Salem Ridge Road in Bracken County, Kentucky (Brooksville 7.5' quadrangle; Figs. 1-2). The location of specific features in the Locust Creek Deformed Zone is indicated with the letters A, B, C, etc. in Figure 1 and in the text. A schematic cross-section of the zone is shown in Figure 2, and Figure 3 shows the zone in greater detail.

***Sedimentology of the Deformed Zone:***

The Pt. Pleasant beds below the Locust Creek Deformed Zone are thin, fossiliferous limestone ledges and gray shale layers and lenses with local cobble-sized concretions. The limestone beds are grainstones with an abundance of fossil fragments and large, nearly symmetrical ripples trending about N30E.

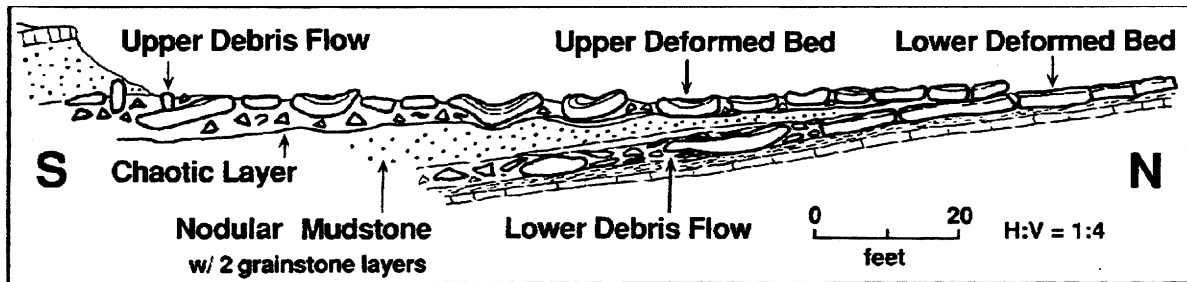


**Figure 1.** Generalized geologic map of the Locust Creek Deformed Zone showing major stratigraphic units. Letters show locations of important features discussed in the text. Location of outcrop marked by asterisk in small inset in lower right; note that the main map is oriented “north down.”

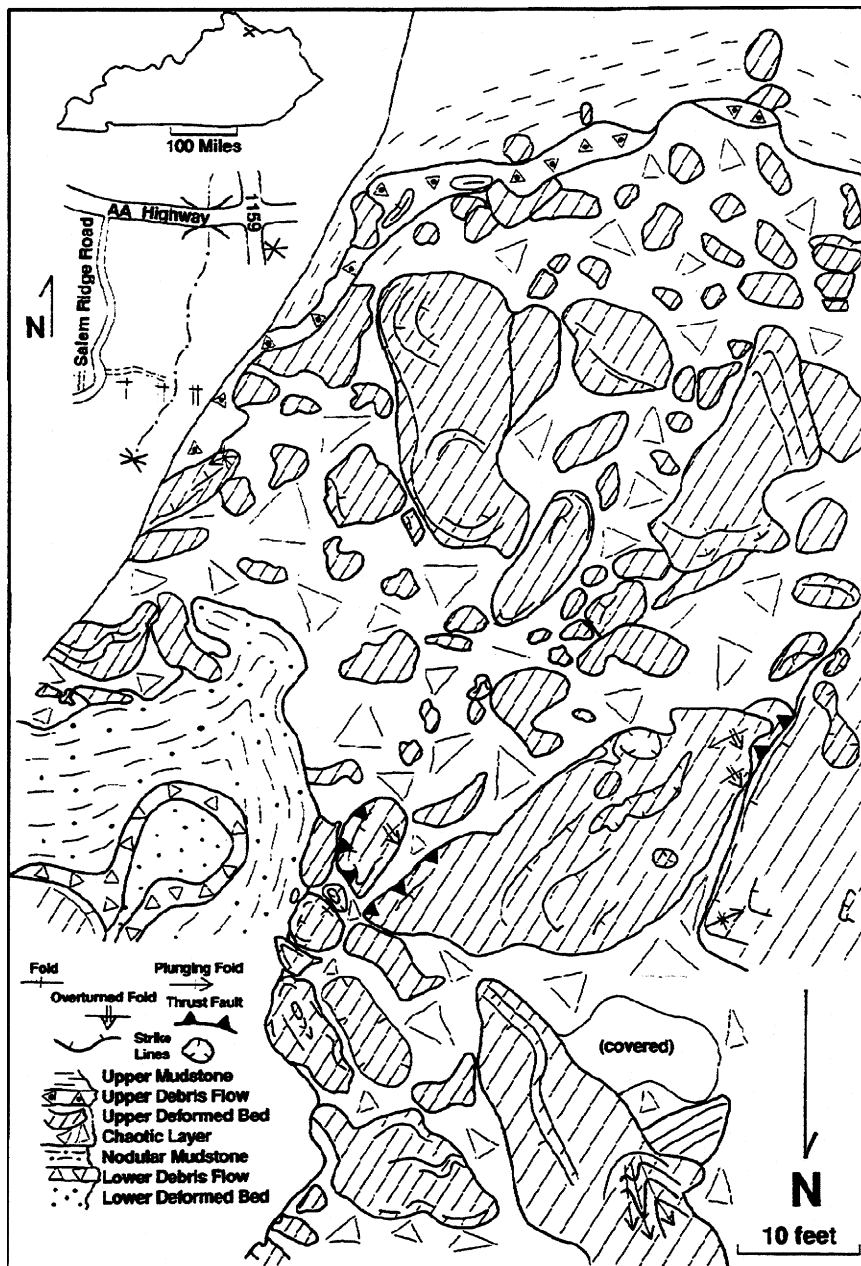
The contact between these beds and the bottom bed of the Locust Creek Deformed Zone is abrupt. This bottom bed is the lower of two 8-20 in. (20-50 cm) thick limestone beds that have been deformed. These beds, named the Lower and Upper Deformed Beds (Figs. 1 and 2), are both massive grainstone in their lower parts and more thinly bedded and laminated in their upper parts.

The Lower Deformed Bed is a light-gray to tan weathering, very fine-grained, dark gray unfossiliferous grainstone 8-12 in. (20-30 cm) thick. The lower part of this bed is massive and the upper part laminated with distinctive, mm-thick layers which weather light gray and tan (Fig. 4). The bed’s lower surface is sharp but appears to be a normal depositional contact with a thin shale layer. Locally, the base of the limestone is undulatory. The bed, which can be followed laterally for about 50 ft. (15 m), breaks up into polygonal slabs up to 6-10 ft. (2-3 m) across. Fractures in the Lower Deformed Bed are shown schematically in Figure 1. At one location (A), it can be seen that a tongue of the underlying shale has moved up between two adjacent blocks which appear to have subsided and somewhat deformed (“dewatering flame structure”). Bedding along the edges of some of the slabs is bent upwards with dips up to about 25°, i.e., an incipient ball-and-pillow structure.

The blocks of the Lower Deformed Bed are overlain by a conglomerate, particularly well exposed in the vertical northeastern edge of the creek (B). Clasts in this conglomerate are subrounded to subangular, and range in size from small pebbles to boulders 3 ft. (90 cm) in diameter (Fig. 5). The clasts are lo-



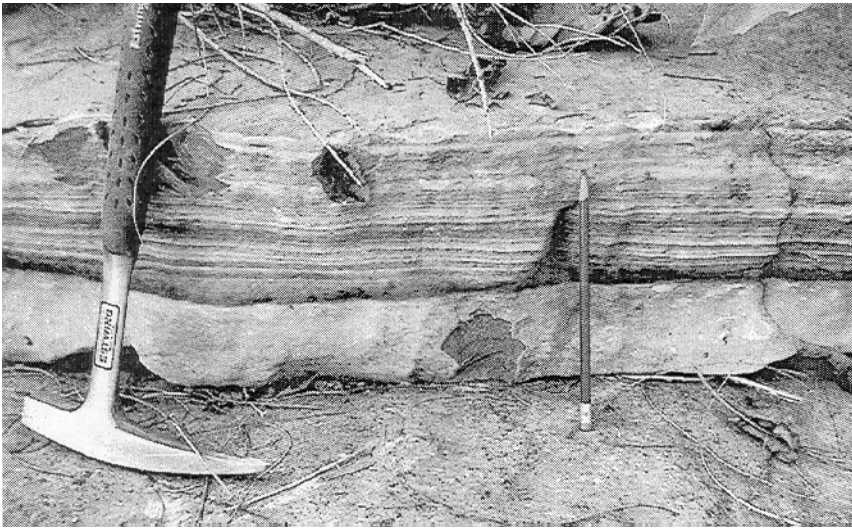
**Figure 2.** Schematic cross-section of the Locust Creek Deformed Zone.



**Figure 3.** Detailed geologic map of the Locust Creek Deformed Zone. Location shown by asterisk in small inset in upper left; note that main map is oriented “north down.” The original mapping scale was 1:20.

cally in contact with each other, but towards the top of the layer (as seen along the creek edge) they are clearly surrounded by a fine-grained grainstone matrix. The clasts are all limestone but have varied lithologies and this observation, combined with “floating” of the clasts in the matrix, suggests that the conglomerate had been deposited as a debris flow. One 15x20 ft. (4.5x6 m) slab (C) is interpreted as a very large broken clast in this debris flow with much smaller clasts both below and above it. We name this conglomerate the Lower Debris Flow.

The Lower Debris Flow rests directly on Pt. Pleasant beds, without interfingering of the Lower Deformed Bed (D). The Lower Debris Flow is locally overlain by a fine-grained, rippled grainstone bed 1-3 in. (2-8 cm) thick deposited on the uneven surface of the debris flow (Fig. 5). The grainstone bed wedges out, and a dark-gray, very fine-grained nodular mudstone rests directly on top of the Lower Debris Flow (B). Burrows are relatively abundant in the mudstone and there are also a few concretions about 10 in. (25 cm) across. On top of this mudstone is another



**Figure 4.** The Lower Deformed Bed, massive at the bottom and laminated at the top. Notice the fossil fragments in the underlying limestone. This block is slightly displaced, obscuring the shale seen elsewhere below the Lower Deformed Bed.



**Figure 5.** Conglomerate interpreted as a debris flow (Lower Debris Flow). The Lower Deformed Bed is at the bottom of the picture. The conglomerate is overlain by a thin grainstone of varying thickness. Ripples in grainstone are oriented NW-SE. Above grainstone is the nodular mudstone (darker gray), and above that are slabs of the Upper Deformed Bed resting on the Chaotic Layer.

discontinuous fine-grained grainstone bed 1-2 in. (2-5 cm) thick.

The thin grainstone beds and the nodular mudstone wedge out toward the north, and as a result, another deformed limestone bed (the Upper Deformed Bed) rests directly on the Lower Deformed Bed (E). The distinction between the massive lower part and layered upper part of the Upper Deformed Bed appears more pronounced than in the Lower Deformed Bed and is obvious in its folding style. The massive part of the Upper De-

formed Bed is folded gently, with locally tight folds in the layered part. At a few places (F) the Upper Deformed Bed rests directly on the nodular mudstone. More commonly, the Upper Deformed Bed rests on a stratigraphic unit we name the Chaotic Layer (Fig. 6): a breccia or conglomerate with limestone clasts and ribbons floating in a matrix of very fine-grained, dark gray silty mudstone with fossil fragments that, too, are isolated in the matrix. The Upper Deformed Bed has a thickness ranging from less than 1 ft. (30 cm) to more than 2 ft. (60 cm). At least at one locality (G), a discontinuous layer of fossiliferous limestone occurs at the very bottom of the Upper Deformed Bed. In the southeast corner of the outcrop (H), slabs of the Upper Deformed Bed are locally overlain by another conglomerate with limestone clasts in a very fine-grained silty mudstone matrix. These clasts include a variety of limestone types (including fossiliferous limestone) and fossil fragments. They are commonly rectangular



**Figure 6.** The Chaotic Layer. Both clasts of various sizes and thin, folded beds are visible. Partial toe of size 11 shoe in lower left corner for scale.

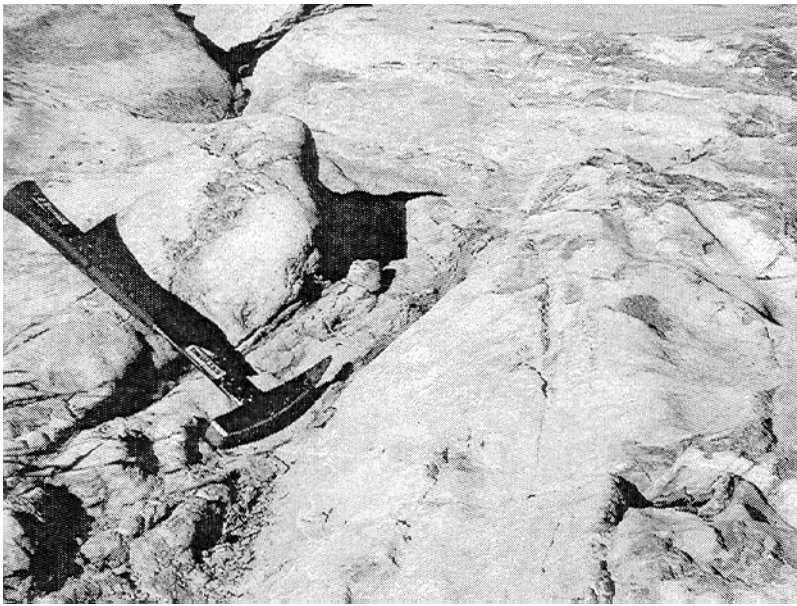
with a variety of orientations: the largest clasts are boulders 30 in. (80 cm) long and 6 in. (15 cm) thick consisting of fossiliferous limestone (grainstone) and the Upper Deformed Bed. Some clasts are oriented nearly vertically in the matrix (Fig. 7). This breccia is interpreted as another debris flow, and we name it the Upper Debris Flow. Overlying the Upper Debris Flow is a layer 24-37 in. (60-95 cm) thick of fossiliferous, very fine-grained mud-

stone with abundant matrix-supported fossils and fossil fragments. This layer is overlain by a gray calcareous siltstone, nodular towards the top, and capped by a fossiliferous limestone representing a return to more typical Pt. Pleasant sedimentation.

***Structural Geology of the Deformed Zone:*** The Lower Deformed Bed is fractured with local tilting of the bed's upper part. Similar fractures and tilting are observed in the

**Figure 7.** Conglomerate with clasts of various sizes, interpreted as a debris flow (Upper Debris Flow). Large, central clast is oriented vertically.

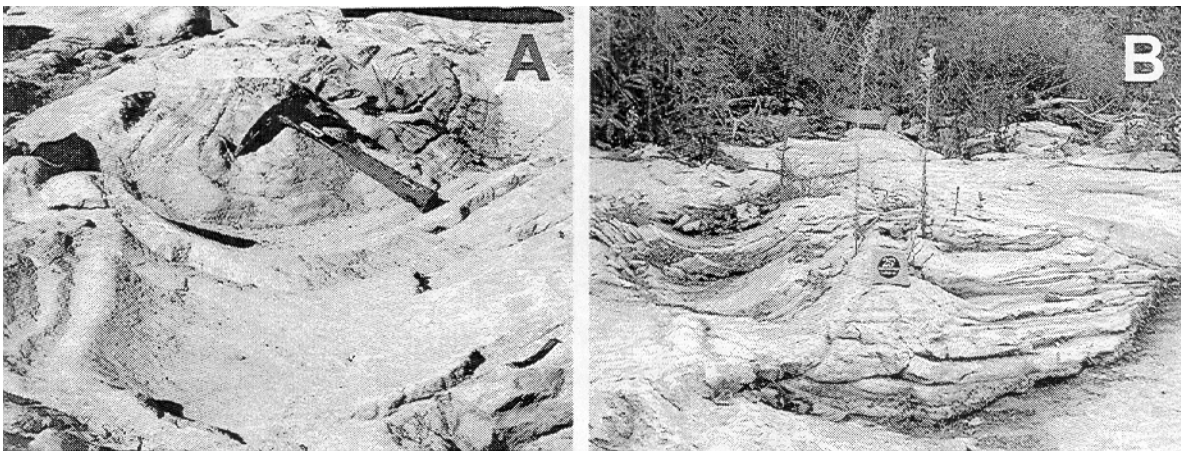




**Figure 8.** Thrusting of the Upper Deformed Bed. Slab at left (west; beneath hammer handle) overrides slab with subvertical layering at right. Sliver of the Chaotic Layer (beneath hammer head) is between the two slabs.

westernmost exposures of the Upper Deformed Bed (I). At most other locations, however, the slabs of the Upper Deformed Bed appear to have moved a foot (0.3 m) or more after fracturing. At one location (J), slabs of the Upper Deformed Bed “scissored,” i.e., north of the rotation axis they moved apart, and to the south, one was thrust over the other. An east-vergent thrust fault is shown in Fig. 8. Slabs of the Upper Deformed Bed moved apart, and this was accompanied by the diapiric ascent of the underlying Chaotic Layer and the descent of the slabs. Contacts between the slabs and the Chaotic Layer are steep. Some of the slabs that subsided are now in

contact with the underlying nodular calcareous mudstone. These slabs obtained a bowl shape with dips rarely exceeding 30 degrees. In one of the very large slabs, four different bowl-shaped subsidence sites can be observed (K). The gentle bowl-formation of the slabs contrasts with the folding of its upper laminated part. Folds can be tight, and are commonly overturned (Fig. 9A). Crowding of folds in a bowl (L) resulted from sliding of the upper layers towards the bowl center, implying detachment of the upper part of the Upper Deformed Bed (Fig. 9B). Along the western side of the Deformed Zone, the large exposure of the Upper Deformed Bed may



**Figure 9.** Folds in the upper laminated part of the Upper Deformed Bed. (A) Tight, overturned fold with eastward vergence. (B) Two synclines and an intermediate anticline in bowl-shaped slab.

represent a part that has not moved at all. Disintegration of this large exposure towards the east, resulting in eastward movement as indicated by thrust faults (Fig. 8), would indicate a (submarine) slope towards the east. A careful analysis of the various directional features suggests southeastward movement (David Ray, pers. comm., 1999).

## DISCUSSION

The Locust Creek Deformed Zone is a synsedimentary interruption in the Pt. Pleasant Formation, consisting of the deposition of six sedimentary units different from other Pt. Pleasant shales and limestones, and the deformation of at least two of units (the Lower and Upper Deformed Beds). The depositional mechanism(s) of the stratigraphic units in the Deformed Zone was hotly debated during various visits to the outcrop, and we have not been able to reach consensus about the genesis of any layer other than the two conglomerates. These latter units exhibit strong evidence indicating a debris flow origin, and consequently we named them the Lower and Upper Debris Flows.

The Lower and Upper Deformed Beds, massive at their bottoms and laminated or layered at their tops can be interpreted as turbidites, Ta and Tb in the Bouma Sequence. The formation of turbidites requires a lengthy descent of turbidity currents in order to develop the turbulence necessary to suspend the grains; turbidites are therefore typically deep-water deposits. The depth of deposition of the Deformed Beds is unknown, but most likely not more than 20-30 m as indicated by symmetric megaripples in the Pt. Pleasant Formation, although this may constitute an argument against a turbidite interpretation. The lower part of the Deformed Beds is ungraded, and the upper part may be graded. A possible explanation of a lack of grading may be that the source material had been extremely well sorted (Carl Brett, pers. comm., 1999). Thus, although normal grading is one of the most useful criteria to interpret beds as turbidity current deposits, a turbidite interpretation of the Deformed Beds cannot be ruled out *a priori*. If the Deformed Beds (or their lower parts) are in fact ungraded, turbidity currents can be excluded as the depositional mechanism.

Alternative explanations of similar layers elsewhere are summarized in Shanmugan (1997), who concluded that some massive, fine-grained clastic beds are best explained by assuming plastic rheology (as in a debris flow) during deposition. Supporting field evidence would include floating clasts and dewatering structures. Shanmugan (1996) introduced the term "sandy debris flow" for fine-grained clastic rocks deposited *en masse* (grains are not deposited one by one, but flow into place, and then "freeze"), and we consider the "sandy debris flow" model as an alternative to deposition by turbidity currents. Another alternative (Carl Brett, pers. comm., 1999) is storm-generated deposits. Corroborating evidence for a sandy debris flow origin of (the lower parts of) the Deformed Beds such as clasts or internal dewatering structures was not found.

The Chaotic Layer can be explained in two different ways: by emphasizing the clasts of greatly varying size floating in a silty matrix, it may be suggested that this layer was deposited as a debris flow. On the other hand, the presence of thin bands that are folded (Fig. 6) can be explained by "interstratal deformation" resulting from the sliding of a relatively coherent slab (the Upper Deformed Bed) over softer, less competent sediments. The Chaotic Layer contains numerous fragments of grainstone similar to that of the Upper Deformed Bed, making it difficult to explain their occurrence by fragmentation and incorporation of the fragments by a movement of the Upper Deformed Bed that does not appear to have exceeded 10 or 20 ft. (3-6 m). The occurrence of these fragments can be explained by assuming that the Chaotic Layer was emplaced as a debris flow of soft sediments including locally a slightly indurated grainstone layer.

A consequence of a debris flow interpretation of the Chaotic Layer is that the Upper Deformed Bed must have been deposited on top of the debris flow. A minor argument in favor of this interpretation is the remarkable variation in thickness of the lower part of the Upper Deformed Bed, from more than 1.5 ft. (45 cm) to less than 4 in. (10 cm). This thickness variation can be explained as the result of an irregular upper surface of a debris flow. The interstratal deformation model gains strength if one assumes that the western out-

crops of the Upper Deformed Bed are not *in situ*, permitting a much farther translation of the Upper Deformed Bed than was assumed above (ca. 10-20 ft. or 3-6 m).

The nodular mudstone may have been deposited under a fluid regime, but a sandy debris flow origin can be ruled out at present. It should be noted that this unit, about 1 ft. (30 cm) thick, wedges out abruptly northward, as does the Chaotic Layer. We consider even the fossiliferous, very fine-grained mudstone on top of the Upper Debris Flow as suspect: though most probably deposited under fluid conditions, the sediments could also have flowed in place. Dr. Carlton Brett recognized also a slight angular discordance between laminations in this layer and the overlying limestone bed.

The cause of the deformation of the Deformed Beds must have been related to the presence of a slope. This is obvious for the Upper Deformed Bed in which slabs are separated. A slope can be also inferred for the Lower Bed since the Lower Debris Flow rests directly on undeformed Pt. Pleasant Beds and so the Lower Deformed Bed must have slid away before the Lower Debris Flow was deposited. It is also necessary to infer the presence of a slope in order to generate debris flows. A slope was thus present during the formation and deformation of the Locust Creek units.

It is possible, but not necessary, that earthquakes triggered the downslope movements of sediment observed in the Pt. Pleasant Formation. Assigning one earthquake for each

depositional or deformational event, i.e., (1) sandy debris flow (Lower Deformed Bed); (2) fragmentation of Lower Deformed Bed and debris flow (Lower Debris Flow); (3) sandy debris flow (nodular mudstone); (4) debris flow (Chaotic Layer); (5) sandy debris flow (Upper Deformed Bed); (6) sliding of Upper Deformed Bed and debris flow (Upper Debris Flow); (7) sandy debris flow (nodular mudstone), one could infer that as many as seven(!) earthquakes triggered the various units representing downslope movement of sediment. That earthquakes can generate synsedimentary structures is now well-accepted. Pope et al. (1997) described numerous seismites (characterized by the presence of ball-and-pillow and other synsedimentary deformation structures) in Northern Kentucky. A few of those (e.g., near Jephtha Knob) appear to consist of debris flows. The presence of earthquakes in the geological past will remain hypothetical in most cases, whereas the former presence of submarine slopes can be demonstrated both sedimentologically and structurally. The Locust Creek Deformed Zone is a beautiful example of the record, both sedimentary and structural, of a former submarine slope.

#### KY ROUTE 1159 DEFORMED ZONE

The deformed zone in the Pt. Pleasant Formation along KY Route 1159 extends about 150 ft. (45 m) from the northern end of the outcrop (Fig. 10). The principal, deformed limestone bed in the deformed zone is differ-

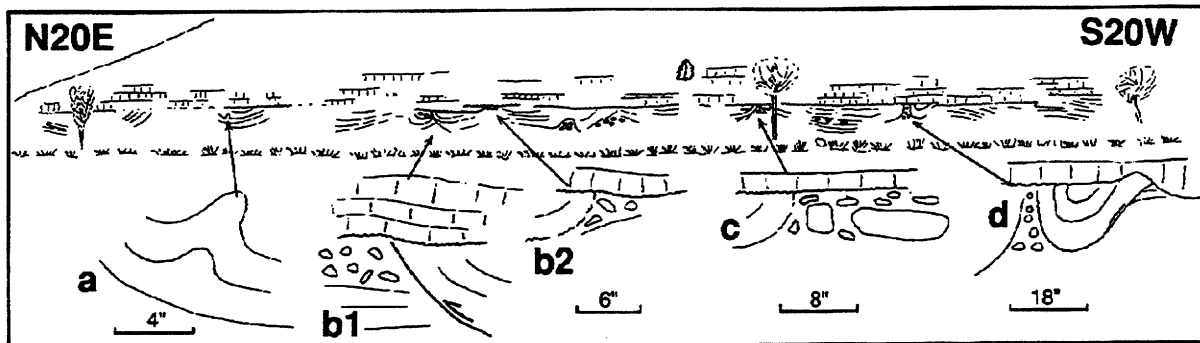


Figure 10. Sketch of the Route 1159 Deformed Zone.

ent from the overlying limestone beds. The deformed unit is a grainstone generally lacking large shell fragments, whereas shell debris is abundant in the overlying limestone beds. The upper part of the deformed grainstone is laminated, and appears locally more tightly folded than the lower part (“a” in Fig. 10). This grainstone is similar to the Lower and Upper Deformed Beds of the Locust Creek Deformed Zone, though there is more variation in grain size in the Route 1159 exposure.

The deformation took place in at least two phases: locally, a tilted lower layer is truncated below a middle layer (“b1” in Fig. 10), and this layer is truncated in turn below an upper layer (“b2” in Fig. 10). At both contacts the bottom layer was deformed and then eroded, followed by deposition of the upper layer. In Figure 10, “b1” represents the grainstone bed, a thrust fault, and a small outcrop of a conglomerate. Where this conglomerate is best exposed (behind a tree in “c” in Fig. 10), we notice variation in clast size and the presence of a matrix surrounding the clasts. This could be explained, of course, as the effect of (submarine) erosion of the deformed grainstone, but it could also be argued that this conglomerate was deposited as a debris flow. There are also several locations where conglomerate is present below or amidst the grainstone, and at which more folds are evident (“d” in Fig. 10).

## DISCUSSION

Both deformed zones at Locust Creek and at Route 1159 occur in about the same stratigraphic position, approximately 25 ft. (7.5 m) below the contact of the Pt. Pleasant Formation with the Kope Formation (Carl Brett, pers. comm., 1999); thus, they are probably different aspects of the same deformed layer. The thrust fault and the folds along Route 1159 are not easy to explain as “ball-and-pillow” structures. They might be the result of downslope sliding. The conglomerate may also be a debris flow, implying a submarine slope. In addition, the truncation of layers may

be easier to explain with mass movements than with submarine erosion.

## CONCLUSION

Recognition of a submarine slope during deposition of the Pt. Pleasant Formation is the major result of this study. The slope direction appears to have been eastward but may have been southeastward. Two debris flows are recognized and other deposits (in particular the Chaotic Layer) may also be the result of sediment flow. Earthquakes may have triggered the downslope movements, and it is perhaps even likely that this happened. Because of the presence of a paleoslope, however, we are not convinced that the Locust Creek Deformed Zone is a seismite, or even a “secondary seismite” (Pope et al., 1997).

## ACKNOWLEDGMENTS

We thank Steve Felton for discovering the Locust Creek outcrop; Bracken County Sheriff Mike Nelson for permission to study the outcrop; and Sean Cornell and David Ray for insightful discussions. Dr. Carlton Brett instigated this study and generously gave valuable editorial comments.

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# PROBABLE SEISMITES IN THE UPPER ORDOVICIAN FAIRVIEW FORMATION NEAR MAYSVILLE, KENTUCKY

Gregory A. Schumacher

Ohio Department of Natural Resources, Division of Geological Survey  
4383 Fountain Square Drive, Columbus, OH 43224-1362

## INTRODUCTION

Seismites and possible seismites are reported from restricted stratigraphic intervals throughout the Middle and Upper Ordovician rocks of Kentucky and Ohio (Weir and Greene, 1965; Weir et al., 1984; Potter et al., 1991; Pope and Read, 1992; Schumacher, 1992; Rast and Etensohn, 1995; Pope et al., 1997; Krekeler et al., 1999; Potter et al., in press). These intervals of deformed strata displaying ball and pillow structures and convolute laminations occur in the Lexington Limestone (Logana and Tanglewood Members), the Clays Ferry Formation, the Point Pleasant Tongue of the Clays Ferry Formation, the Garrard Siltstone, and the Fairview Formation. Unpublished field studies conducted by Paul Potter and the writer have documented similar deformed beds in the Kope Formation and the Corryville Member of the Grant Lake Limestone in northeastern Kentucky and southwestern Ohio.

Our stop at the spectacular new roadcuts for the Kentucky Route 3071 by-pass of Maysville, Kentucky, provide 1.2 kilometers of continuous exposure of at least four seismites (Krekeler et al., 1999). These beds are in the upper part of the Fairview Formation approximately 3.5 meters below the Fairview-Grant Lake Limestone contact. This stratigraphic zone ranges in thickness from 0.6 to 5.0 meters, and individual ball and pillow structures range from 0.15 to 1.5 meters in diameter. The seismites occur as discrete beds overlain, underlain, and separated by slightly deformed to undeformed interbedded limestone and shale beds. Individual beds have sharp upper and lower contacts and are generally discontinuous. Beds pinch out and reappear laterally within the zone. Grain size

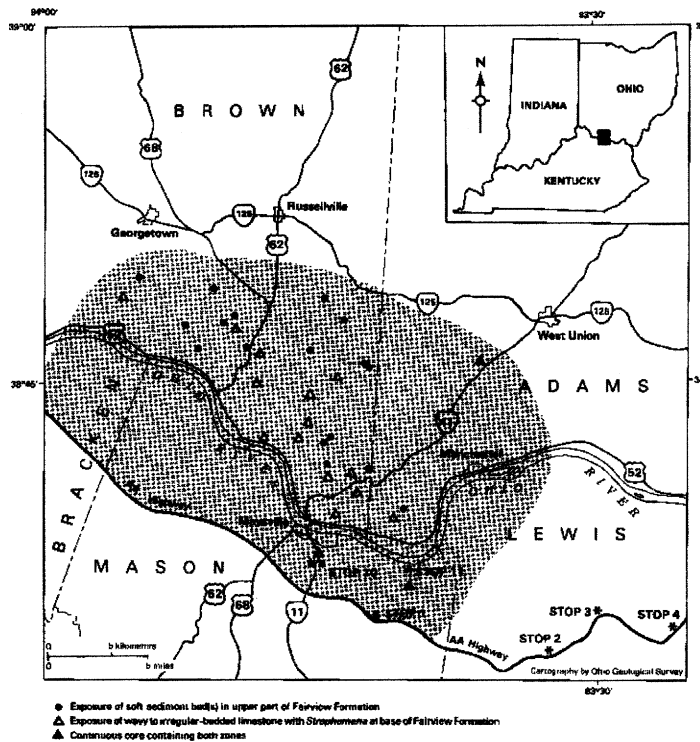
ranges from silt to fine sand. Other features present include shale injection structures, broken beds, breccias, upturned rounded edges of some pillows, and imbrication of balls and pillows.

## REGIONAL DISTRIBUTION

Similar deformed calcisiltite beds have been mapped in approximately 400 square kilometers and identified in 25 exposures of the upper part of the Fairview Formation throughout northern Mason County, Kentucky, southwestern Adams County, Ohio, and southern Brown County, Ohio (Fig. 1). A single deformed bed was recognized in 22 of 25 exposures, and multiple deformed beds were present in three exposures. Four beds occur at our stop at the Maysville by-pass road cuts, three beds are present in Kentucky Route 11 road cut (Schumacher, 1992), and two beds are exposed in an unnamed tributary of Eagle Creek in Brown County, Ohio.

The zone of deformed beds occurs between 1.0 and 9.0 meters below the Fairview-Grant Lake formational contact. Single deformed beds occur between 1.0 and 2.0 meters below the contact in two exposures, 4.5 and 6.5 meters below the contact in 18 exposures, and 8.0 and 9.0 meters below the contact in three exposures. The distance below the contact could not be determined in two exposures. These observations support the suggestion of Krekeler et al. (1999) that four distinct deformed beds are present throughout the Maysville region. The upper and lower beds are weakly developed and occur locally, and the middle one or two beds are well developed and regionally correlative.

Do the seismites in the upper Fairview Formation correlate to similar beds in the



**Figure 1.** Probable seismite distribution (soft-sediment beds) north of the Ashland-Alexandria Highway in northern Kentucky and southwestern Ohio. Exposures containing probable seismite located after 1991 are not shown (from Potter et al., 1991, their fig. 36).

Garrard Siltstone, exposed 60 kilometers to the south, as suggested by Pope et al. (1997, their fig. 2)? At present, this question cannot be answered because the distribution of this zone south of the Alexandria-Ashland Highway has not been mapped and is presently unknown. A preliminary cross-section suggests this zone can be traced 15 kilometers south of Maysville to beyond Flemingsburg, Kentucky (Fig. 2). If this zone could be correlated to similar beds in the Garrard, it would provide an isochronous marker horizon throughout southern Ohio and east-central Kentucky. Clearly, additional field work is needed to define the southern boundary of this widespread zone in Kentucky.

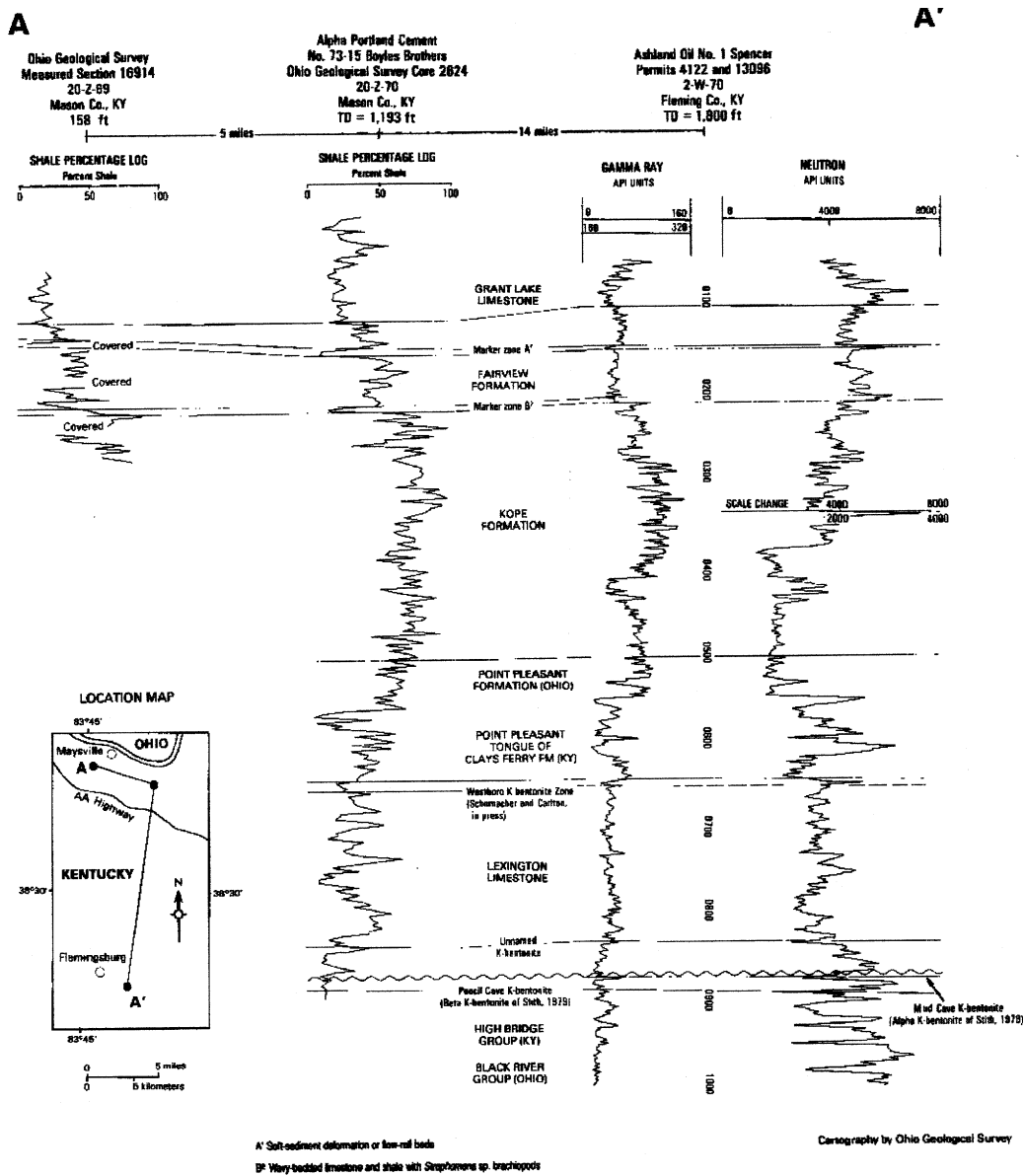
## ORIGIN

What is the evidence that led Pope et al. (1997) and Krekeler et al. (1999) to conclude that the ball and pillow beds in the upper Fairview Formation are seismites caused by major earthquakes and not the result of large-scale debris flows or other nonseismic pro-

cesses? Large-scale debris flows are ruled out because ball and pillow structures lack a preferred orientation, glide planes are absent, and beds do not thicken downslope or laterally interfinger with undisturbed beds. Tide-induced liquefaction of silt- and sand-sized sediments is unlikely in the storm-dominated subtidal depositional setting of the Fairview. Storm-induced liquefaction is discounted because studies of modern hurricane-influenced shelves have not reported soft-sediment deformation in the form of ball and pillow structures. Load-induced liquefaction is unlikely because the thick storm beds necessary to produce failure of underlying water-saturated shale are not present.

## SEISMITES LINKED TO LOCAL STRUCTURE?

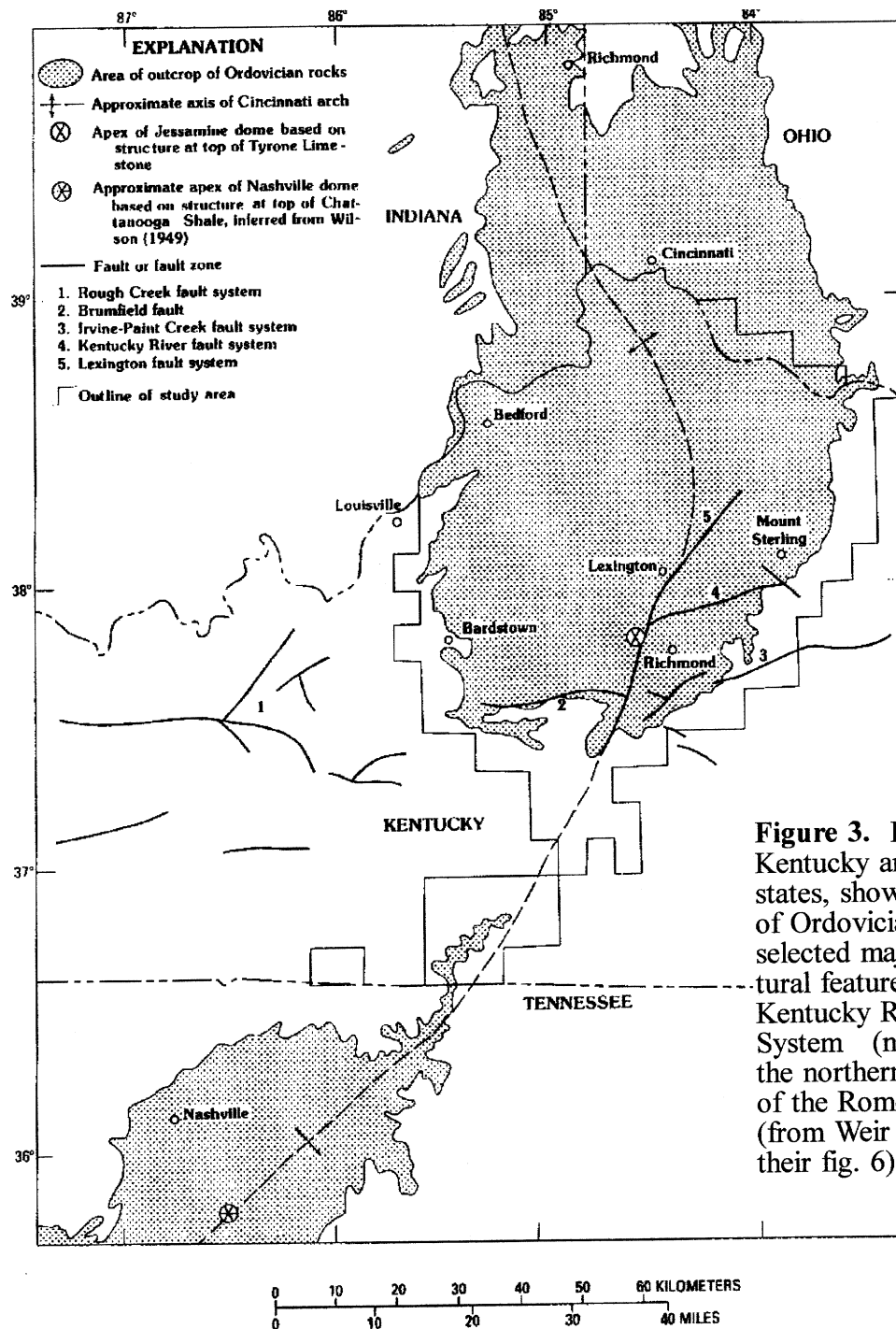
Drahovzal et al. (1992) and Drahovzal and Noger (1995) mapped the Grenville Front or the deep-crustal suture zone as a reverse fault separating the East Continent Rift Basin to the west from the Grenville Province



**Figure 2.** Surface to subsurface correlation of probable seismites (flow-roll beds) from Maysville to Flemingsburg, Kentucky, based on shale-percentage and geo-physical logs. The middle (4.5 to 6.5 meters) and lower (8.0 to 9.0 meters) beds are present in marker zone A' (from Potter et al. 1991, their fig. 35).

in the Precambrian basement rocks of Mason County. The Rome Trough and Lexington fault zone are present 50 to 100 kilometers to the south of Maysville, Kentucky (Fig. 3). The Rome Trough and adjoining structures were reactivated during the Middle and Late Ordovician, influencing sedimentation and possibly producing earthquakes (Borella and Osborne, 1978; Weir et al., 1984; Ettensohn, 1992).

Faults and inferred faults have been mapped in the surface rocks of Mason County and observed in the Camp Nelson Limestone being deep mined by the Dravo Lime Company in eastern Mason County (Schilling and Peck, 1967; Potter et al., in press). Historical records show that four small-magnitude, poorly constrained earthquakes have occurred close to the Maysville by-pass cuts (Hansen, 1984). Unfortunately, the timing of faulting



**Figure 3.** Parts of Kentucky and adjacent states, showing outcrop of Ordovician rocks and selected major structural features. The Kentucky River Fault System (number 4) is the northern boundary of the Rome Trough (from Weir et al., 1984, their fig. 6).

and fault movements is poorly constrained (Potter et al., in press) and the link between surface and basement faults has not been established. Thus, linking the Fairview seismites to any specific fault or movement along that fault is not possible at this time.

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# MULTI-SCALE ANALYSIS OF SPATIAL FAUNAL VARIABILITY AND MICROSTRATIGRAPHY IN THE FAIRVIEW FORMATION (UPPER ORDOVICIAN), NORTHERN KENTUCKY

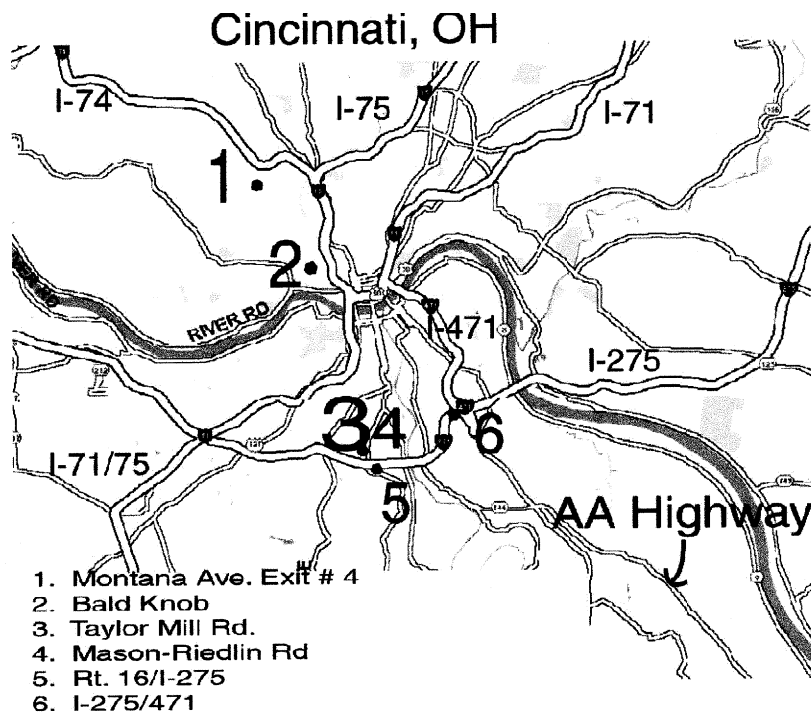
Susan L. Barbour

Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013

## INTRODUCTION

This research, which is ongoing, is an expansion of an earlier study by Miller (1997), who collected faunal samples at 10 m lateral intervals along the amalgamated cap of cycle 49 (Holland et al., 1997), or “Cycle B” of Jennette (1986) at the Taylor Mill Road (or Riedlin-Mason Road) locality. He found that the faunal composition did not vary randomly from sample to sample but, rather, showed systematic variation along the transect that did not appear to be a product of storm sorting or other post-mortem transport. This, in turn, suggests that biologically meaningful spatial variation may be preserved at the 10 m scale, despite the fact that deposition of beds was influenced by storms.

In Miller’s (1997) analysis of the original transect at Taylor Mill Road, faunal counts were taken from an amalgamated bed with no detailed assessment of “microstratigraphy” contained within the bed. Moreover, counts were not taken from beds other than the cycle capping bed. Given that this bed is a “multi-event” amalgamation, analysis of the microstratigraphy will provide insight into the important question of whether sample compositions identified were random averages of compositions among layers, or whether the separate layers, or subhorizons, maintained compositions that are discrete from one another. Additional outcrops will be added to the study in the near future aside from the two (Mason-Riedlin Rd. and Bald Knob, see Fig. 1) in the original study. This will allow



**Figure 1.** Location map for Taylor Mill Road section (3) and other well-studied sections of the Fairview Formation in the Greater Cincinnati area.

identification of any larger scale faunal gradients as well as direct comparison among outcrops, both upramp, and along strike, in the Cincinnati area. The intention of this preliminary paper is to describe the lateral variability of cycle 49 at Taylor Mill Road.

## BACKGROUND

The Upper Ordovician Fairview Formation of the type Cincinnati is 20 to 35 m thick (Jennette and Pryor, 1993), and consists of alternating limestones and shales deposited on the western edge of the Appalachian basin (Holland et al., 1997; Jennette & Pryor, 1993). Within the Fairview, meter-scale bundling of limestones and shale is particularly well developed near its base. Meter-scale deposition is thought to comprise high-frequency cycles (Holland et al., 1997; Miller et al., 1997), which are part of a larger-scale regressional sequence, near the base of the C2 sequence of Holland and Patzkowsky (1996; Holland et al., 1997; Jennette and Pryor, 1993).

Several researchers have studied the anatomy of the Fairview cycles (Holland et al., 1997; Jennette and Pryor 1993; Jennette 1986; Tobin and Pryor 1981; Diekmeyer, 1998). Complications have been recognized in describing and correlating cycles among localities because of significant lateral cycle variability (see Holland et al., 1997, for discussion).

Deposition of the Fairview Fm. has been interpreted as taking place "between fair-weather and storm wave base" (Holland et al., 1997; Jennette and Pryor, 1993; Diekmeyer, 1998), at a time when Laurentia was oriented 20-25 degrees south and would have been subjected to intense storms (Ettensohn, 1992; Jennette, 1986). Storm deposition is apparent in the beds of the Fairview, adding further variability to the interval. Jennette (1986) and Jennette and Pryor (1993) discussed details of storm effects in the lower Fairview and Kope formations. Many cycles, including the study interval, show a stratigraphic transformation from distal to proximal storm deposits (see Holland et al., 1997, and Jennette and Pryor, 1993, for discussion). Cycle caps are marked by thick (13 to 30 cm for Cycle B) amalgamated (i.e., multi-event), proximal storm-beds, which are laterally con-

tinuous and traceable throughout the study area (Miller, 1997; Jennette & Pryor, 1993; Jennette, 1986). These amalgamated beds will be discussed in greater detail later in this paper.

## METHODS

The goal of this study is to provide a detailed, multi-scale analysis of spatial faunal variability and microstratigraphy. Ultimately, it will incorporate 15 to 20 field localities throughout the Cincinnati region that contain the cap of Fairview Cycle B. Figure 1 shows several localities in Ohio and extreme Northern Kentucky. Other outcrops near and around Cincinnati and Northern Kentucky will be added, as well as several to the south (up dip on the paleoramp) along the AA Highway (Fig. 1) in Kentucky. The "anchor" locality, Taylor Mill Road in Northern Kentucky, is being used for fine scale (10 m and less) lateral sampling. At this locality, bulk samples were collected at 10 m intervals along a 140 m transect. Finer (essentially continuous) lateral sampling, most likely between the 30 and 50 m stations (Fig. 2) will be completed in the near future. Combined, these samples will help to gauge the resolving power in the sample horizon at very fine lateral scales. Two to three widely spaced samples will be taken from the other localities to assess the nature of the faunal gradient and stratigraphy across the entire study area.

Sub-horizons within each sample will be prepared for a "microstratigraphic" analysis of faunal compositions. This will involve slabbing the sample parallel to bedding at multiple micro-horizons that contain highly concentrated skeletal materials. For the laboratory work up of samples, acetate peels are being produced from polished samples etched with acid to allow species identification and point counts of bryozoan colonies. Samples will be censused to the species level using the acetate peels and megafauna collected directly from crushed sample material, as well as through field census. Faunal count data will be subjected to multivariate and other statistical techniques to determine faunal relationships among them. Comparisons of samples within and among transects will permit identification of patchiness, if any, in the distribution of ancient marine organisms versus

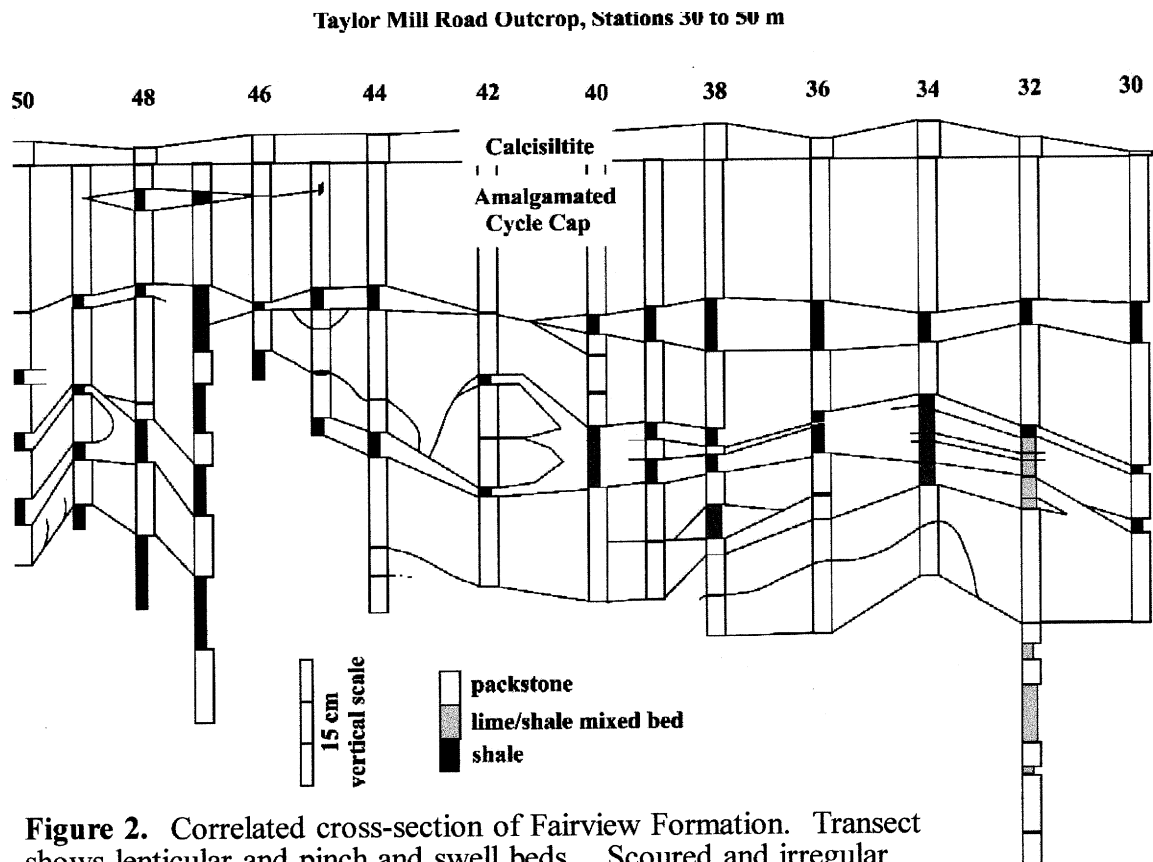
gradients associated with environmental change.

The interval was measured and correlated at the 1 m level at Taylor Mill Road for 20 meters total to discern small-scale stratigraphic variations. Other outcrops will also be measured in the near future. Figure 3 shows the lenticular nature of the beds. Digital images were taken of the interval and of the cycle cap for the 20 meters. These images were made into a photomosaic to accompany the stratigraphic drawing, field correlations, and cut rock slabs as an aid to interpretation of small-scale stratigraphy.

## RESULTS

The study interval has been traced with confidence in outcrops over 45 km from Cincinnati, OH, to near Brooksville, KY. These beds show evidence of storm action as suggested by Jennette (1986) and are similar to those described in the Martinsburg Forma-

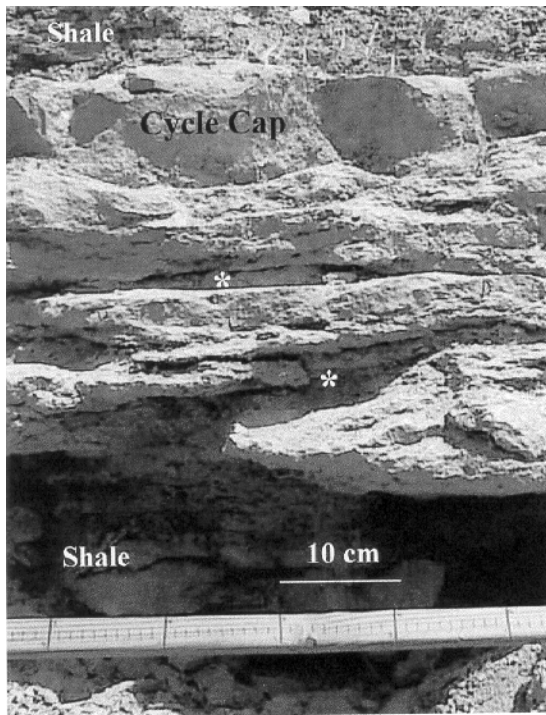
tion by Kriesa (1981). The composite ledge-forming beds 20-25 cm thick are demonstrably continuous within and among outcrops. However, at this fine scale, there is poor lateral continuity of individual beds, suggesting the composite beds, as viewed in outcrop, are made up of a series of amalgamated lenses and scour fills (Brett, personal communication). Causes of lateral variability in individual beds as seen in outcrop include pinching and swelling of a bed due to current action or deposition on irregular erosional surfaces. Also, beds may be erosionally scoured out in places, as described by Jennette (1986) and Kriesa (1981). Kriesa (1981) also suggested that some of the limestone beds represent original patchiness. Figure 2 shows the cycle at Taylor Mill Road, Glendale Rd., and Rte. 1019 (Holts Creek Rd. locality of Holland et al., 1997), which is currently the most southern outcrop where the interval can be traced with confidence. The cycle becomes easier to define northward, and contains more mud.



**Figure 2.** Correlated cross-section of Fairview Formation. Transect shows lenticular and pinch and swell beds. Scoured and irregular erosional surfaces are also apparent. Note vertical exaggeration.

At northern outcrop localities (shown in Fig. 1), the cycle is approximately one meter in thickness. It consists of alternating packstones and shale, with minor calcisiltites, which most often lie above the well defined, ledge forming amalgamated cycle cap. Calcisiltites pinch and swell laterally as shown on Figure 2, and sometimes disappear entirely. To the southeast, along the AA Highway (Fig. 1), the study interval appears to be coarser grained overall, with fewer, thinner shales. The amalgamated cycle cap is often largely amalgamated, combining many beds. These beds are believed to represent more proximal storm features, as they tend to contain a greater abundance of tabular beds as described by Jennette and Pryor (1993) and Jennette (1986). The interval contains more calcisiltites, which may be found dispersed throughout.

Many beds within the interval have sharp bases that may scour into lower beds (Fig. 3); this observation is consistent with storm erosion described by Kreisa (1981). Some packstones in the interval do not appear to have scoured bases, and may represent shift-



**Figure 3.** Cycle 49. Note bounding shales, lenticular beds and scoured surfaces (\*), and amalgamated cycle cap.

ing and redeposition of sediments without erosion (Kreisa, 1981). Erosional bases of beds in the interval are not uniform (Fig. 3), and beds typically vary laterally in thickness. Few fossils are found in shale beds, suggesting that they were the product of resuspension and rapid deposition of sediment by storms (Kreisa, 1981). However, parting surfaces between or within limestone layers do often contain abundant bryozoan and brachiopod material. The bundle is bound on both sides by thicker shale units (Fig. 3), which often contain minor limestones or calcisiltites.

**Description of Cycle Cap:** The amalgamated cycle cap preserves a “multi-event” history as seen by numerous microhorizons within the bed, composed primarily by bryozoans and brachiopods that represent distinct storm events. Observed storm effects include: mud-filled bryozoan zooids, which show previous burial; sheltered muds; shelter porosity; and geopetal structures. Amalgamation in this “bed” is complex, and may vary in style laterally. *Terminal amalgamation* (Fig. 4A) is where storm activity disrupted and redeposited two or more layers as one. Since settling times vary for the particles, grading may occur. This may be recognized as separate from normal deposition by the presence of storm features, or the lateral tracing into another amalgamation style. *Stacked amalgamation* (Fig. 4B) is where skeletal material from an overlying bed was deposited onto similar lower ones by winnowing, combining them into one large unit. This may also occur if a separating layer pinches out, leaving similar bounding beds “stacked” together. The last type of amalgamation seen in this interval is *sequential amalgamation* (Fig. 4C). This is formed by the deposition of multiple horizons (couplets) of skeletal material with little or no mud in between, suggesting only minor disturbance by storm processes. It is believed that the light gray, bryozoan-rich mud represents background sedimentation followed by a darker gray fine-grained storm-deposited shell debris layer. Contacts between the layers are indistinct, but not gradational, with minor, if any scouring.

Microbeds may occur in conjunction with other varieties of amalgamation at the microhorizon level. For example, several horizons

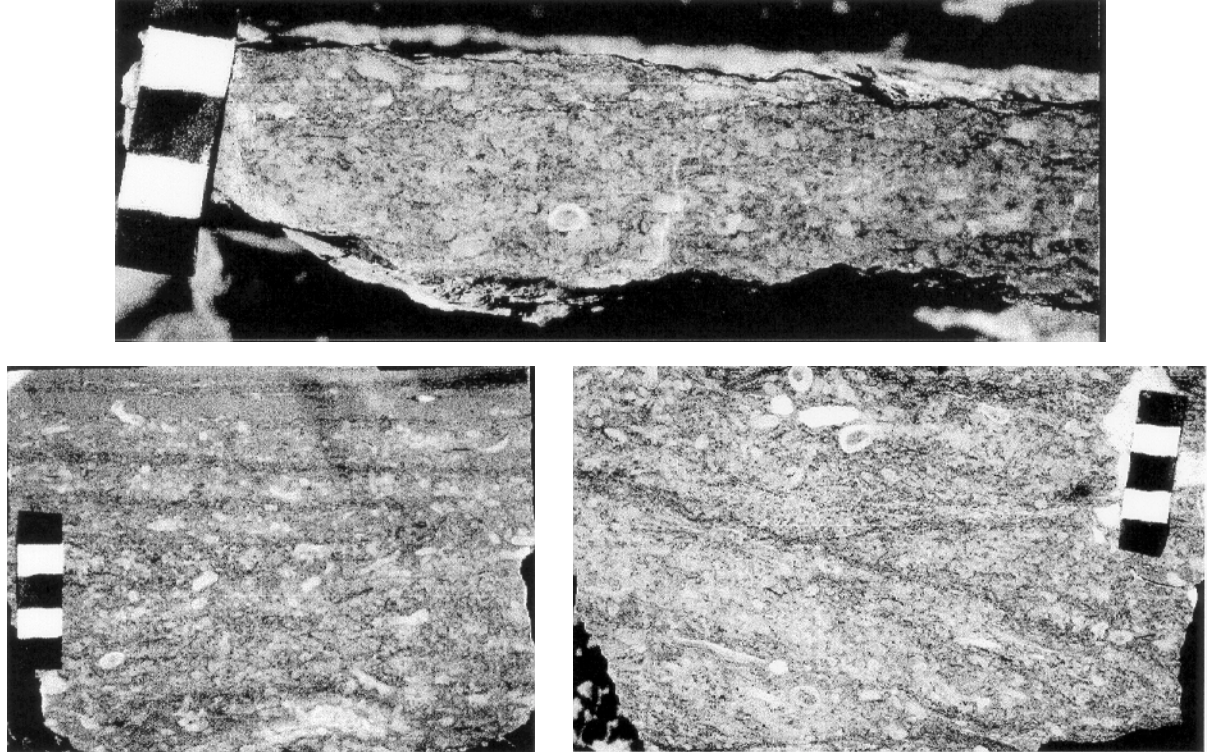
may be terminally amalgamated, and followed by sequential amalgamation deposition. Slabs cut through the amalgamated cap show that all parts of a horizon may not be equally disturbed by storms. Along the 140 m transect, microhorizons were maintained at station 0, yet station 10 was more homogeneous, and nearly terminally amalgamated. Minor differentiation returned at station 20 m, increased at 30 m, and ended at 40 m, which contained many couplets (sequential amalgamation) (Fig. 4C). Stations 50-70 m show decreasing couplet preservation. Station 80 m retained a few hummocky couplets and 90 m was cross-bedded. Station 100 showed slightly tilted couplet horizons, which were also present, but stronger and more horizontal at station 110 m.

## DISCUSSION

Although the effects of storms can be seen throughout the cycle, the thickness of the overall cycle does not vary significantly over

great distances. I believe that the storm-influenced sediments are not being significantly transported, as indicated by the retention of megafaunal gradients (Miller, 1997). Given that megafauna in offshore settings tend to be little disturbed during storm events (Miller et al., 1992; Westrop, 1986; Kriesa, 1981), this does not seem unreasonable. The nature of the depositional environment must be understood, however, before such trends can be fully appreciated, and it is my intention to dissect the microstratigraphy of a single bed to understand the nature of such gradients.

The 150-m-long exposure of the lower Fairview formation (Cincinnatian Series, Upper Ordovician) at Taylor Mill Road (Riedlin-Mason Road locality) in Northern Kentucky provides an ideal section to evaluate variability in faunal composition at a range of scales. The interval is one of many storm-dominated cycles of the Cincinnatian, and is thought to preserve a faunal gradient despite obvious storm processes. This ongoing study will examine the variable stratigraphy and



**Figure 4.** Types of amalgamation as seen in cut slabs from Taylor Mill Road. (A) Terminal amalgamation; (B) Stacked amalgamation; (C) Sequential amalgamation. Scale bar is in centimeters.

arrangement of faunal patterns in an interval within and among outcrops to evaluate spatial variability in faunal composition at a range of scales. From this, it is hoped that a better understanding will be developed of the spatial fidelity of fossil assemblages and the potential spatial resolving power of the fossil record.

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**TAPHONOMY AND PALEOECOLOGY  
OF AN EDRIOASTEROID ENCRUSTED HARDGROUND  
IN THE LOWER BELLEVUE FORMATION  
AT MAYSVILLE, KENTUCKY**

Colin D. Sumrall<sup>1</sup>, Carlton E. Brett<sup>2</sup>, Paula T. Work<sup>1</sup>, and David L. Meyer<sup>2</sup>

<sup>1</sup>Geier Collections and Research Center, Cincinnati Museum Center, Cincinnati, OH 45202;

<sup>2</sup>Department of Geology, University of Cincinnati, Cincinnati, OH 45221-0013

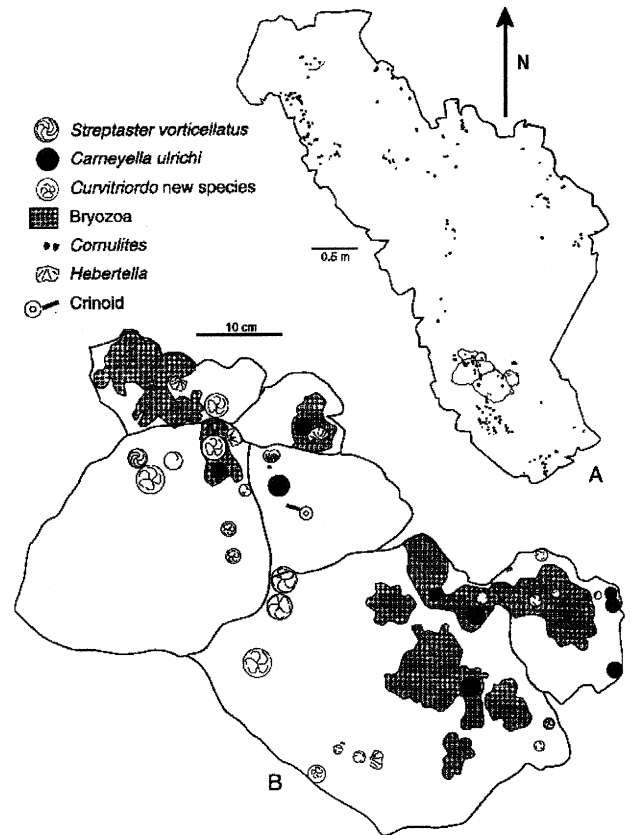
## INTRODUCTION

Hardgrounds provide unique opportunities to conduct *in situ* census-like assessments of non-transported fossils (Wilson and Palmer, 1992). A new hardground community from the Maysvillian (Upper Ordovician) offers a glimpse into hard substrate communities on the eastern flank of the Cincinnati Arch. In this paper, we will describe the taphonomic implications of faunal components and the utilization of surface area for colonization by an edrioasteroid dominated hardground community preserved at the time of burial.

Recently, a heavily encrusted hardground horizon, whose unique terminal community includes four species of edrioasteroids (Echinodermata) and several species of large encrusting bryozoans, was discovered in the rubbly limestones about seven meters above the base of the Bellevue Member of the Grant Lake Formation in a set of new roadcuts along State Rte. 3071 near Maysville, Mason County, Kentucky. Subsequent search showed that the same hardground occurred in several nearby outcrops within two kilometers of the original discovery site. It has not been traced further, although occurrence of similar rare species of edrioasteroids in a railroad cut near Maysville (Bassler and Shideler, in Bassler, 1936) suggests that the surface may be exposed there as well.

## MATERIALS AND METHODS

During the fall and winter of 1998-1999, some five square meters of the hardground surface were excavated and collected for laboratory preparation (Fig. 1). Recovered slabs were oriented, cleaned and reassembled so

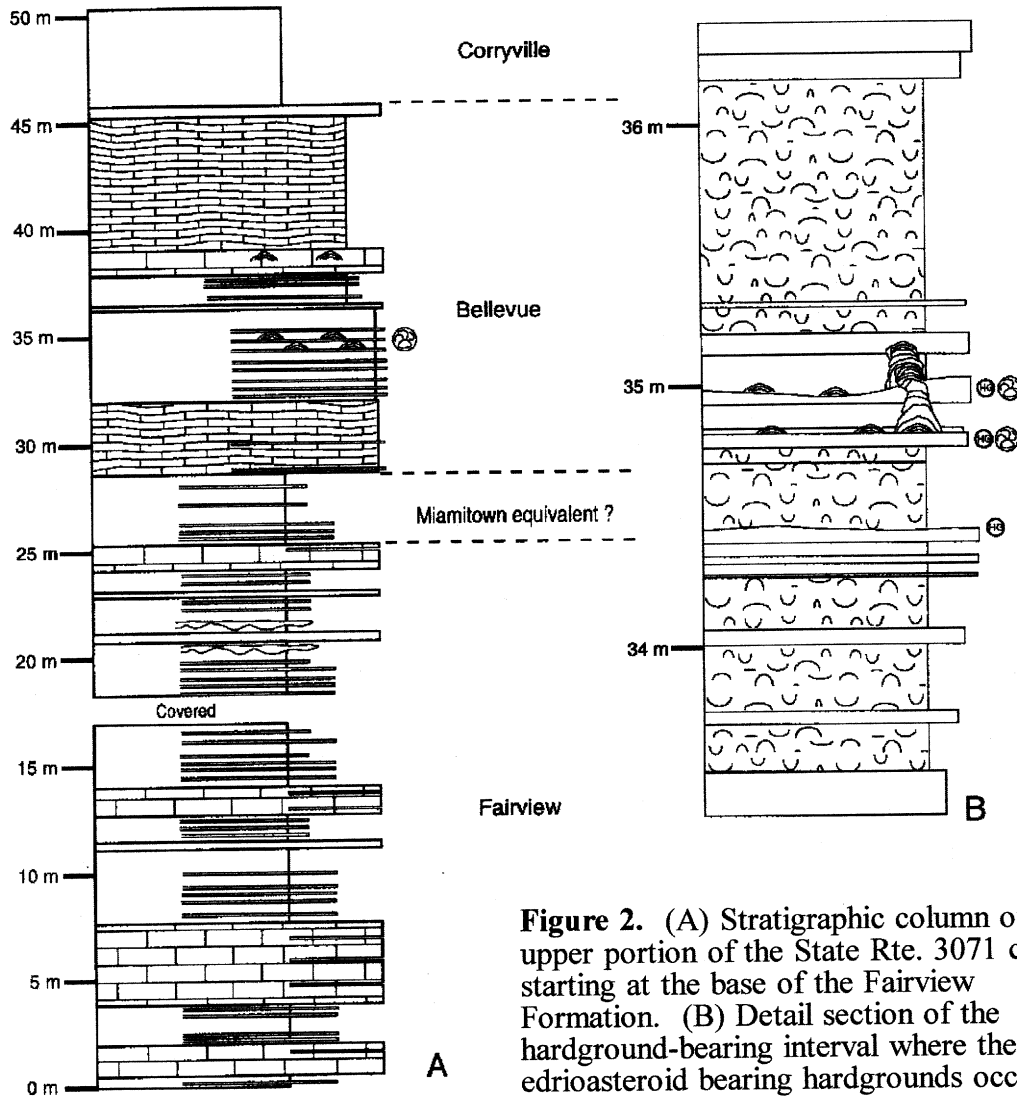


**Figure 1.** (A) Mapped distribution of edrioasteroids on the slab surface; individual pieces of slab are shown as polygons. Note that small pockets of edrioasteroids are vaguely aligned along N-S trends. (B) Detail of hardground surface illustrating the distributions of the members of the terminal community. Note that *Carneyella ulrichi* and *Curviriordo* nov. sp. are attached to both bryozoans and the hardground surface and that there is no preferred orientation of specimens.

that the surface spatial relationships of the hard substrate fauna could be studied. All edrioasteroid specimens were identified, located on a grid, and measured. The surface was also mapped to determine distribution patterns of the edrioasteroids and other fossils and this buried fauna or "terminal community" was compared with the "background community" represented by variably disarticulated and corroded material on and embedded in the hardground surface. These observations provide significant insights into the nature and distribution of an Upper Ordovician hard substrate community.

## GEOLOGIC SETTING

The hardground horizon occurs about seven meters above the base of the Bellevue Formation exposed on the second highest bench in the road cut (Fig. 2). It occurs on the top of a series of beds between 10 and 25 cm in thickness that range from clay-rich, rubbly skeletal packstones to grainstones interbedded with thinner, more compact beds of grainstones and packstones. Most have sharp bases and sharp, irregular tops. A number of bed tops exhibit features such as sharp, irregular relief, staining, borings and/or encrusting organisms, indicative of firmground or hardground development.



**Figure 2.** (A) Stratigraphic column of the upper portion of the State Rte. 3071 cut starting at the base of the Fairview Formation. (B) Detail section of the hardground-bearing interval where the two edrioasteroid bearing hardgrounds occurred.

Using the stratigraphic definitions of Schumacher (1992, 1998), these beds are assigned to the lower Bellevue Member of the Grant Lake Formation. They abruptly overlie a series of shales and thin to medium bedded limestones typically referred to the upper Fairview, but possibly correlative with the Miamitown Shale of Ohio. The Bellevue contact, in turn, occurs about 10 m above the base of an interval of distinctive ball-and-pillow deformation (possible seismites) in the upper Fairview Formation (Schumacher, 1992). The hardground interval falls within the middle of the Maysvillian Stage of the Cincinnati series; its age is thus estimated to be about 440 Ma.

During Maysvillian time, the region of the eastern flank of the Cincinnati Arch is thought to have been a gently north sloping ramp flanking the Lexington Platform, a relatively positive area, possibly associated with a forebulge produced by load induced flexure (see Ettensohn, 1992). To the south, the Bellevue grades into very shallow subtidal shoal deposits of the Calloway Creek Formation in the area of the Lexington Platform; to the northwest relatively deeper conditions are recorded by the appearance of shaly tongues within the Bellevue. The Bellevue grades laterally into thin, shaly, nodular limestones and shales in the subsurface about 40 km north of Cincinnati. This suggests that a remnant of the Sebree Trough, a narrow northeast-southwest trending deep water area developed during Edenian time, was still present at this time (Hay, 1998; Dattilo, 1998). During the Maysvillian, continued tectonism associated with the Taconic Orogeny affected eastern Laurentia. Taconic uplifts supplied muds and silts to the interior seaway. This region lay about 0-25° south of the paleoequator (Scotese, 1990). Abundant tempestites of various types (see Tobin and Pryor, 1981; Jennette and Pryor, 1993) indicate that the region was affected by episodic large tropical storms that reworked sediment and in some instances resuspended muds. Silts and muds were transported downslope and rapidly deposited as mud tempestites. Substantial times of non-deposition are recorded at the sharp diastemic contacts of many shell-rich beds, including the hardgrounds described herein. The Bellevue facies was probably deposited slightly below normal

wavebase (~5-10 m) but well within reach of storm waves. The preservation of thin muddy layers, such as that which buries this hardground, suggests normally low energy conditions, but interbedded graded pack- and grainstone beds, some with wave ripples, indicate occasional high energy stirring of sea floor sediments (Schumacher, 1992). Occurrence of cyclocrinoids (dasycladacean green algae; Beedle and Johnson, 1986; Beedle, 1988; Brett et al., 1993) in the Fairview and Bellevue (some found about 2.7 m above the hardground; S. Felton, pers. comm.) indicates deposition of these sediments in the upper part of the photic zone, probably in about 10-20 meters of water.

### HARDGROUND CHARACTERISTICS AND FAUNA

The Maysville hardground is developed on the upper surface of a brachiopod-rich packstone bed that ranges from at least two to ten centimeters in thickness and may pinch out completely in one area. The limestone contains abundant, large valves of *Platystrophia ponderosa*, in varied stages of preservation from complete and unaltered to heavily corroded and bored remnants. Most of the hardground surface itself shows relatively minor relief although a small scarp about 2 cm high is present along the edge of the excavated slab. The entire surface is irregular on a centimeter high scale with lots of irregular anastomosing raised areas suggestive of interference ripples. Edrioasteroids and other encrusting fossils occur on a small fraction (less than 1 percent) of the total surface area and yet are clustered primarily into vaguely elongate north-south oriented patches along the surface (Fig. 1). Bryozoans on the surface are generally encrusting forms which in some areas form lips where they apparently overgrew mud on the surface of the hardground. Some surface areas are riddled with *Trypanites* type borings. These borings are generally associated with areas colonized by bryozoans and typically penetrate the bryozoan and extend through the hardground bed.

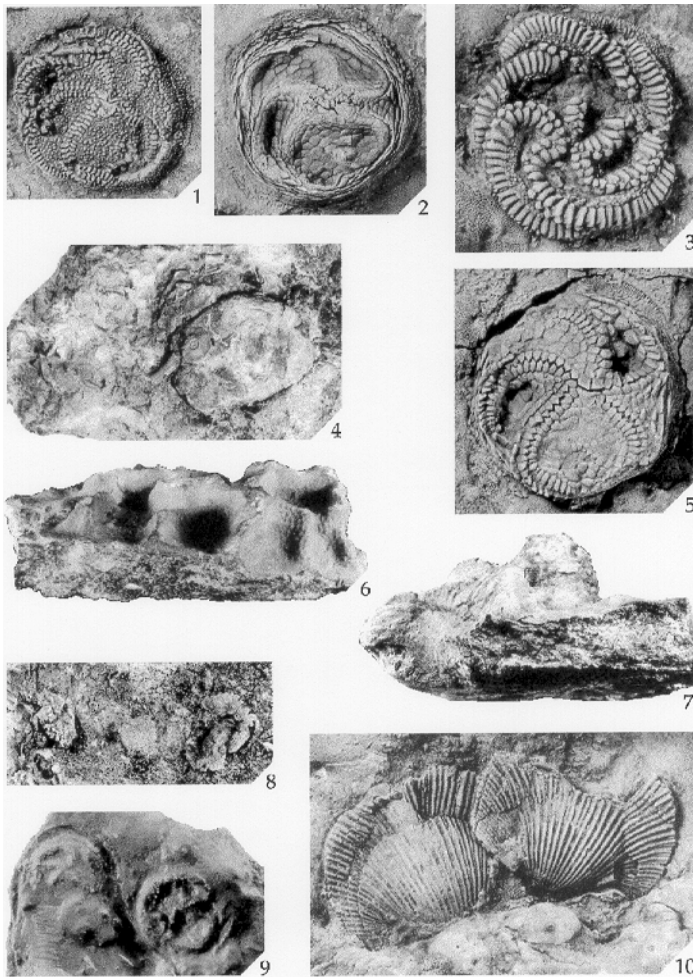
The Maysville hardground was overlain in places by yellowish-weathering calcisiltite up to 5 mm thick. This material includes buried edrioasteroids and other members of the

terminal community (Fig. 3). Edgewise brachiopod valves also occur in this matrix, indicating stirring of coarser sediments in the final burial event. This calcisiltite bed is overlain by 2-5 cm of clay shale. Some portions of this shale have proven to be more or less barren, while other shale samples yielded abundant brachiopod valves and a phosphatic microfauna (mainly steinkerns of tiny gastropods and conodonts) and an exceptionally rich assemblage of scolecodonts including 52 form taxa (R. Fuchs, pers. comm.). This mudstone layer shows indistinct burrows, which in a few instances penetrated down to and disrupted plates of buried edrioasteroids and in other cases encircled them (Fig. 3.9).

The hardground fauna is dominated by about three species of trepostome bryozoans. The bryozoan colonies are large (1 to 40 cm across) irregular mounds, some of which have flat sided carinae (keels) that may project several centimeters above the hardground sur-

face (Fig. 3.6). Other faunal elements include: brachiopods (*Hebertella occidentalis*, *Platystrophia ponderosa*, *Petrocrania scabiosa*), cyclostome bryozoans (*Cuffeyella* sp.), annelid worms (*Cornulites* sp.), crinoids (*Cincinnatiacrinus* sp.), and edrioasteroids (*Carneyella ulrichi*, *Carneyella pilea*, *Curviriordo* new species? and *Streptaster vorticellatus*).

The four species of edrioasteroids, although locally abundant (up to 50 individuals per square meter), comprise a unique community dominated by rare forms, both in terms of species composition and specimen size (Table 1). *Carneyella ulrichi* (Fig. 3.1) was previously known from a single specimen. The species of *Curviriordo* (Fig. 3.2) is new and several specimens of *Streptaster vorticellatus* (Fig. 3.3) are among the largest known for their species reaching 25 mm in thecal diameter. Large and small edrioasteroids are attached to bryozoans and



**Figure 3.** Edrioasteroids and other fauna of the Maysville Hardground. (1) Mature specimen of *Carneyella ulrichi*. Note surface covered with large pustules and wide ambulacra, X2. (2) Mature specimen of *Curviriordo* n. sp. Note narrow ambulacra, X1.25. (3) Mature specimen of *Streptaster vorticellatus*. Note extremely wide and high ambulacra, X2.25. (4) Slab surface showing corroded skeletal debris and a *Cincinnatiacrinus* holdfast, X0.5. (5) Mature specimen of *Carneyella pilea*. Note wide ambulacra and lack of large pustules, X3. (6) Oblique view of carinate bryozoan colony, X0.5. (7) Oblique view of bryozoan colony overgrowing broken edge of hardground, X1. (8) View of a cryptic assemblage in a cavity. *Carneyella ulrichi* left, small bryozoan center, *Petrocrania scabiosa* right, X2. (9) Two specimens of *Carneyella ulrichi* encircled by burrow, X0.75. (10) Two specimens of *Hebertella* articulated and in life position attached to a bryozoan. Both specimens have epifauna encrusted on them, X2.

less commonly directly to the hardground. Several juvenile edrioasteroids, however, are attached to brachiopods in life position. A cryptic fauna occurs beneath an overhang formed by the binding of skeletal debris by a large encrusting bryozoan, with an edrioasteroid, bryozoan, and *Petrocrania* all growing into the cavity (Figure 3.8).

**Table 1.** Numbers of edrioasteroid species present on main hardground.

<i>Streptaster vorticellatus</i>	9
<i>Carneyella ulrichi</i>	107
<i>Carneyella pilea</i>	2
<i>Curvitoriordo</i> n. sp.	92

## DISCUSSION

**Taphonomic aspects:** Hardgrounds are diastemic surfaces whose very existence indicates prolonged breaks in sedimentation. The taphonomy of the fossils immediately overlying the Maysville hardground support this. The abundance of phosphatized fossil steinkerns, conodonts, and chitinous scolecodonts in some samples of shale directly adherent to the hardground suggest that the surface was partially overlain by a thin, condensed lag deposit of worm jaws and other geochemically resistant debris which gradually accumulated on the hardground surfaces. Barren shale samples, also recovered from the site, may represent rapidly deposited obrutionary muds.

Hardground cementation is thought to occur somewhat below a sediment-water interface in the zone of sulfate reduction where alkalinity buildup promotes precipitation of carbonate cements (Wilson and Palmer, 1992). The exposure of a hardground pavement, therefore, requires erosional removal of at least a few centimeters of sediment. The rarity of encrusted hardgrounds in the Cincinnati as a whole may reflect rates of mud accumulation that were typically too high for prolonged exposure. Even in this example, there is evidence that for much of the time, the surface was not fully exposed, despite low net rates of accumulation. Most surface areas are nearly planar, though uneven, with few pockets or corrosion pits. The surface does not show dark staining and *Trypanites* borings are rare in most areas,

suggesting that the surface may have been covered by a thin film of sediment much of the time. Furthermore, many edrioasteroids occur on the slightly elevated sides of the bryozoan colonies, not directly on the paleo-sea floor, and the occurrence of juvenile edrioasteroids (late recruits) on brachiopods and bryozoans may indicate that the hardground itself was at least partially mud covered prior to its final burial. That these newly settling edrioasteroids attached to small, suboptimal hard substrates while most of the hardground itself is clean of epibionts strongly suggests that a mud blanket covered much of the surface.

Emplacement of the final mud layer was obviously rapid. Fragile imbricated skeletons of edrioasteroids clearly could only be preserved if they were buried very rapidly after death or were buried alive by sediment (Brett et al., 1997). We surmise that the final depositional pulse probably came in the form of a suspended flow of mud or mud tempestite. SEM studies of similar muds enclosing fragile fossils have shown that in most cases the muds were flocculated and therefore settled as rapidly as silt or even fine sand-sized particles (of clay density) (O'Brien et al., 1994, 1998). It is clear that the burial mud blanket was not particularly thick, probably not more than about ten centimeters uncompacted. Post burial burrowing organisms were able to penetrate downward to the hardground and slightly disrupt some of the entombed carcasses or pass around the perimeter of others.

**Biological aspects:** As noted, the bryozoans form large mound-like and often carinate (keeled) colonies, that may extend upward for over eight cm above the hardground surface. In several instances a bryozoan colony appears to have survived the burial event and extended upward from a lower hardground 11 centimeters below the one described here in detail, and continued through the deposition of the sediment that comprises the main hardground and upwards into the overlying thin shale and fossil packstone layer. Morphology of these bryozoan colonies shows that they cantilevered outward onto the packstone or mud layers indicating that they survived episodes of partial burial and regrew. Such evidence not only

**Table 2.** Comparison between *Platystrophia* and *Hebertella*. Note that *Platystrophia* valves show nearly a 5:1 ratio between pedicle and brachial valves whereas *Hebertella* exhibits roughly a 1:1 ratio. The anomalously high number of uncorroded brachial valves for *Hebertella* may reflect a misidentification of articulated specimens in life position.

	<i>Platystrophia</i>			<i>Hebertella</i>		
	<i>pedicle</i>	<i>brachial</i>	<i>life pos.</i>	<i>pedicle</i>	<i>brachial</i>	<i>life pos.</i>
broken and corroded	18	3	--	5	1	--
broken not corroded	4	0	--	14	10	--
corroded	60	4	--	18	2	--
slightly corroded	19	5	--	22	12	--
not corroded	6	10	--	17	53	--
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Total	107	22	19	76	78	26

attests to the persistence of colonies through adverse conditions but also help to bracket the approximate duration of beds immediately overlying the hardground (only a few centuries at most). It also suggests that the keeled growth form of the colony may have been adaptive in preventing complete smothering by mud layers. As it seems unlikely that organisms could adapt to infrequent and unpredictable obrutionary events, we suggest that this was an adaptation to life in environments that were normally prone to some mud deposition.

Edrioasteroids and other encrusters are not evenly distributed on the slab surface, rather they are highly clumped and aligned following a vaguely north-south trend (Fig. 1A). Distributions of other faunal elements smothered by the same obrutionary event are highly correlated with edrioasteroid placements. We surmise that these may follow very shallow, gutter-like scours which stripped silt and mud off the hardground and provided elongate areas of exposed hard pavement for colonization. The N-S trend of colonized areas is consistent with the direction of gutter casts measured in the Upper Kope Formation and may reflect the direction of paleoslope (Jennette and Pryor, 1993). Other nonencrusted portions of the surface may have been covered by sediments which precluded colonization. The morphology of the bryozoans which over-grew the mud confirms this supposition (Fig. 3.7).

Preservational differences of fossils allow "live vs. dead" counts of skeletonized organ-

isms on the surface (Table 2), and may also point to prolonged sediment starvation and reworking of skeletal material. For example, articulated, spar-filled, and *in situ* brachiopods (Fig. 3.10) are assumed to come from the terminal community, i.e., the population that encrusted the surface immediately before burial; whereas variably disarticulated, fragmented, and corroded specimens may be counted among the background, time averaged death assemblage. Comparison of counts of these two constituents of the fossil assemblage, suggest that the time-averaged death assemblage was much richer in *Platystrophia* than the terminal community found articulated and/or attached directly to the hardground at the time of burial. This terminal community appears to have been dominated by *Hebertella* with slightly lesser numbers of *Platystrophia*. The death assemblage, however, is enriched with the more robust pedicle valves of *Platystrophia* to nearly a 5:1 ratio. Since in life the ratio of pedicle to brachial valves is 1:1, this enrichment suggests a strong bias due to prolonged mechanical reworking. This sharply differs from the 1:1 ratio of disarticulated *Hebertella* valves suggesting that the thinner *Hebertella* valves are more subject to fragmentation and therefore underrepresented in the death assemblage. This too points to a period of little or no sediment aggradation and low burial rates, prior to the final obrutionary event. It also suggests that conditions were not entirely "low energy" as most of the more fragile skeletal remains have been fragmented and corroded to form

debris.

A number of edrioasteroid beds have been reported previously from the Cincinnati of the Cincinnati Arch region (Kesling and Mintz, 1960; Meyer, 1990; Datillo, 1998). However, the Maysville occurrence is distinct from the others in several aspects. Most previously reported edrioasteroid occurrences have been derived mainly from the Miamitown and Corryville shaly intervals, which lie respectively slightly below and above the present horizon. These assemblages were dominated by the edrioasteroids *Isorophus*, and *Carneyella* while *Streptaster* occurs only very rarely. *Curviriordo* is virtually absent from these faunas. Previously described Cincinnati edrioasteroid beds were mainly associated with pavements of *Rafinesquina* brachiopods rather than true hardgrounds (Meyer, 1990). Such pavements may have been stabilized by early cementation (Rassman, 1981) but in no cases were edrioasteroids found directly encrusting limestone surfaces.

For the *Carneyella-Curviriordo* assemblage, all species were spatially intermingled, with no species demonstrating a preference for type of substrate attachment or height above substrate (Fig. 1B). This suggests that there was little interspecific competition among them. Indeed, all three genera belong to different edrioasteroid families and all show substantially different abulacral morphology suggesting distinct food gathering techniques. The community, however, appears to have been spatially limited, this despite the fact that more than 99% of the hardground surface is clean of encrusters. The same appears to be true for juvenile recruitment. Although juveniles were not found for all species, those which were present showed no selective substrate preference, occurring on brachiopods, bryozoans and in one case on the hardground surface.

The *Carneyella-Curviriordo* assemblage may have been specifically adapted to encrusting hard, relatively smooth surfaces as opposed to brachiopod shells. Although a few specimens were found attached to brachiopods, the majority were either on bryozoans or directly on the hardground. The prevalence of these species on the Maysville hardground records both a taphonomic and an ecological

epibole (*sensu* Brett et al., 1997). Obviously, specific occurrences of any edrioasteroid assemblage reflects rapid smothering by muds. However, this cannot explain the difference in taxonomic composition nor substrate behavior of the Maysville vs. other Cincinnati edrioasteroid occurrences. We suggest that this assemblage represented a suite of opportunistic species adapted to shallower water hardgrounds. The brachiopod pavements occurring in the Miamitown and Corryville developed in somewhat deeper water below common storm wavebase. Here pavements of larger shells evidently provided sufficient stability for survival of isorophids. In shallower, somewhat agitated settings represented by the Bellevue, attachment to dead skeletal material may not have afforded adequate stability. Thus, edrioasteroids being relatively sensitive to reorientation, would have required larger surfaces, such as bryozoans, hardgrounds, or firmly attached live brachiopods for stable settlement. *Platystrophia* and *Hebertella* were probably rather nonselective, heavier, pedically attached hard substrate forms that could have attached to a variety of substrates from shells to hardgrounds or even have been free resting at times (Richards, 1972). Their thickened umbones may have given these organisms a low center of gravity with a stability akin to weebles (A. Seilacher, pers. comm.).

In any case, these edrioasteroids may have been adapted to life on hardgrounds that developed more commonly in other, shoal-marginal environments; such environments probably had much poorer preservation potential. Thus, the very conditions (e.g., higher energy, low sedimentation rate) which favored this suite of edrioasteroids, also may have mitigated against their preservation and only rare (but sometimes dense) outlier populations such as this one are preserved.

In this instance, erosional exposure of a hardground/bryozoan ground substrate provided a narrow window of opportunity for colonization maturation and perhaps minor recruitment of a new generation. The brief colonization episode was abruptly terminated by a pulse of mud sedimentation that smothered the hardground and its faunas over an area of at least a few square kilometers.

## ACKNOWLEDGMENTS

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**SEDIMENTOLOGY AND PALEOECOLOGY  
OF THE CRAB ORCHARD FORMATION (SILURIAN,  
LLANDOVERY)  
AT CHARTERS, KENTUCKY**

Charles E. Mason

Department of Physical Sciences  
Morehead State University  
Morehead, Kentucky 40351

## INTRODUCTION

The Charters Section is located in the upper shale member of the Crab Orchard Formation of Early Silurian (late Llandovery age; Fig. 1). This is a relatively fresh outcrop that permits detailed examination of the (typically poorly exposed) upper Crab Orchard shale. This report discusses aspects of the stratigraphy, paleontology, and even minor structural features of the Crab Orchard shale, based on detailed study and sampling of the Charters section and other outcrops in northern Kentucky.

## STRATIGRAPHY AND SEDIMENTOLOGY

The Crab Orchard Formation in this area varies from 47.2 to 59.4 m in thickness. This interval on some U.S.G.S. Geologic maps is called the Estill Shale Member (McDowell and Weir, 1977). The Crab Orchard Formation is underlain by the Brassfield Formation (early Llandovery) and normally overlain by the Bisher Formation (Wenlock), except where the latter has been removed by Devonian erosion (Peck, 1967). At this stop only the upper 17.5 m are exposed. It consists predominantly of mudstone with minor thin (up to 5 cm) discontinuous beds of dolostone. The shale at the top of the section is greenish gray and the shale at the bottom is maroon, whereas, the middle part of the section shows mixed maroon/greenish-gray layers. A study by Higgins (1992) examined the maroon and greenish-gray shales (Samples B1\* and B2\*;

Fig. 1) for differences in macrofossil content and their mode of preservation. In this study, no significant differences were found in either macrofossil diversity or mode of preservation. Also, there was no apparent difference noted in these shales while collecting and processing them other than color. It has been suggested (F. Ettensohn, pers. comm.) that the maroon sediment was reworked older red bed deposits and thus inherited their color. The shales are poorly fissile and heavily bioturbated to completely homogenized. Thus, physical sedimentary structures within the shales and distinct trace fossils are rare to absent (Ichnofabric index 6 of Bottjer and Droser, 1994). The dolostones are silty dolomicrites that are finely crystalline and slightly calcareous with a medium-gray fresh color that weathers to a dark orange or brown. These individual beds of dolostone, found in the section, have sharp erosional bases and tops which grade upward into overlying shales. Their soles have preserved tool marks, while the tops have a hummocky appearance. Internal sedimentary structures have mostly been destroyed from dolomitization; however, a few beds do show fine parallel laminae as well as even rarer wavy, or hummocky cross lamination.

An equivalent interval of the Crab Orchard Formation is found exposed in an area of classic badlands topography, 33 aerial miles to the southwest in Bath County, Kentucky. This section, which was examined by Mason and others (1991), has several notable differences in both lithology and fossil content. The major lithologic differences are (1)



The results were compared to those of a similar study of this stratigraphic interval at the Knob Lick Section in Bath County, Kentucky (Mason et al., 1991). The washed residues from the six shale samples at this stop contained a good open-marine macrofossil fauna which included: brachiopods, bryozoans, gastropods, pelecypods, *Sphenothallus* (phosphatic worm tubes), as well as fragments of both crinoids and trilobites. Also, six graptolite specimens were collected from the interval of shale sample B2\* (see Fig. 1). They were complete and preserved as carbonaceous films on what appeared to be localized bedding planes. The mode of preservation of the macrofauna here is either replacement by pyrite or recrystallization by calcite (initially). Macrofossils (mostly juveniles) were found in all six samples.

Although there are some notable differences, the results of this study are similar to those reported by Mason et al. (1991) for the Knob Lick Section. At Knob Lick, all macrofossils and some ostracods are replaced by pyrite, whereas at this stop some macrofossils are preserved by recrystallization. It is believed that the recrystallized fossils found here were preserved under aerobic conditions or under dysaerobic conditions just below the aerobic/dysaerobic boundary, whereas the pyrite-replaced forms were deposited under normal dysaerobic conditions. Also, mixing by storm activity (presence of tempestites) may have altered or disrupted the normal condition of oxygen content in the water column as well as below the sediment water interface. The dominant macrofossils at both this stop and Knob Lick are crinoids, brachiopods, and bryozoans. At Knob Lick, extensive surface collecting of the badlands exposure has resulted in a sizable collection of macrofossils. The diversity found in this collection includes everything found to date at the Charters section as well as nautiloids, blastoids, and complete articulated crinoids and trilobites. It should also be pointed out here that macrofossils found in washed sample residues at Knob Lick have the same dominance as that of surface collections.

The macrofauna found at this stop in the upper Crab Orchard Formation as well as that from the Knob Lick is similar to reported late Paleozoic dysaerobic faunas (Mason and

Kammer, 1984; Kammer and others, 1986) in being predominantly composed of juveniles, having low diversity for an open-marine fauna and the mode of preservation, replacement by pyrite. However, unlike typical late Paleozoic dysaerobic faunas, the faunas in this section and that at Knob Lick are dominated by brachiopods, bryozoans, and crinoids (sessile forms) rather than molluscs (vagile forms). Their trophic structure is also different in that filter feeders predominate rather than deposit-feeding gastropods or scavenging cephalopods found in late Paleozoic dysoxic settings. The report by Mason et al. (1991) for the Knob Lick Section and Mason et al. (1992) for this section constituted the first reports of a Silurian-age dysaerobic fauna. In summary, the Crab Orchard Fauna found at this section and that found at Knob Lick are similar in all respects to Devonian and post-Devonian dysaerobic faunas except for dominance and trophic structure.

The washed residues in Higgins' (1992) study were also examined for microfossils, as were samples from Knob Lick (Mason et al., 1991). The most noticeable difference was that foraminifera were found to be the most diverse and abundant type of microfossil form found at Knob Lick but were not present at all in the washed residues at this section. Microfossils overall were found to be abundant and fairly diverse at both localities. Other than forams, the microfossils found were the same for both localities and included ostracods (most abundant at this locality), conodonts, scolecodonts, chitinozoans and graptolite fragments. It should be noted that, although macrofossils are replaced by pyrite in dysoxic settings, microfossils with the exception of some ostracodes are not. Also, to my knowledge at this point, no study of dysaerobic faunas has included the associated microfossil fauna in their examination. Thus, this section, as well as that at Knob Lick, merits further study based on the uniqueness of their contained dysaerobic macrofossil fauna and the need to examine the associated microfossil fauna and possibly flora as well.

The upper Crab Orchard Formation at this locality is thought to represent offshore deposition on the outer part of the shelf generally below storm wave base. This is evident from

the overall dominance of mudstone and extremely high ichnofabric index of bioturbation. The minor interspersed dolostone layers are believed to be distal tempestites (storm deposits). They are thought to be derived from nearshore carbonate sediments and terrigenous muds which were re-suspended during storms and later redeposited offshore as the storms waned. This same interval, as observed in Bath County, is thought to have been deposited similarly but in deeper waters farther offshore where the dysaerobic oxygen level was essentially continuous. Oxygen levels of the Crab Orchard deposits, at this locality, appear to have fluctuated between dysoxic and fully oxic levels: this is evident from the presence of maroon shale beds and the presence of recrystallized macrofossil remains rather than pyritic replacement. It is also believed that the upper part, if not all, of the water column was aerobic at both localities, due to the presence of a normal-marine pelagic microfauna (Mason et al., 1992).

#### **OTHER GEOLOGIC ASPECTS OF THE CRAB ORCHARD FORMATION NEAR CHARTERS**

At this stop, another point of interest is the presence of a small, normal growth-fault. This subtle fault has been overlooked by previous workers for many years. It offsets beds throughout the Crab Orchard interval but terminates in the lower part of the Bisher Section. It has a vertical displacement of 0.7 m. Evidence supporting the presence of this fault includes (1) slickensides along the fault plane, (2) reversed dip of beds on the downthrown block (east side), (3) offset of beds across the fault plane, and (4) the development of a large gully along the fault plane. The latter point is the most obvious aspect of the fault, as there are no other gullies approaching this size along the roadcut at this stop (Mason and others, 1992). Finally, it should be pointed out that the upper Crab Orchard Formation is a problematic unit to build on due primarily to its expansive clay content and impervious nature. Slumping of this unit is commonplace throughout the region, as is the development of badland topography. It is, however, an excellent unit in which to build farm ponds and small reservoirs.

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## CONDONT BIOSTRATIGRAPHY OF "OLENTANGY" SHALE IN NORTHEASTERN KENTUCKY

Stephanie Fuentes<sup>1</sup>, D. Jeffrey Over<sup>1</sup>  
and Carlton E. Brett<sup>2</sup>

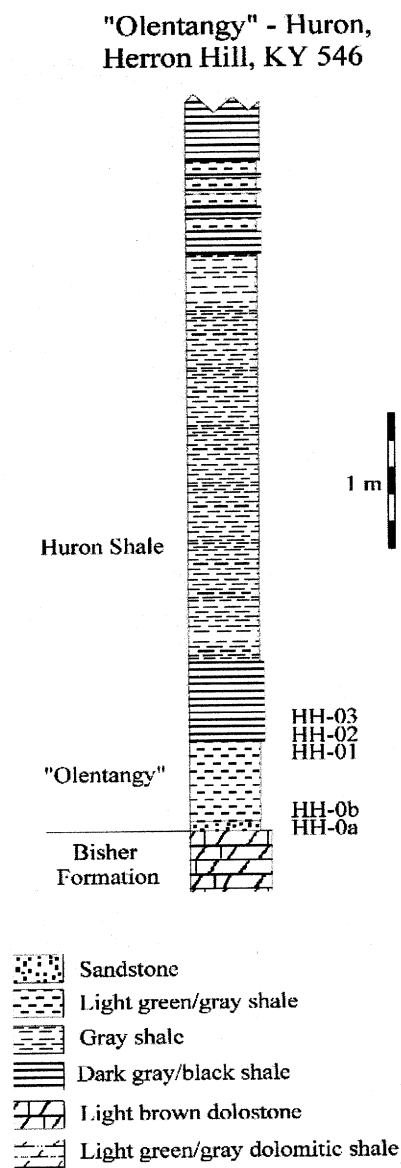
<sup>1</sup>Department of Geological Sciences, SUNY-Geneseo, Geneseo, New York 14554

<sup>2</sup>Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221-0013

The "Olentangy" Shale of northeastern Kentucky, exposed on Rte. 546 at Herron Hill, Kentucky, and along I-64 near Morehead, Kentucky, is distinct from the Olentangy Shale of central Ohio. The type Olentangy Shale, exposed along the Olentangy River in Delaware, Ohio, is a calcareous greenish gray shale immediately overlain by the Huron Shale. Two distinct units are recognized, the Middle Devonian Lower Olentangy Shale and the Upper Devonian Upper Olentangy Shale (Hoover, 1960). Equivalents to the Lower Olentangy Shale include the Plum Brook, and in part, the Hamilton Group shales of Ohio, Ontario, and New York (Stauffer, 1938; Tillman, 1970). The Upper Olentangy Shale is equivalent to the Hanover Shale in New York (Over and Rhodes, in press).

The greater resistance to weathering of the Huron Shale results in a recognizable ledge over the Olentangy Shale in outcrop; the significantly higher organic content of the Huron produces a diagnostic positive shift in gamma ray logs in subsurface records. In northeastern Kentucky greenish gray shale underlying the Huron Shale have been correlated with the Upper Olentangy of Ohio based on general lithology, gamma ray logs, and stratigraphic position (Wallace et al., 1977; Kepferle et al., 1978). The "Olentangy" in Kentucky is clearly younger (Ettensohn et al., 1989), bound by unconformities, and distinct based on lithology and fauna.

At Herron Hill, the "Olentangy" Shale lies on an unconformity over the Bisher Dolomite (Silurian). The "Olentangy" is 67 cm thick, soft greenish gray, pyritic, non-calcareous shale overlain by the Huron Shale Member of the Ohio Shale (Fig. 1). The basal



**Figure 1.** Measured section and sample interval of "Olentangy" Shale and lower Huron Shale exposed above the Bisher Dolomite on KY Rte. 546 at Herron Hill.

“Olentangy” consists of a fossiliferous, phosphatic, sandy pyrite bed and siltstone abruptly overlain by grayish green shale. Conodonts recovered from this basal lag (Table 1) include *Palmatolepis minuta minuta*, and *Ancyrognathus bifurcata*, as well as *Pa. glabra pectinata* and *Pa. perlobata schinewolffi*, long-ranging taxa that are no older than the Upper *crepida* Zone. The light gray shales have not yielded any conodonts. The dense, dark gray (black) pyritic Huron Shale lies on a sharp contact over the “Olentangy.” Most of the lower 3 m of the Huron is poorly exposed, consisting of medium gray to black platy shales. The basal 15 cm contains silt laminae, pyrite-rich laminae, and numerous conodonts that include *Palmatolepis lobicornis*, *Pa. glabra prima*, *Pa. perlobata schindewolffi*, *Pa. minuta minuta*, *Pa. rhomboidea*, and *Polygnathus* cf. *Po. nodocostata*, indicative of the

*rhomboidea* Zone.

A more detailed study was conducted along I-64, 50 km (30 miles) to the south, near Morehead, Kentucky (see Kepferle and Roen, 1981; Ettensohn, 1992). Here the “Olentangy” Shale is 80 cm thick, consisting of dark greenish gray and gray shale as well as thin darker colored bands (Fig. 2). The contact of the “Olentangy” and the underlying Crab Orchard Shale (Silurian), which underlies the Bisher Dolostone at Herron Hill, is marked by a thin lenticular sandy pyritic bed. This bed yielded *Palmatolepis glabra pectinata*, *Pa. glabra prima*, *Pa. lobicornis*, *Pa. minuta minuta*, *Pa. perlobata ssp.*, *Pa. quadrantinodosalobata*, *Pa. regularis*, *Pa. rhomboidea*, *Pa. sp. A. of Schülke*, *Polygnathus nodocostatus*, and *Polylophodonta confluens* (Table 1). The overlying 10 cm interval contains *Palmatolepis glabra prima*, *Pa. lobicornis*, *Pa. minuta minuta*, *Pa.*

**Table 1.** Occurrence of conodont taxa from the “Olentangy” and Huron shales at Herron Hill and I-64 exposures. *An.* = *Ancyrognathus*; *Pa.* = *Palmatolepis*; *Po.* = *Polygnathus*.

Taxa	A	B	C	D	E	F	Q	R	S	T	U
<i>An. bifurcata</i>				X			X				
<i>Pa. glabra pectinata</i>	X			X			X				
<i>Pa. glabra prima</i>	X	X		X						X	X
<i>Pa. lobicornis</i>	X	X		X	X					X	
<i>Pa. minuta minuta</i>	X	X		X			X			X	
<i>Pa. perlobata ssp.</i>	X	X					X			X	X
<i>Pa. perlobata schinewolffi</i>						X					X
<i>Pa. quadrantinodosalobata</i>	X	X									
<i>Pa. regularis</i>	X										
<i>Pa. rhomboidea</i>	X			X	X					X	X
<i>Pa. subperlobata</i>				X	X						
<i>Pa. tenuipunctata</i>				X	X						
<i>Pa. sp. A of Schülke</i>	X										
<i>Po. glabra glabra</i>		X									
<i>Po. nodocostatus</i>	X	X								?	
<i>Polylophodonta confluens</i>	X										
<b>Zone assignment</b>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>	<i>r</i>

**Locality, sample interval, and distance below base of Huron Member of Ohio Shale**

A - I-64, RW-1#1; M64l 16-VI-99-01, 74-75 cm (base of “Olentangy”)

B - I-64, RW-1 #1-2, 1.7; M64l 16-VI-99-02; 60-74 cm

C - I-64, M64l 16-VI-99-03; M64l 16-VI-99-04; 20-60 cm

D - I-64, M64l 16-VI-99-05; M64l 16-VI-99-06; 0-20 cm

E - I-64, M64l 16-VI-99-07 (base of Huron)

F - I-64, M64 16-VI-99-08 (1.5 m above base of Huron)

Q - KY546, HH-0a (basal sandstone); 59-67 cm

R - KY546, HH-0b (base of greenish gray shale); 55-59 cm

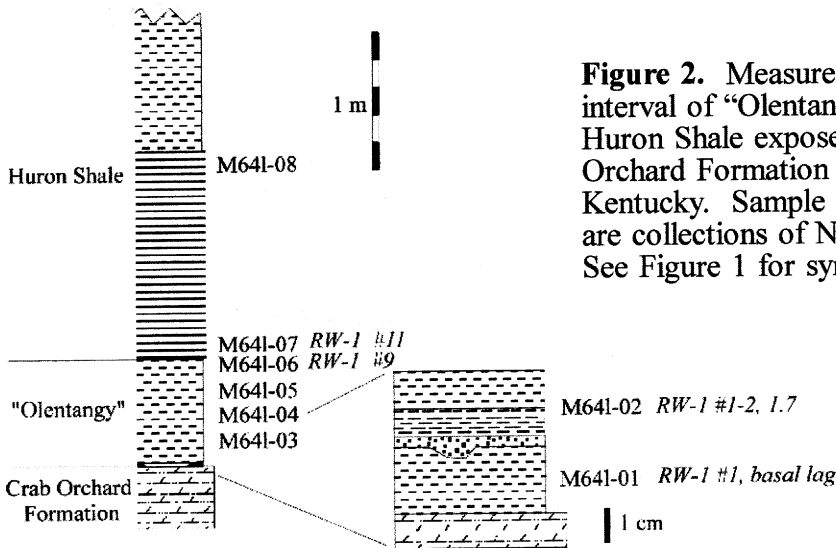
S - KY546, HH-01 (top of “Olentangy”); 0-15 cm

T - KY546, HH-02 (base of Huron)

U - KY546, HH-03; 10-15 cm above base of Huron

*r* - *rhomboidea* Zone

"Olentangy" - Huron, I-64 (Morehead, KY)



**Figure 2.** Measured section and sample interval of "Olentangy" Shale and lower Huron Shale exposed above the Crab Orchard Formation on I-64 near Morehead, Kentucky. Sample designations in italics are collections of Norby and Shaw (1988). See Figure 1 for symbols.

*perlobata* ssp., *Pa. quadrantinodosalobata*, *Polygnathus glabra glabra*, and *Po. nodocostatus*. The greenish gray shale 10 to 60 cm above the base did not yield conodonts; the uppermost 20 cm yielded *Ancyrognathus bifurcata*, *Palmatolepis glabra pectinata*, *Pa. glabra prima*, *Pa. lobicornis*, *Pa. minuta minuta*, *Pa. rhomboidea*, *Pa. subperlobata*, *Pa. tenuipunctata*, and *Branmehla* sp. The base of the Huron Shale contains *Palmatolepis lobicornis*, *Pa. rhomboidea*, *Pa. subperlobata*, and *Pa. tenuipunctata*.

The "Olentangy" Shale in northeastern

Kentucky is in the *rhomboidea* Zone or younger; although no taxa diagnostic of younger zones were recovered. The associated fauna consists of taxa common in the Upper *crepida* Zone or younger, and additional reworked material. The absence of the Bisher Dolostone at Morehead, Kentucky, indicates greater truncation and erosion on the sub-"Olentangy" unconformity south of Herron Hill. The "Olentangy" correlates with the Shulma Siltstone and Northeast Shale of the upper Canadaway Group in New York and the Chagrin Shale of Ohio (Fig. 3).

St.	conodont zone	NE Kentucky	C Ohio	NE Ohio	New York
Famennian	<i>marginifera</i>	Huron	Huron	Chagrin	Northeast
	<i>rhomboidea</i>	"Olentangy"			Shulma
	<i>crepida</i>				Westfield
					Laona
Frasnian	<i>triangularis</i>		U. Olentangy	Huron	Gowanda
					South Wales
					Dunkirk
Fr.	MN 13				Hanover

**Figure 3.** Lower portion of the Famennian conodont zonation of Ziegler (1962) most recently updated by Ziegler and Sandberg (1990), the upper part of the Frasnian MN Zonation of Klapper (1989), and relative position of the "Olentangy" Shale of northeastern Kentucky, Upper Olentangy Shale, Chagrin Shale, and equivalent strata in western New York (Rickard, 1975; Woodrow et al., 1989; Over, 1997). Organic-rich shales are shaded.

*Palmatolepis* elements assigned to *Palmatolepis minuta minuta* in the “Olentangy” Shale show a wide range of variation. The more gracile forms (Fig. 4.6, 4.7) are typical of morphotypes that first appear in the Upper *crepida* Zone. Specimens of *Palmatolepis lobicornis* are distinct from the holotype described by Schülke (1995) in that the outer platform extends to the anterior tip of the blade. This is a form illustrated as *Pa. superlobata* sp. A by Helms (1963) and synonymized with *Pa. lobicornis* by Schülke (1995). *Palmatolepis lobicornis* ranges from the Lower *crepida* Zone through the *rhomboidea* Zone.

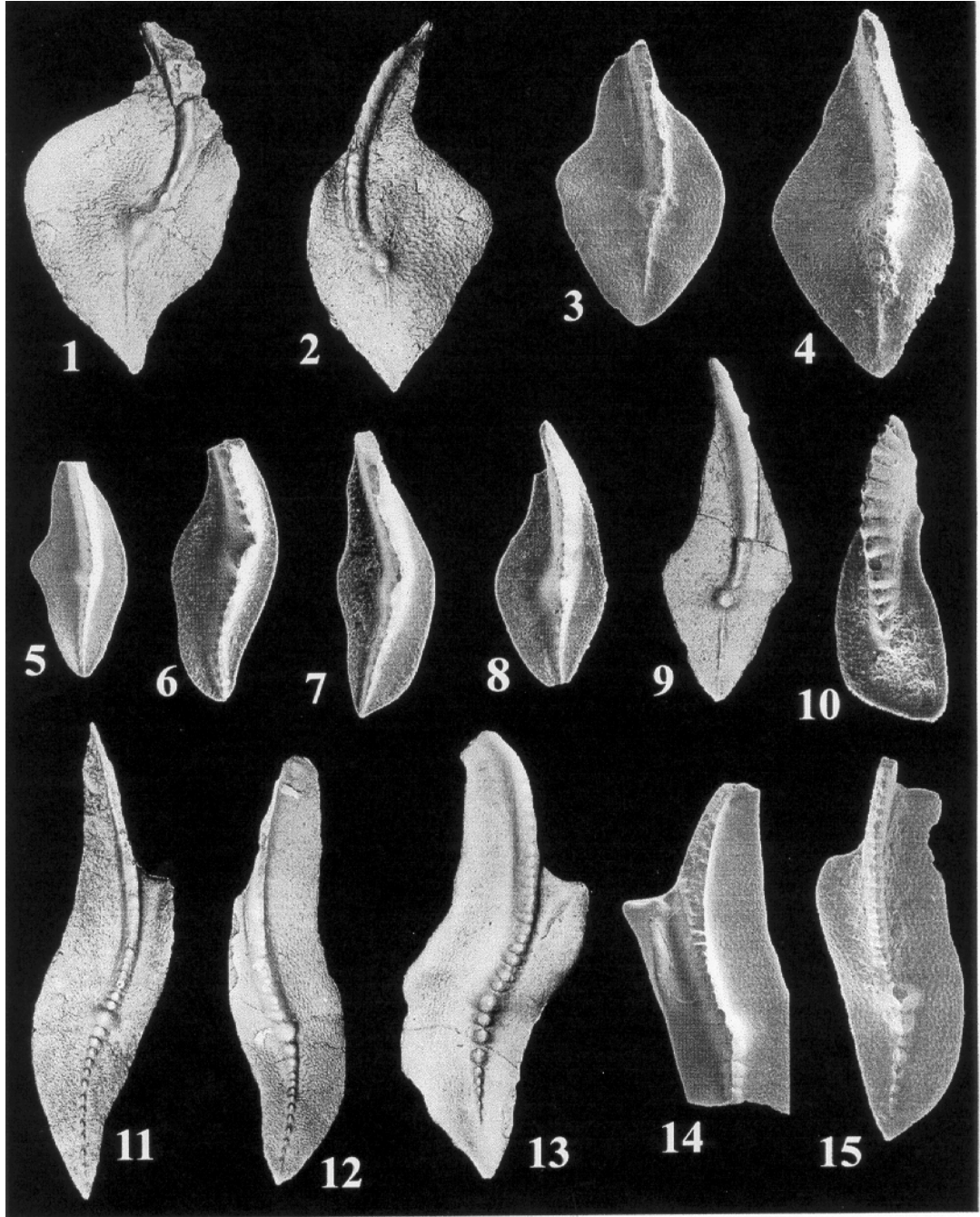
## CONCLUSION

Based on conodonts, the “Olentangy” Shale at Herron Hill, Kentucky, is placed in the *rhomboidea* Zone; it is not equivalent to the Upper Olentangy Shale of central Ohio.

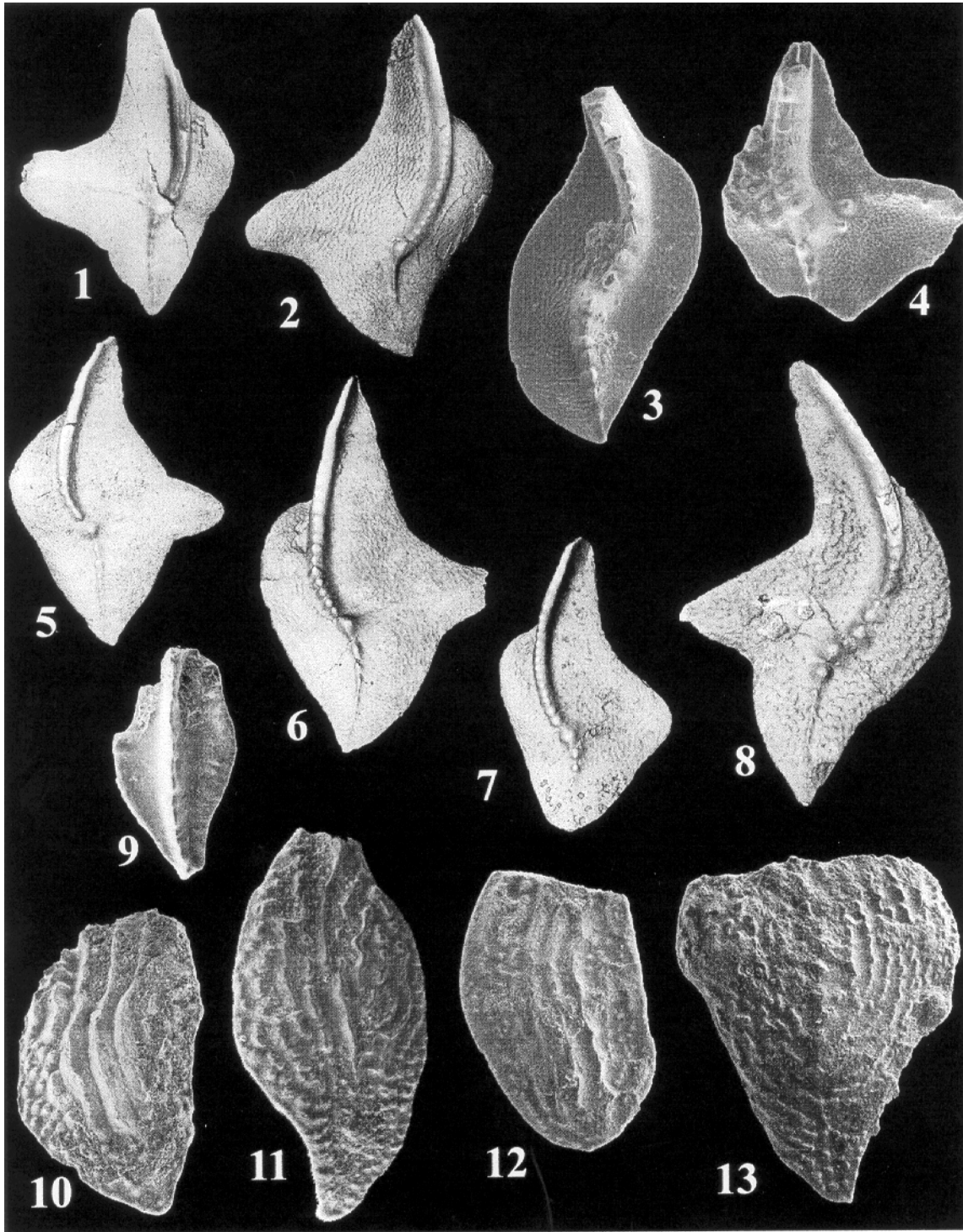
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**Figure 4.** Digital scanning electron microscope images of conodont *Pa.* and *Pb.* elements from the “Olentangy” Shale along I-64 near Morehead, Kentucky. See page 143 for complete figure caption.



**Figure 5.** Digital scanning electron microscope images of conodont *Pa.* elements from the "Olentangy" Shale along I-64 near Morehead, Kentucky. See page 143 for complete figure caption.

**Figure 4.** Conodont *Pa.* and *Pb.* elements from the “Olentangy” Shale along I-64 near Morehead, Kentucky.

(1, 2) *Palmatolepis rhomboidea* Sannemann, 1955. 1, upper view of *Pa.* element, OSU 50301, M641-01, X80; 2, upper view of *Pa.* element, OSU 50302, M641-07, X90.

(3) *Palmatolepis* sp. A Schülke, 1995, upper view of *Pa.* element, OSU 50303, M641-01, X60.

(4) *Palmatolepis minuta minuta* Ziegler, 1962 (*Palmatolepis* sp. A of Schülke, 1995, upper view of *Pa.* element, OSU 50304, M641-01, X60.

(5-9) *Palmatolepis minuta minuta* Branson and Mehl, 1934. 5, upper view of *Pa.* element, OSU 50305, M641-02, X60; 6, upper view of *Pa.* element, OSU 50306, M641-02, X95; 7, upper view of *Pa.* element, OSU 50307, M641-02, X80; 8, upper view of *Pa.* element, OSU 50308, M641-02, X65; 9, upper view of *Pa.* element, OSU 50309, M641-01, X40.

(10) *Palmatolepis perlobata* ssp. (?), upper view of *Pb.* element, OSU 50310, M641-02, X90.

(11, 12, 15) *Palmatolepis glabra prima* Ziegler and Huddle, 1969; 11, upper view of *Pa.* element, OSU 50311, M641-06, X45; 12, upper view of *Pa.* element, OSU 50312, M641-01, X50; 15, upper view of *Pa.* element, OSU 50315, M641-01, X85.

(13, 14) *Palmatolepis glabra pectinata* Ziegler, 1962; 13, upper view of *Pa.* element, OSU 50313, M641-06, X35; 14, upper view of *Pa.* element, OSU 50314, M641-01, X55.

**Figure 5.** Conodont *Pa.* elements from the “Olentangy” Shale along I-64 near Morehead, Kentucky.

(1) *Palmatolepis lobicornus* Schülke, 1995, upper view of *Pa.* element, OSU 50316, M641-07, X40.

(2, 7) *Palmatolepis tenuipunctata* Sannemann, 1955; 2, upper view of *Pa.* element, OSU 50317, M641-07, X50; 7, upper view of *Pa.* element, OSU 50322, M641-05, X85.

(3) *Palmatolepis regularis* Cooper, 1931, upper view of *Pa.* element, OSU 50319, M641-02, X75.

(4) *Palmatolepis quadrantinosalobata* Sannemann, 1955, upper view of *Pa.* element, OSU 50318, M641-01, X80.

(5, 6) *Palmatolepis subperlobata* Branson and Mehl, 1934. 5, upper view of *Pa.* element, OSU 50320, M641-06, X55; 6, upper view of *Pa.* element, OSU 50321, M641-07, X70.

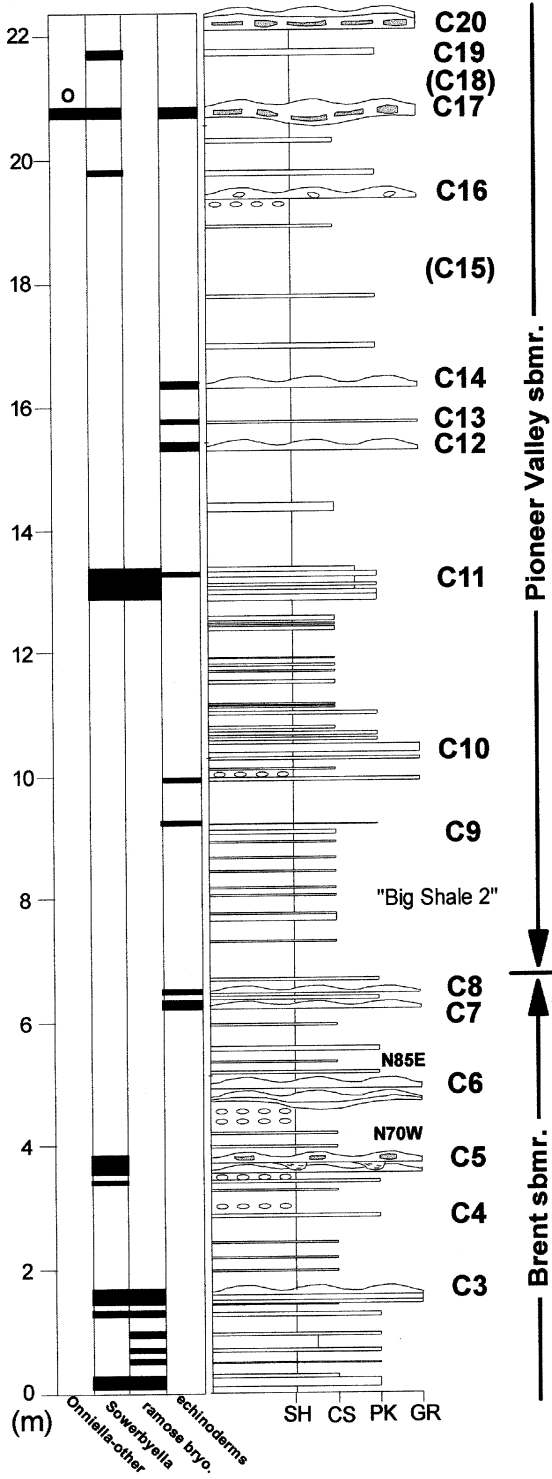
(8) *Palmatolepis perlobata* sp. A of Schülke, 1995, upper view of *Pa.* element, OSU 50323, M641-01, X45.

(9) *Polygnathus glabra glabra* Ulrich and Bassler, 1926, upper view of *Pa.* element, OSU 50324, M641-02, X55.

(10-12) *Polygnathus nodocostatus*, Branson and Mehl, 1934. 10, upper view of *Pa.* element, OSU 50325, M641-01, X60; 11, upper view of *Pa.* element, OSU 50326, M641-02, X60; 12, upper view of *Pa.* element, OSU 50327, M641-01, X50.

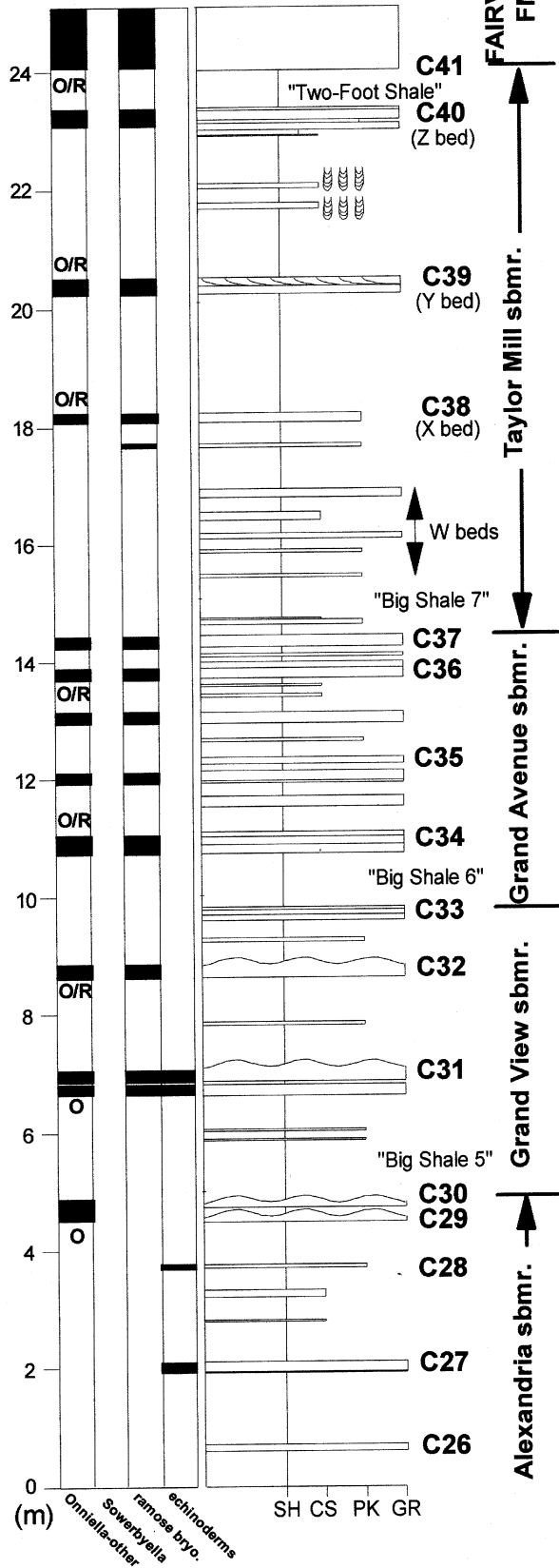
(13) *Polylophodonta confluens* Ulrich and Bassler, 1926, upper view of *Pa.* element, OSU 50328, M641-01, X40.

### White Castle/PMI



Appendix A.

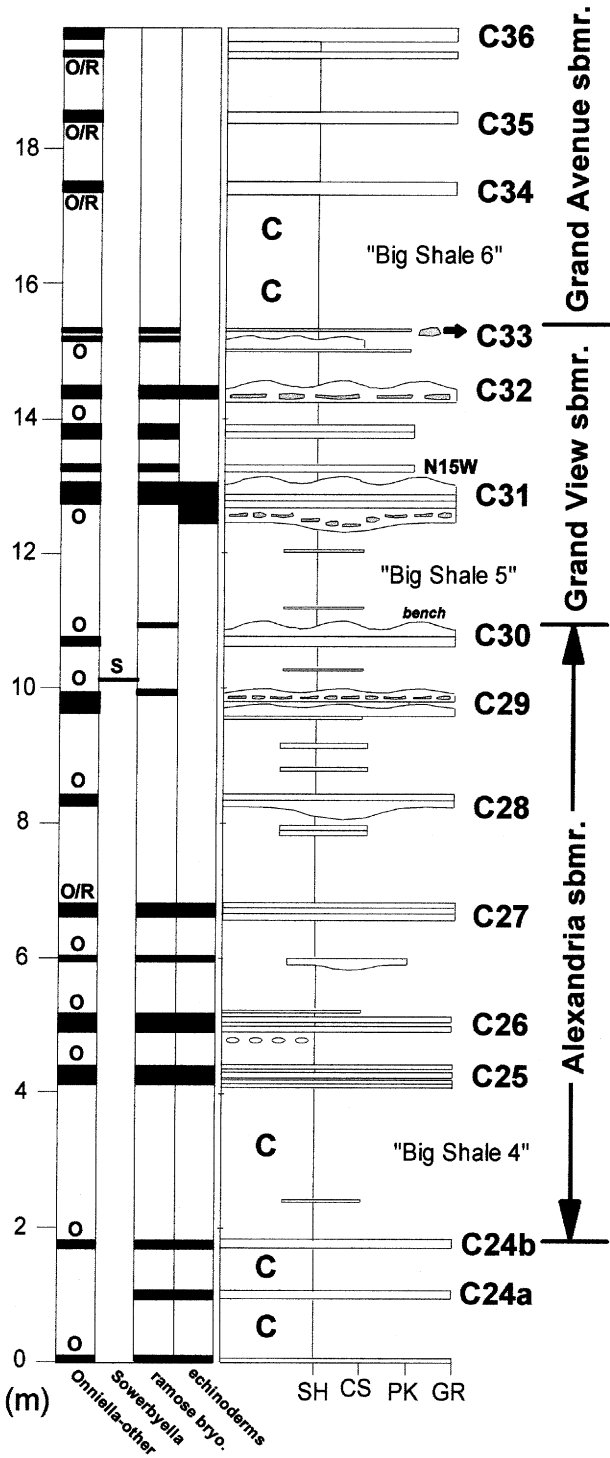
### Hwy. 471 Grand Ave. exit



Appendix B.

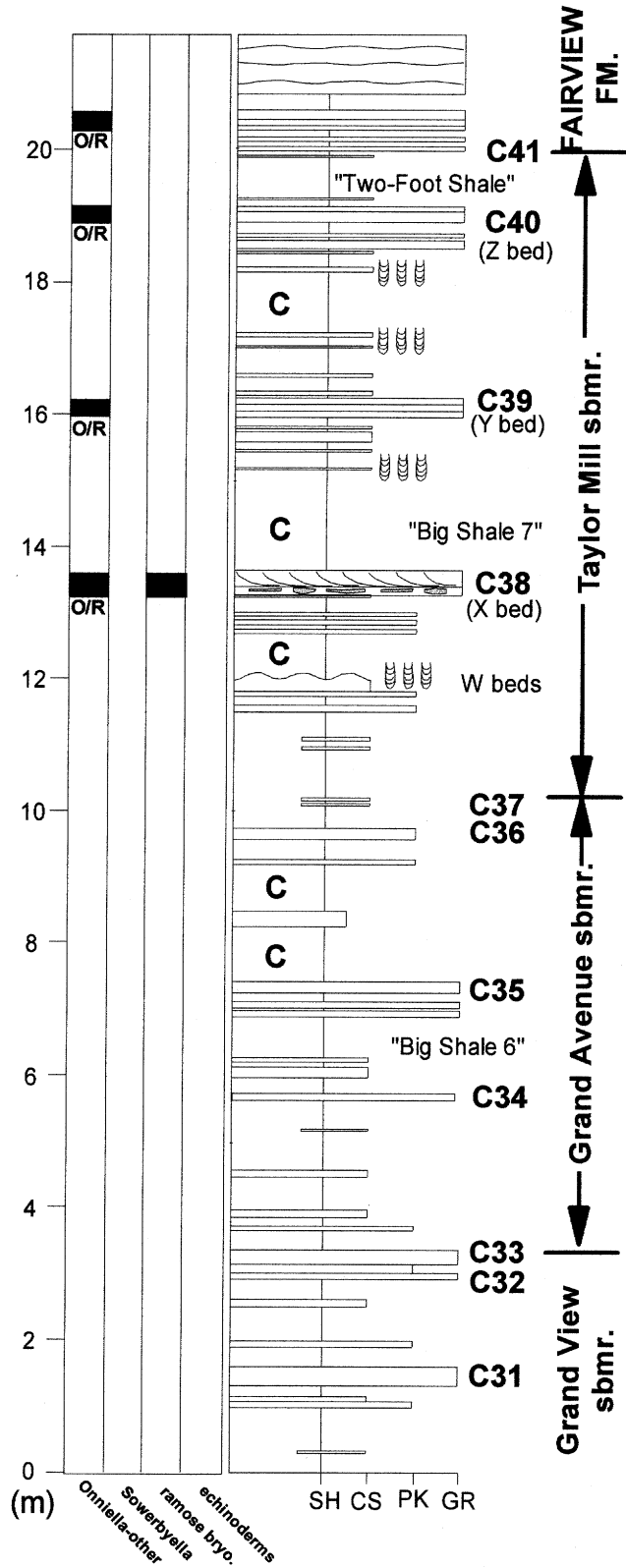


# AA Hwy. Outcrop 4



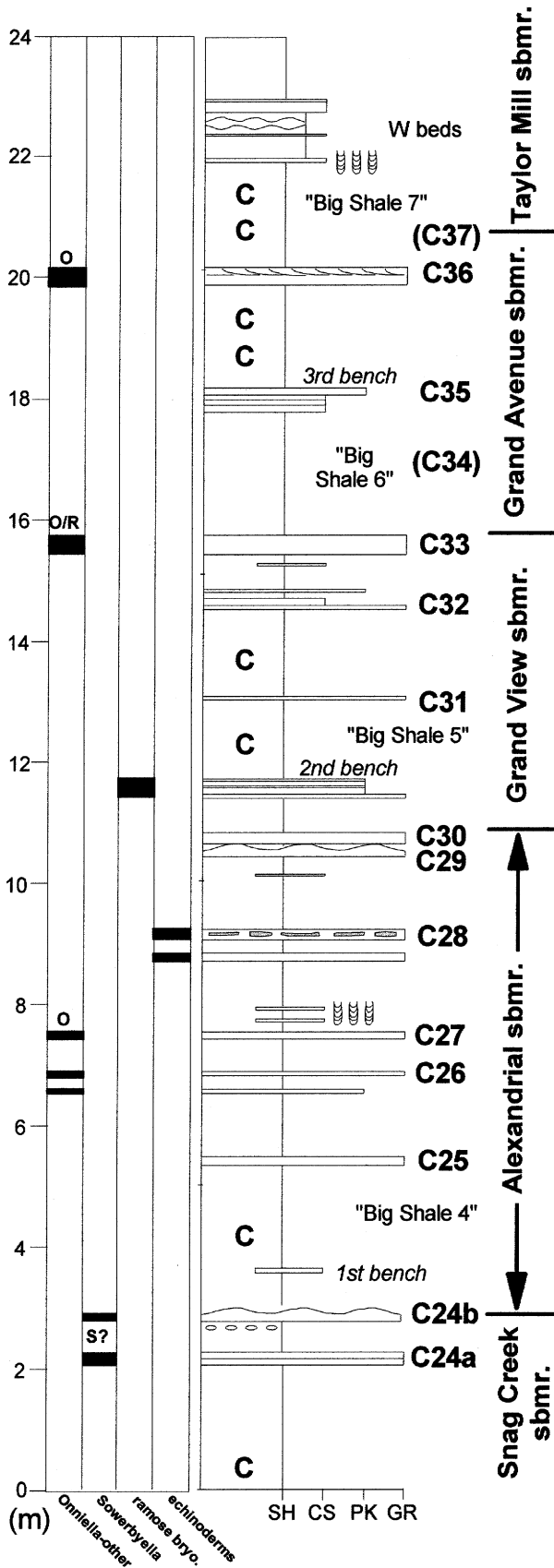
Appendix D.

# AA Hwy. Outcrop 5



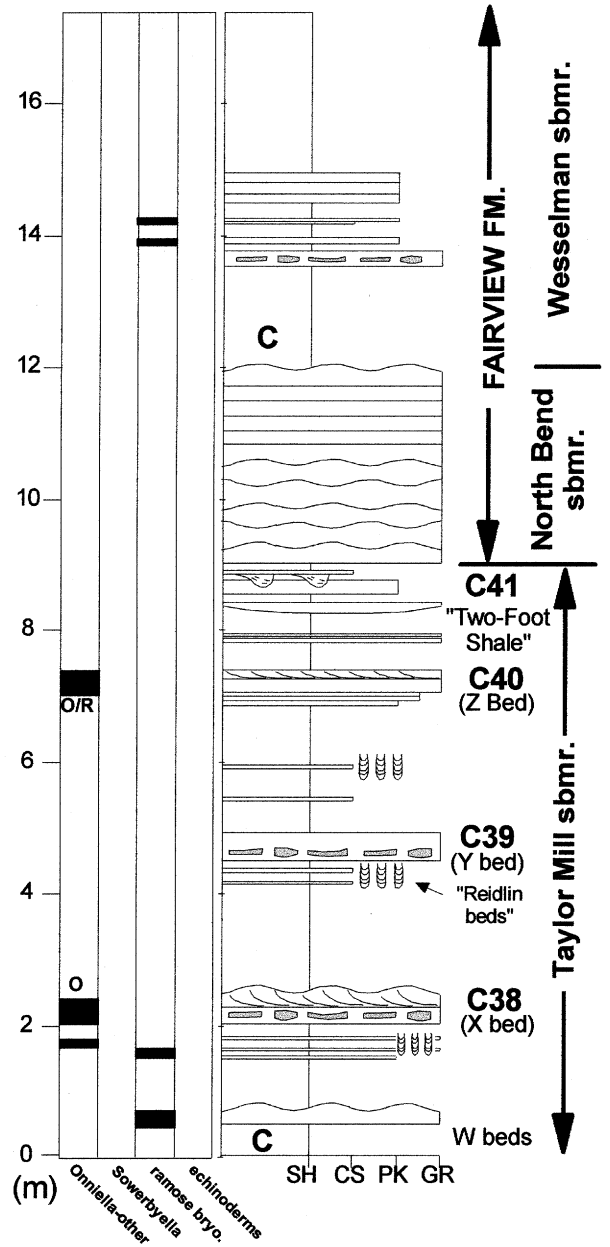
Appendix E.

# AA Hwy. Outcrop 7



Appendix G.

# AA Hwy. Outcrop 12

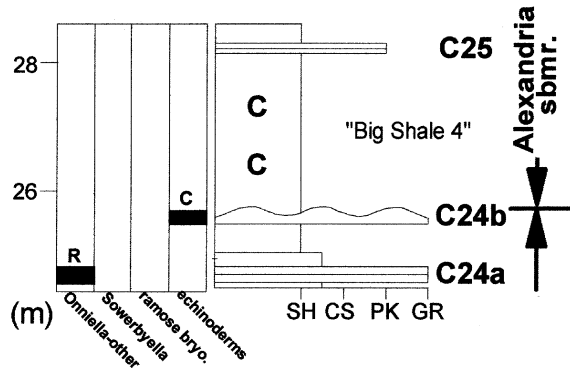
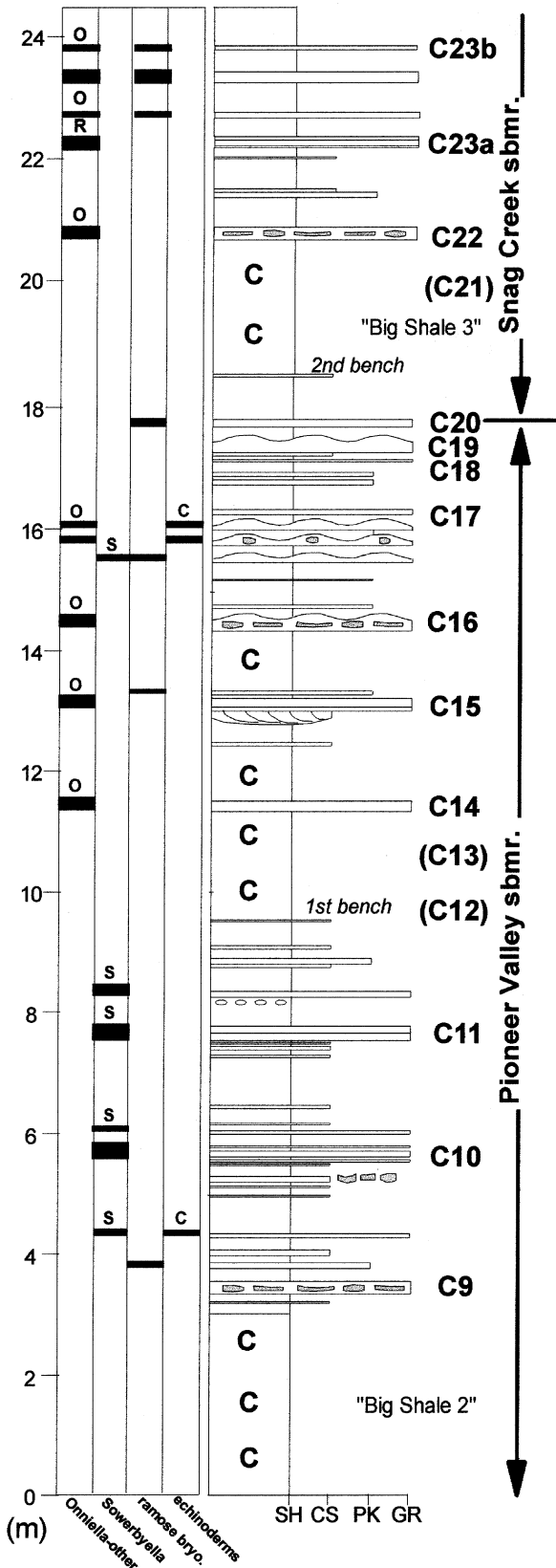


Appendix H.

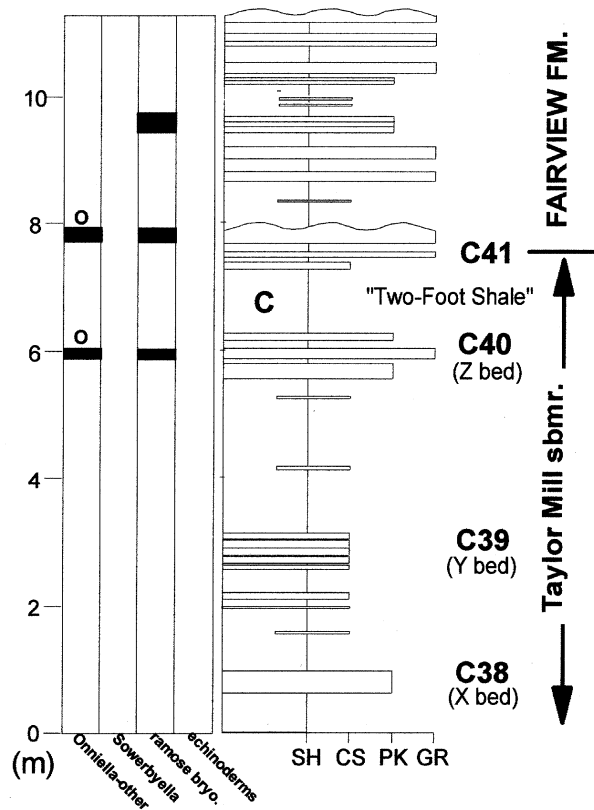
# AA Hwy. Outcrop 18

(lower)

(upper)



# AA Hwy. Outcrop 14



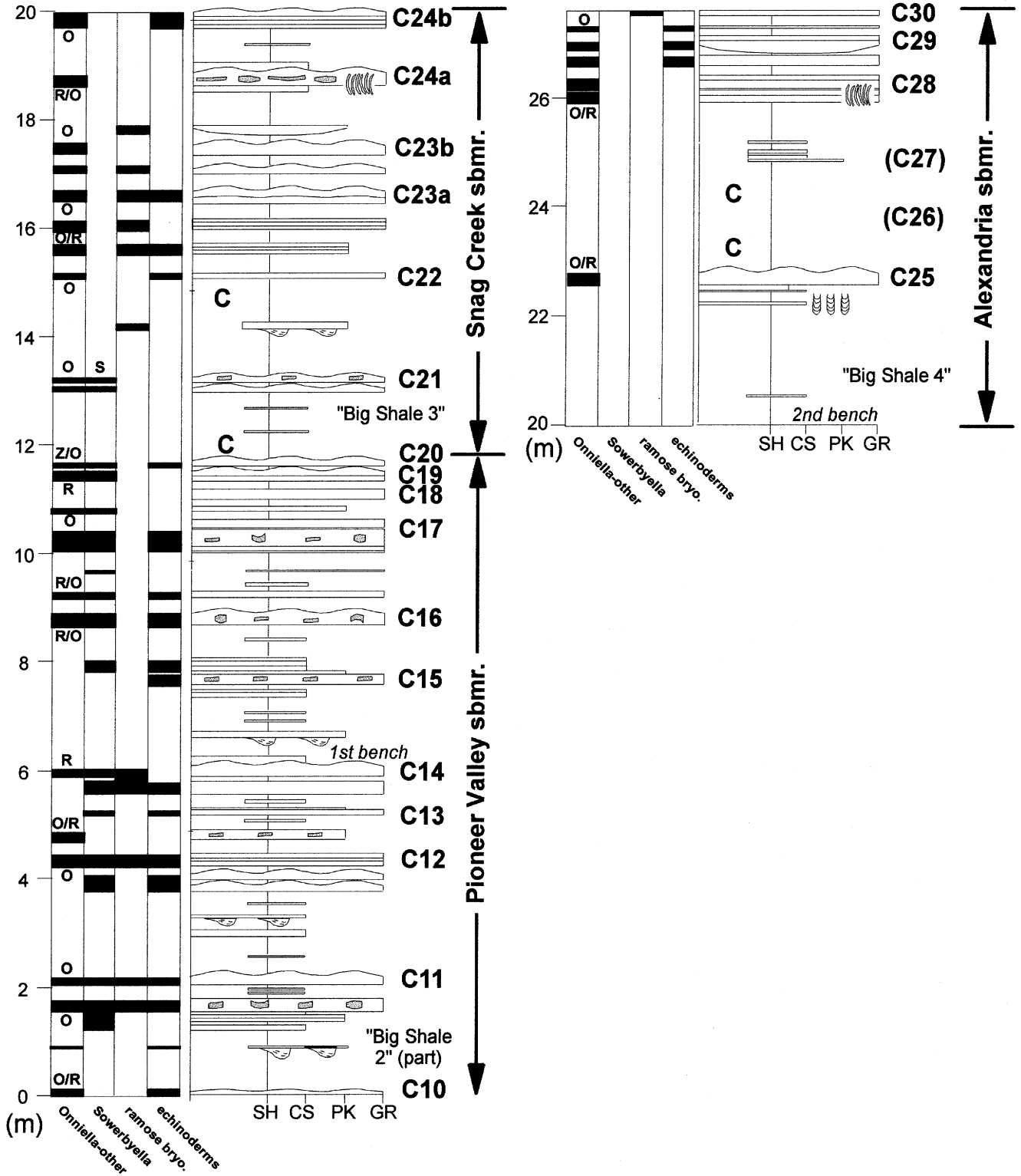
Appendix J.

Appendix I.

# AA Hwy. Outcrop 20

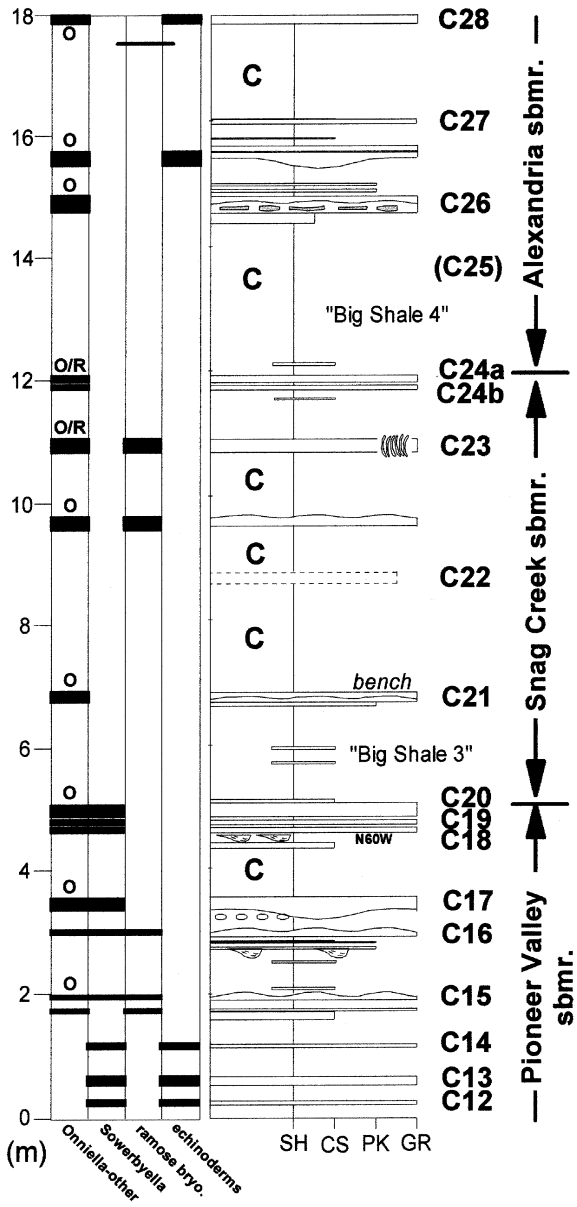
(lower)

(upper)



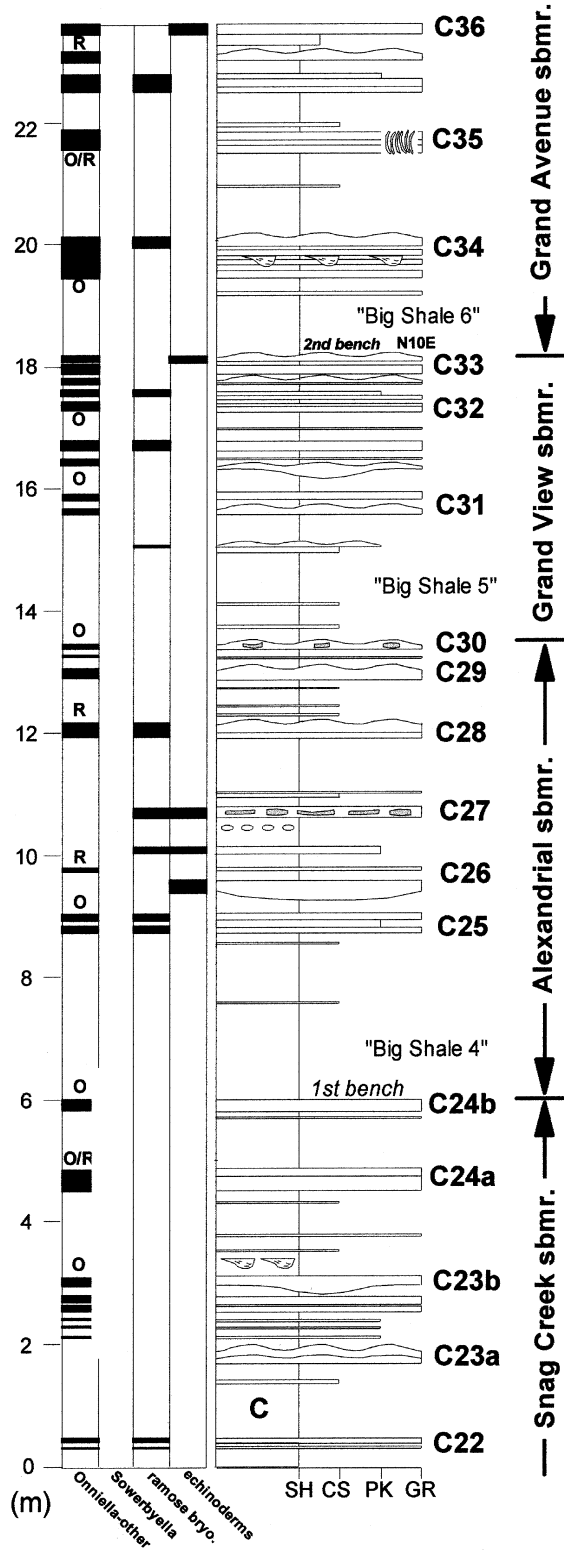
Appendix K.

### AA Hwy. Outcrop 23



Appendix L.

### AA Hwy. Outcrop 28

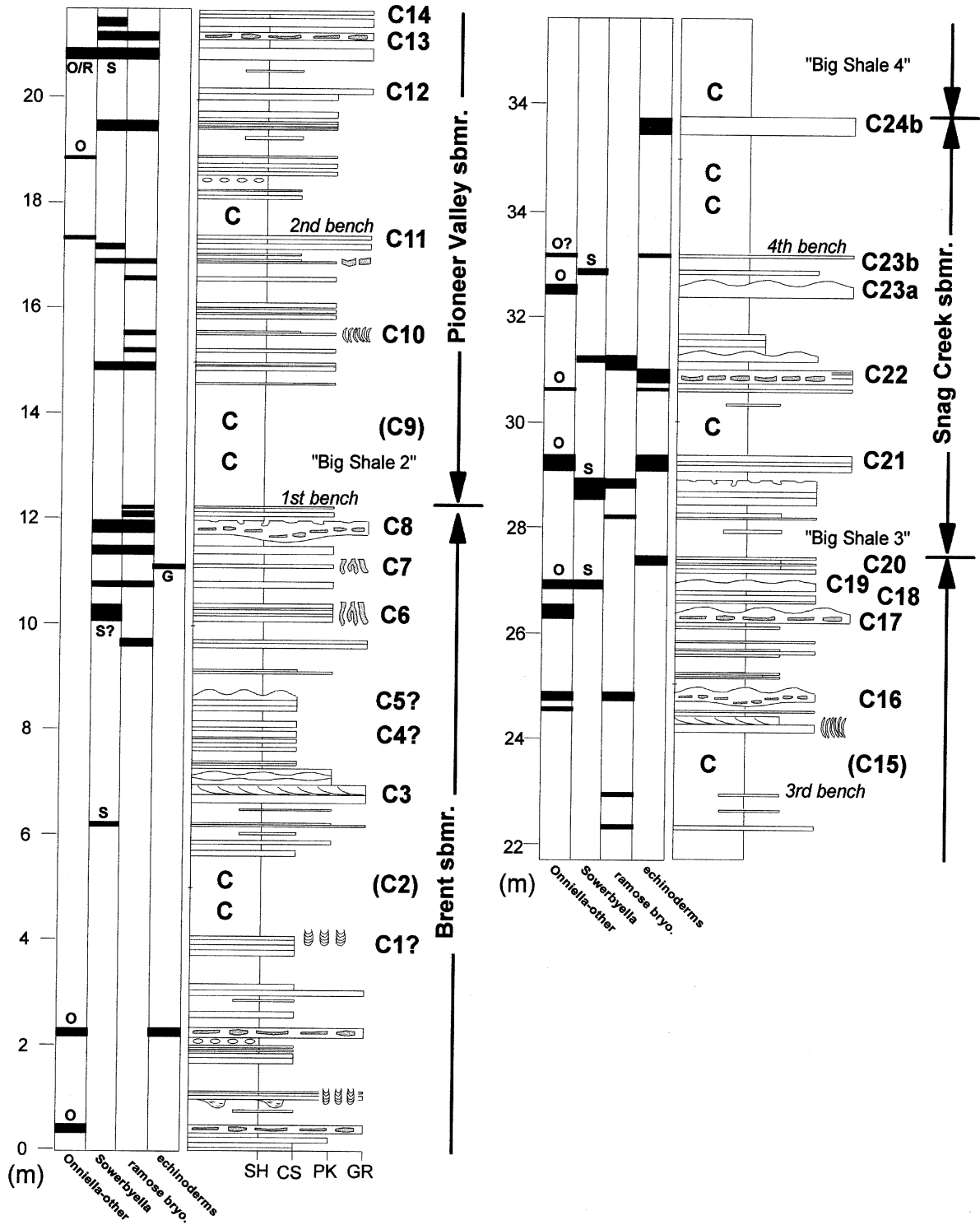


Appendix N.

# AA Hwy. Outcrop 25

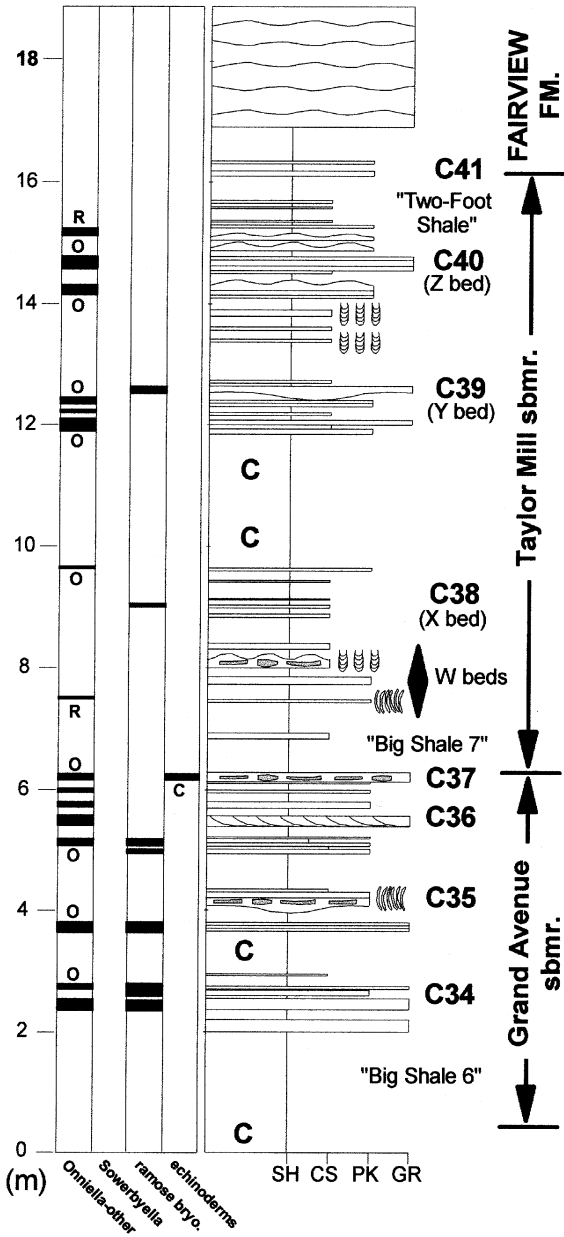
(lower)

(upper)



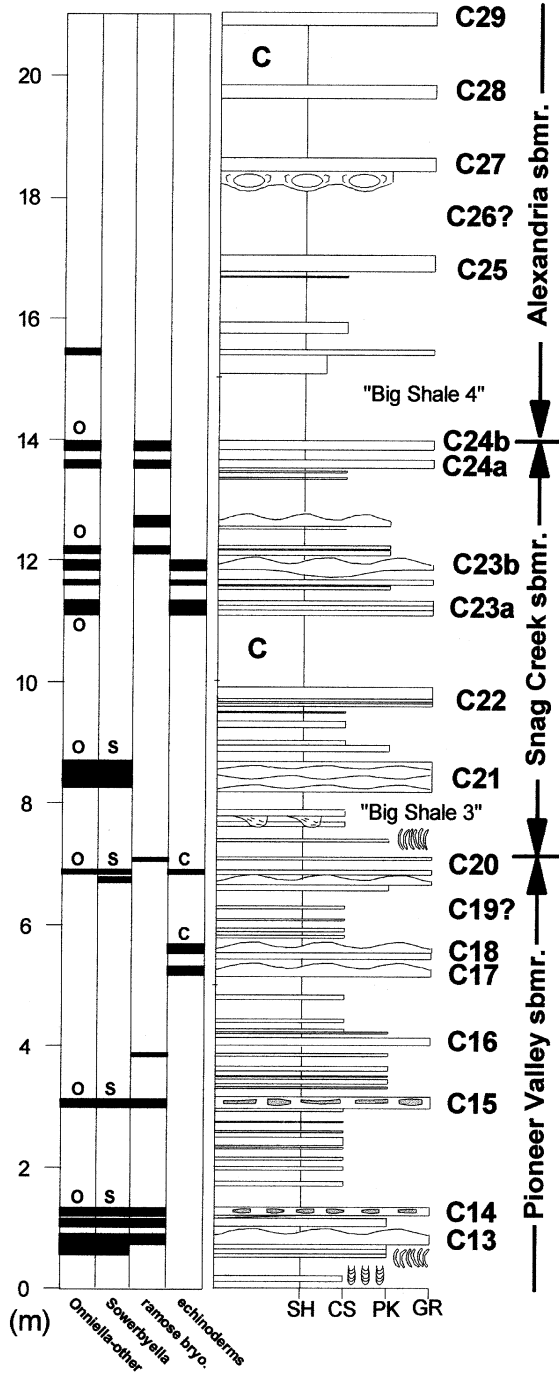
Appendix M.

### AA Hwy. Outcrop 29



Appendix O.

### AA Hwy. Outcrop 33



Appendix P.