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ScienceDirect

Palaeoworld 24 (2015) 149–159

Palaeoworld

www.elsevier.com/locate/palwor

# Faunal epiboles in the Upper Ordovician of north-central Kentucky: Implications for high-resolution sequence and event stratigraphy and recognition of a major unconformity

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Received 11 October 2014; received in revised form 31 December 2014; accepted 26 January 2015
Available online 4 February 2015

**Abstract**

Mixed carbonate-siliciclastic strata of the lower Richmondian (Upper Ordovician, Cincinnatian) in the Cincinnati Arch region represent deposition along a gentle epeiric ramp in the Taconic foreland basin. Previous stratigraphic investigation of this interval largely emphasized local facies, with little consideration of regionally persistent patterns and widespread marker horizons. The current study describes a distinctive package within the lower Rowland Member of the Drakes Formation of northern Kentucky; this interval comprises a four-part succession of units, several of which are characterized by unusually high abundance of particular taxa (proliferation epiboles). Similar (to nearly identical) successions, including epiboles in corresponding positions, are present within the undifferentiated Bull Fork Formation of central Kentucky and the Fort Ancient Member of the Waynesville Formation in southwestern Ohio. Further, progressive erosion of the widely traceable "lower Rowland" succession beneath a distinctive, prominent marker bed indicates the presence of a previously undocumented, regionally angular unconformity within the middle Rowland Member (the "mid-Richmondian unconformity" predicted by some earlier workers). Hence, a widely persistent, nearly layer-cake pattern can be documented over 150 km across the Cincinnati Arch. Although the mechanism(s) responsible for such widespread epiboles is (are) enigmatic, this study demonstrates the significant value of epiboles in regional stratigraphic correlation and recognition of unconformities.


*Keywords:* Cincinnatian; Richmondian; Faunal events; Proliferation epiboles; High-resolution stratigraphy

## 1. Introduction

Epiboles constitute thin, widespread intervals characterized by the unusual abundance of a fossil taxon or taxa that are otherwise significantly less common or absent in a given depositional basin (Brett and Baird, 1997). Multiple types of epibole have been documented throughout the Paleozoic, but proliferation epiboles — thin intervals defined by the exceptional abundance of taxa that were normally present, but otherwise insignificant components of assemblages — remain enigmatic. Such epiboles were widely recognized in the classic Cincinnatian (Upper Ordovician: Katian) strata of the Cincinnati Arch region of eastern Laurentia by paleontologists in the late 1800s and early 1900s, and workers such as August Foerste (1903, 1912) used these "faunal zones" to good advantage in correlating strata. For example, in the lower Waynesville Formation, a series of beds and epiboles were described and utilized in regional stratigraphic analyses: the *Dalmanella meeki* beds with a distinct orthid brachiopod now called *Cincinnetina meeki*, the *Flexicalymene* butter shales, the incursion of the Clarksville fauna including the brachiopods *Eochonetes* (formerly *Thaerodonta*) and *Leptaena*, and the *Glyptorthis* bed were used to help develop a detailed correlated stratigraphic framework within Ohio. However, in spite of the efforts of Foerste (1912) to extend these markers southward into shallower water settings by documenting overlapping diagnostic epibole taxa in different areas, the

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http://dx.doi.org/10.1016/j.palwor.2015.01.004
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rapid facies changes in Kentucky frustrated efforts to develop a refined synthetic, regional stratigraphy. Thus, partly because of these problems, the Cincinnatian epiboles were dismissed during much of the later 20th century as being of little or no stratigraphic significance. Such faunal markers were generally treated as non-biostratigraphic phenomena and were instead interpreted as simply marking particular, laterally restricted biofacies (see Davis and Cuffey, 1998). Yet, even though the ecological controls on such proliferation events remain poorly understood, it is clear that they do exist as discrete, widely traceable intervals (e.g., Brett et al., 2003; McLaughlin and Brett, 2007) and therefore have great utility in local and regional correlation and chronostratigraphic calibration (Brett, 2000; Brett et al., 2007).

The failure to recognize the importance of epiboles and other types of event beds and key surfaces by more recent workers has led to an overly lumped stratigraphy and a much less precise, and often redundant and confusing, terminology. In spite of the admirable feat of mapping every quadrangle in the commonwealth of Kentucky by USGS field geologists during the 1960s and 1970s, a more highly refined and consistent stratigraphy had already been worked out by earlier workers (e.g., Foerste, 1903; Butts, 1915) but subsequently discarded in an attempt to produce a strict lithostratigraphy. For example, in some areas, stratigraphic terminology was changed, somewhat arbitrarily, across the boundaries of quadrangles. This fed into a view of facies mosaics with little continuity of any horizons throughout the greater Cincinnati Arch region (see, for example, Cuffey, 1998).

A series of relatively recent road cuts along interstate highways and state roads, however, provides new insights into high-resolution event and sequence stratigraphy and re-affirms the utility of epiboles (and other markers) in providing highly refined regional correlations. This, of course, also raises questions as to the origin and significance of these beds and their role in the paradox of "layer cake" stratigraphy (Brett et al., 2007), and suggests a highly predictable pattern of sedimentary packages, even at a refined scale. Further, these regionally traceable faunal markers provide evidence of previously unrecognized, sequence-bounding disconformities. Failure to recognize these regionally angular erosional unconformities (sensu Brett et al., 1990) is one of the factors that clouded previous attempts at correlation and hampered a more realistic view of the stratal architecture of the type Cincinnatian.

Although integrated study of this temporal interval throughout the region has been complicated by uplift and erosion of the Cincinnati Arch, probable a late Paleozoic forebulge which has removed the record of Cincinnatian beds over a large area (Beaumont et al., 1988; Ettensohn, 2008), as well as the application of a plethora of lithostratigraphic terms, distinctive faunal markers — primarily proliferation epiboles — nevertheless serve as important tools for high-resolution correlation. These faunal and lithological markers, which had been largely discounted by many previous workers, permit recognition of widespread stratigraphic patterns over a broad geographic area (cf. Brett et al., 2007) and aid in recognition of a regional unconformity that locally cuts them out.

The objectives of the current study are: (1) to document faunal epiboles in an interval of the Upper Ordovician of Kentucky; (2) to utilize these faunal events as marker horizons that can shed light on the presence of discontinuities and sequence stratigraphy of the study interval; and (3) to interpret the nature of these epiboles and their ecologic and sedimentologic significance.

## 2. Stratigraphic relations

### 2.1. Regional setting

Strata of Upper Ordovician (Katian: lower Richmondian) age are well exposed around the periphery of the Cincinnati Arch in north-central Kentucky (Fig. 1A), where they are variably assigned to the Arnheim and Waynesville formations of Ohio and the Bull Fork, upper Grant Lake, and lower Drakes formations to the south (Fig. 1B). These units comprise mixed siliciclastic-carbonate rocks deposited in the distal Taconic foreland basin. Locally, this basin was subdivided by a shallow platform, referred to as the Lexington Platform, with a likely back-bulge basin, the Sebree Trough, to the north (Kolata et al., 2001).

These strata were thus accumulated along a gently north-sloping ramp with shallow peritidal facies to the south and shoal to deeper ramp environments to the north. Siliciclastic sediments were derived from tectonic source areas uplifted in the Vermontian tectophase of the Taconic Orogeny (e.g., Ettensohn, 2008). Carbonates were locally derived and include micritic wackestones in the shallowest environments, and skeletal grainstones and rudstones in mid-ramp environments, grading into muddy packstones with occasional grainstones in areas below wave-base to the north. We are currently attempting to calibrate the absolute depths and gradient dynamics of this ramp, which ranged from above mean sea level in desiccation cracked micrites in the south to deeper ramp but within the photic zone — probably < 30 m of depth — in the north (Brett et al., in press). The present study primarily considers the upramp, proximal settings and their associated epiboles.

### 2.2. Stratigraphic overview

A relatively detailed stratigraphy for the lower Richmondian Stage, long recognized in southern Ohio and eastern Indiana, comprises the upper Arnheim and Waynesville formations, the latter of which is further subdivided into three units: the Fort Ancient, Clarksville, and Blanchester members, in ascending order (Figs. 1B and 2). However, in Kentucky the apparently correlative interval undergoes relatively abrupt facies changes with a resultant lack of detailed correlations. This is further complicated by the uplift of the Cincinnati Arch, a feature which, in its present form, probably represents a forebulge of Carboniferous–Early Permian age that very gently upwarped foreland strata during the Alleghenian Orogeny (Ettensohn, 2008). More than 300 million years of erosion has removed higher beds from the center of the Cincinnati Arch, revealing beds as old as Sandbian-age near Lexington, Kentucky, but losing the record of overlying strata in this area. Consequently, the

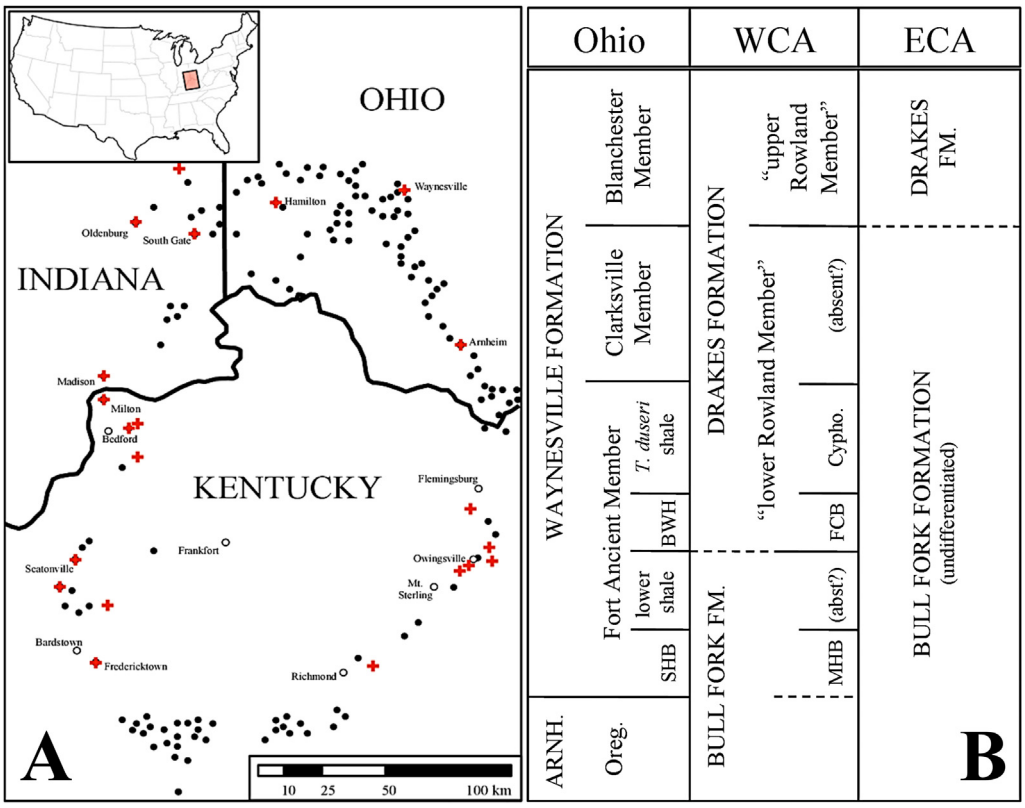


Fig. 1. Location and general stratigraphy of study area. (A) Location map of the Indiana-Ohio-Kentucky tri-state area of eastern USA (see inset map); open circles represent cities or towns for geographic reference, closed circles represent studied outcrops, and +'s represent critical sections described in detail within the text; note that outcrops of the stratigraphic interval studied here form a ring around the margin of the Cincinnati Arch, and no data can be derived from locations within this ring; many of these localities are also described by Foerste (1912). (B) Schematic diagram of stratigraphic and terminological relationships between strata in southern Ohio (Ohio), the western Cincinnati Arch region in Kentucky (WCA), and the eastern Cincinnati Arch in Kentucky (ECA). ARNH. = Arnheim Formation; Oreg. = Oregonia Member; SHB = Southgate Hill bed; BWH = Bon Well Hill bed; *T. duseri* shale = *Treptoceras duseri* shale; MHB = Marble Hill bed; abst? = locally absent; FCB = Fisherville coral beds; Cypho. = *Cyphotrypa* shale.

horizons considered herein cannot be directly traced across the center of the Cincinnati Arch, where they have been removed by post-Paleozoic erosion, in an area as much as 275 km wide in places.

Ongoing research tentatively links a distinctive, five to seven meter-thick package studied herein to the lower two members of the Waynesville Formation of southern Ohio (Fig. 1B). In particular, the basal, Fort Ancient Member in Ohio and Indiana seems to be divisible into a three- or four-part stratigraphy that can be traced southward into Kentucky (Fig. 2). In ascending order, this succession comprises: (1) an approximately one meter thick, phosphatic, skeletal limestone (the South Gate Hill bed, new term, herein); (2) a sparsely fossiliferous, gray clay shale (sometimes referred to as the lower Fort Ancient "barren shale"); (3) a bundle of coquinoid, dalmanellid-rich limestones (the Bon Well Hill beds); and (4) a soft, blue-gray claystone, or "butter shale", referred to as the "trilobite shale" or *Treptoceras duseri* shale (Frey, 1987); these beds are overlain by a series of limestones and shales, termed the Clarksville Member, with a distinctive fauna including abundant *Leptaena* and the first appearance of *Eochonetes clarksvillensis*, *Hiscobeccus capax*, and the rugose coral *Grewingkia canadensis*. Recent study has identified two regionally angular unconformities, one at the base and one above the top of this package (Fig. 2), partly on the basis of the epiboles discussed herein (Aucoin et al., 2014). These will be discussed elsewhere.

The apparent equivalents of this succession, as well as the bounding erosional surfaces, can be traced southward into a distinctive lower interval within Rowland Member of the Drakes Formation in north central Kentucky (Fig. 2), where the units described above appear to grade laterally, in ascending order, respectively, into: (1) a basal grainstone-packstone interval (locally termed the lower Marble Hill bed); (2) a sparsely fossiliferous mudstone and cherty calcisiltite; (3) the Fisherville coral bed; and (4) a soft *Cyphotrypa* bryozoan-bearing shale (Butts, 1915); the Clarksville interval, however, appears to be largely absent. The correlation of the Fort Ancient Member with the lower Rowland has been corroborated by unpublished carbonate carbon isotopic studies, which indicate the Waynesville positive excursion (Bergström et al., 2010) in both units. In the following sections, we consider the detailed stratigraphy and correlations of these epiboles and marker intervals from the northwestern area of the Cincinnati Arch, near Louisville, Kentucky, moving counterclockwise to the southeastern and eastern side of the Cincinnati Arch near Mt. Sterling, Owingsville, and Flemingsburg, Kentucky (Fig. 1).

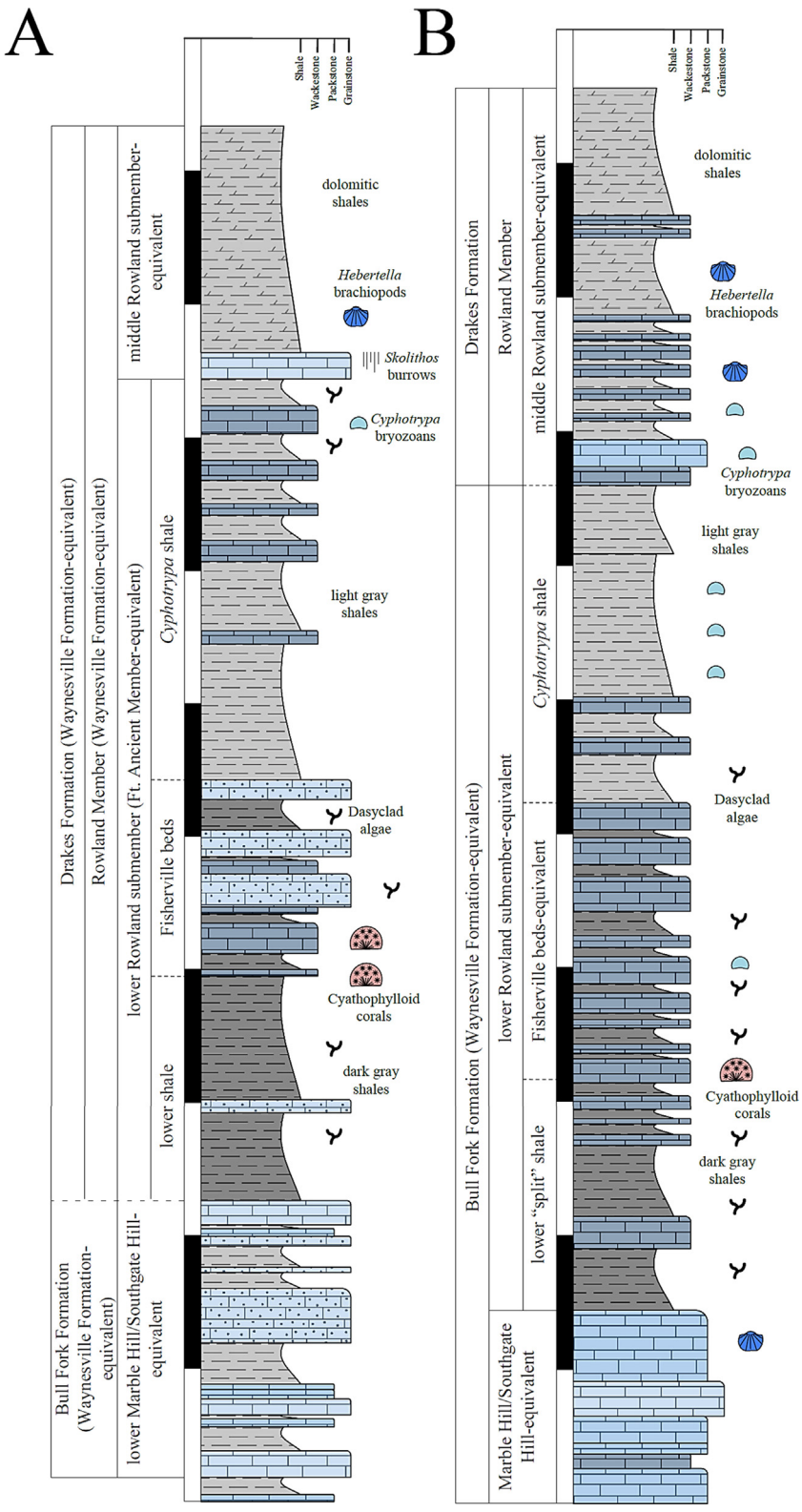


Fig. 2. Stratigraphic columns for two sections from far ends of the studied interval showing local terminology (left of columns) and inferred equivalent units. (A) Roadcut on I-71N, near Smithfield, Henry County, Kentucky (N38°28′41″, W85°16′12″). (B) Roadcut on I-64E, near mile marker 117, west of crossing of Salt Well Creek, ~6 km southwest of Owingsville, Bath County, Kentucky (N38°06′32″, W83°49′01″). Section A is about 160 km northwest of Section B, on opposite sides of the Cincinnati Arch.

### 2.3. Northwestern Cincinnati Arch stratigraphic relations

The stratigraphic interval considered here comprises a thin but highly distinctive package typically mapped in the area of Louisville, Kentucky, as the lower portion of the Rowland Member of the Drakes Formation and herein referred to as the "lower Rowland succession" (Figs. 2 and 3). This interval underlies an abrupt, and evidently disconformable, contact with a distinctive basal bed of the middle Rowland interval, which further south is regarded as the base of the Rowland. In the area of the northwestern Cincinnati Arch, from about Bedford southwestward to Mt. Washington, Kentucky, this marker is everywhere underlain by a distinctive series of four units, described individually in ascending order below.

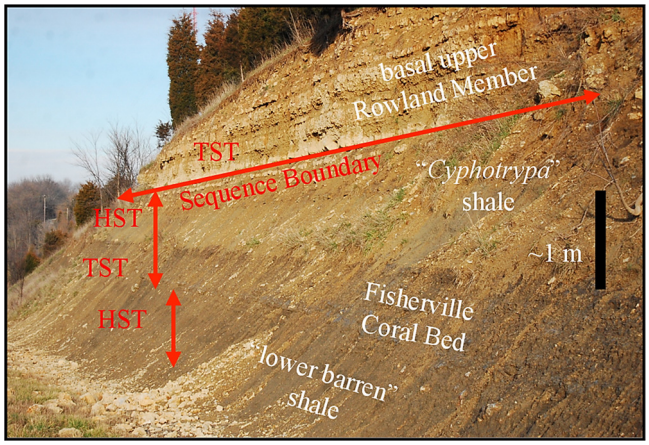


Fig. 3. Outcrop photograph of the lower and upper Rowland Member along highway I-71 at milepost 29 near Sulphur, Henry County, Kentucky, showing the major units recognized in this report. A major sequence boundary is marked by the solid horizontal line; small-scale sequences are marked by the double-sided vertical lines and are divided into transgressive systems tracts (TST) and highstand systems tracts (HST).

#### 2.3.1. Basal grainstone and lower Marble Hill bed

The base of the lower Rowland succession in this region is marked by a relatively thin package of phosphatic, skeletal pack- to grainstones and, locally, a unit of gastropod-rich grainstone that has been previously identified as the lower tongue of the Marble Hill beds (Swadley, 1979; Weir et al., 1984). The latter unit is a distinctive coarse, skeletal grainstone, locally extremely rich in well preserved specimens of the high-spired gastropod *Loxoplocus bowdeni* (Fig. 4C); this bed crops out in a narrow belt south of the Ohio River near Milton and Bedford, Kentucky. It has been interpreted as an offshore skeletal shoal (Swadley, 1979). This basal interval is thought to be the lateral equivalent of the informally named South Gate Hill bed, a phosphatic, brachiopod-rich pack- and grainstone unit that forms the base of the Waynesville Formation in southeastern Indiana (Figs. 1B, 2, 4C). This correlation is based partly on stratigraphic position, but also because of the

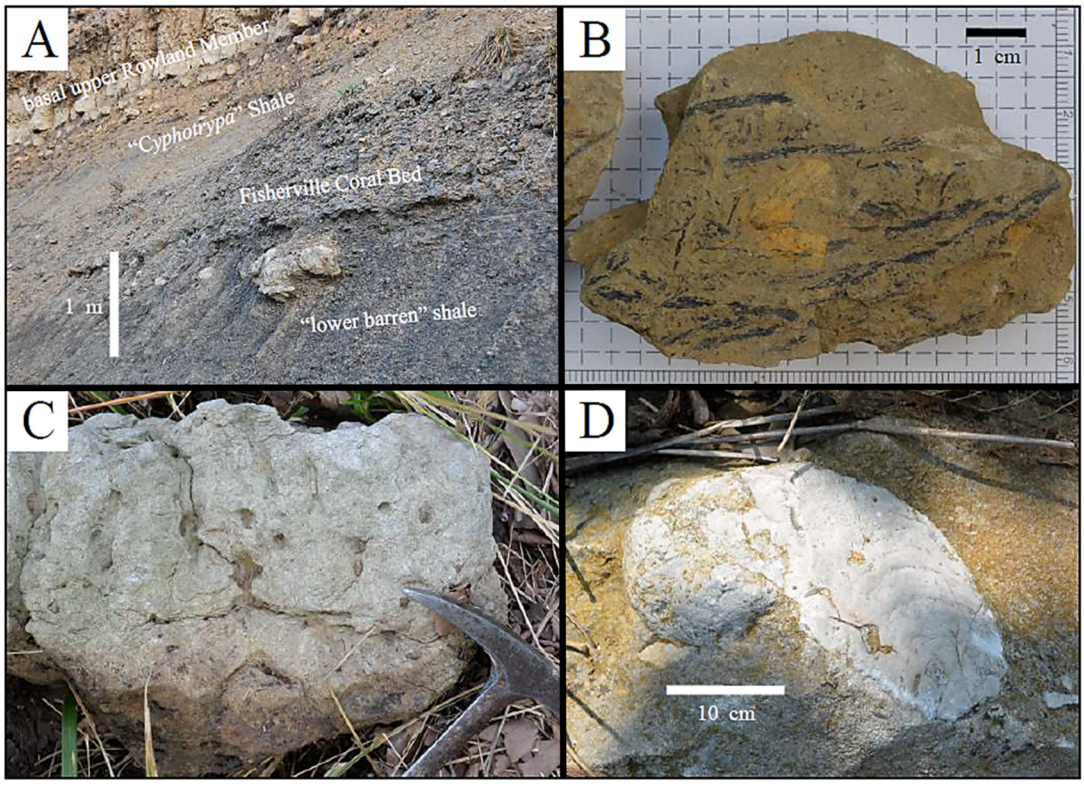


Fig. 4. Selected details of significant stratigraphic units. (A) Outcrop on I-71 near Sulphur, Kentucky showing the "lower barren" shale, which contains a large coral head (*Cyathophylloides*) near the top of the unit, overlain by the Fisherville coral bed, the *Cyphotrypa* shale, and the basal carbonate bed of the upper Rowland Member. (B) Non-calcified dasyclad algae, common within the "lower barren" shale interval. (C) A block of the basal unit of the upper Rowland Member, showing abundant *Skolithos*; this photograph was taken at a creek along US-421 southeast of Bedford, Trimble County, Kentucky. (D) Large solenoporid (red algae?) thallus in the basal upper Rowland bed at the same locality as in (C), occurring slightly above the unconformity forming the base of this unit.

evidence for the taphonomic complexity of these units, which we interpret as a reflection of stratigraphic condensation during an interval of relatively rapid base-level rise. This correlation is also supported by the concentration of phosphate in both units and the abundance of high-spired gastropods in the Marble Hill beds, which seemingly reflects a time-specific episode of elevated primary productivity during deposition of these units (cf. Allmon, 1992; see Section 3).

#### 2.3.2. *"Lower barren" shale*

The basal grainstone unit is overlain by approximately one and a half to three meters of soft, greenish-gray, silty mudstone (Fig. 4A). This interval is sparsely fossiliferous and contains few packstone or grainstone beds; however, along I-71 south of Bedford, Kentucky, large heads of the colonial corals *Cyathophylloides* and *Tetradium* occur in the upper half-meter of this unit. This dark shale is rich in carbonized dasyclad algae. To the southwest, this mudrock interval becomes increasingly silty and locally contains cherty calcisiltites. The presence of nodules of pale gray "amoeba-form" chert forms a distinctive marker for this shaly unit that is recognized in several quadrangles south of Louisville, Kentucky.

#### 2.3.3. *Fisherville coral beds*

In turn, the lower mudrock interval is overlain by a unit ~1 to 2.5 m thick that is characterized by a facies motif, referred to as rhythmic bedding. One component of these rhythms is medium gray, pale-weathering, hard, micritic limestone (lime mudstone and wackestone) that contains scattered brachiopods (large, robust specimens of *Hebertella occidentalis*, small *Platystrophia*), ramose bryozoans, cap-shaped *Cyphotrypa* bryozoans, gastropods (*Loxoplocus*, *Lophospira*), bivalves (*Modiolopsis*, *Ambonychia*, *Caritodens*), as well as abundant *Tetradium* sp., and *Cyathophylloides stellata* (formerly called *Columnaria alveolata*), including heads up to nearly a meter in diameter. Surprisingly, solitary rugose corals, common in the upper Waynesville Formation and equivalent middle-upper Rowland Member (Elias, 1983), have not been documented from the Fisherville coral bed. This lithology alternates evenly with very dark brownish-gray, fissile, carbonaceous shales (Fig. 4B), which commonly show small *Chondrites* burrows and carbonized dasycladacean algae. These beds weather to a striped appearance because of the alternation of pale chalky micrites and recessive dark shales.

This interval was previously identified as the Fisherville "reef", for coral beds or biostromes west of Fisherville, KY, an epibole of the colonial rugose coral *Cyathophylloides stellata* and *Tetradium* spp. (Foerste, 1903; Brown, 1964). This is an important regional marker, which previously has been traced from the vicinity of Mount Washington, Kentucky northeastward to the area of Sulphur, KY (see Fig. 1). It has been used to define the base of the southern "Waynesville-equivalent" (Butts, 1915) and, subsequently, as the base of the Rowland Member of the Drakes Formation in certain quadrangles of Kentucky (e.g., the Fisherville Quadrangle; Kepferle, 1976). However, as noted in Section 2.3, we consider the underlying succession to be equivalent to the lower beds of the Fort Ancient Member of the Waynesville Formation and also include them within the Rowland Member; the equivalent cherty calcisiltites and shale below the Fisherville bed have also been used as the base of the Rowland in some geological quadrangles mapped by the US Geological Survey.

#### 2.3.4. Cyphotrypa *shale*

In all outcrops between the Smithfield Quadrangle to the north and Seatonville, Kentucky, within the Jeffersontown Quadrangle, to the south, the Fisherville beds are overlain by two to three meters of mudstone that locally contain an exceptional abundance of the small, domal, slightly monticular bryozoan generally identified as *Cyphotrypa clarksvillensis* (Fig. 2; also see Fig. 7). The interval is otherwise sparsely fossiliferous except for scattered shells of the brachiopod *Hebertella* and the bivalve *Modiolopsis*, which also forms the most common substrate for the *Cyphotrypa* bryozoans (see also Schwalbach et al., 2014). Both the base and top of this interval pass into thin, rhythmically interbedded, pale-gray wackestones, and dark gray shales with carbonized dasyclad algae; these resemble the Fisherville facies, but, significantly, lack corals. This interval appears to be cut out at a major regional erosion surface between Seatonville, and Bardstown, Kentucky (Fig. 1).

#### 2.3.5. *Middle Rowland basal beds*

The lower Rowland beds are sharply overlain by a distinctive series of beds, at the abrupt, and evidently, disconformable contact with the middle part of the Rowland Member. The basal bed, typically approximately one half to one meter thick, is composed of massive, pale olive-green, yellow- to buff-weathering, silty argillaceous lime mudstones to wackestones. This bed is characterized by the presence of small spheroidal bryozoans (*Cyphotrypa*), stromatoporoids, and corals and, in many localities dark green, glauconite-filled *Skolithos* burrows near its top (Fig. 3). This bed serves as an important regional marker and is herein referred to as the "*Skolithos* bed". Slightly higher beds show gastropod rich grainstone with large solenoporid algae (Fig. 4D).

A key discovery of this work is that the *Skolithos* bed and other middle and upper Rowland markers persist to the south, whereas the critical markers of the lower Rowland are progressively truncated and overlapped. The *Cyphotrypa* shale persists southward to about Seatonville, but 10 km to the south, near Mount Washington, the Fisherville bed occurs immediately below the basal middle Rowland *Skolithos* bed, with the intervening *Cyphotrypa*-bearing mudstone having apparently been removed by erosion (see Fig. 7). The Fisherville interval is absent south of this region, where the *Skolithos* bed comes to rest first on the cherty calcisiltite facies and then, south of Bardstown, Kentucky area, on successively older beds equivalent to the lower Arnheim Formation and mapped as Reba Member of the Ashlock Formation. This evidence defines a significant and previously undocumented regionally angular unconformity that removes the lower Waynesville/lower Rowland Member units and ultimately cuts away most of the underlying Arnheim Formation to the south.

### 2.4. Southeastern Cincinnati Arch stratigraphic relations

The lower Rowland interval appears to be absent south of Bardstown, Kentucky along the southwestern and southern flanks of the Cincinnati Arch, and has not previously been recognized anywhere to the east. However, our recent fieldwork has revealed a similar succession along the southeastern flank of the Cincinnati Arch between Mount Sterling and Flemingsburg, KY, where it has been mapped as part of the undifferentiated Bull Fork Formation (Figs. 1, 2 and 5). We argue, on the basis of an extremely similar suite of faunal epiboles and key beds, as well as the persistence of bounding (upper and lower) markers for this interval, that this succession (Fig. 1B) is, in fact, very similar to the lower Rowland succession of the west side of the Cincinnati Arch. The interval of interest is well exposed from Howards Mill, 8 km east of Mt. Sterling, northeastward to the vicinity of Owingsville, Kentucky (Fig. 1). Although it was not recognized as a distinct unit during quadrangle mapping by the USGS, it is clear that at least the basal middle Rowland interval was noted near Owingsville, where it was considered simply to be a local bed rich in bryozoans (especially *Cyphotrypa*, which may be densely packed; see Fig. 6D), *Tetradium*, and stromatoporoids. This bed overlies a somewhat thicker succession that includes all of the sub-units of the lower Rowland succession (Fig. 6A). Moreover, careful mapping by the US Geological Survey, summarized by Weir et al. (1984), indicated that the upper Bull Fork Member shows dramatic thinning in the area from the Owingsville southwest to the Mount Sterling Quadrangle. We regard this as evidence for a regionally angular unconformity coextensive with that which

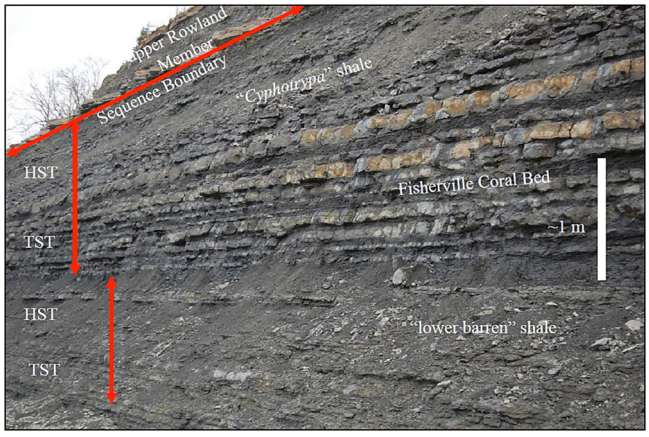


Fig. 5. Outcrop of the lower and upper Rowland Member-equivalents (mapped as the middle Bull Fork Formation) along I-64 at milepost 117, ~4 miles west of Owingsville, Bath County, Kentucky (see Fig. 1A). Note the strongly rhythmic bedding of the Fisherville coral bed-equivalent. Small-scale sequences within units underlying the major unconformity are delineated as in Fig. 3.

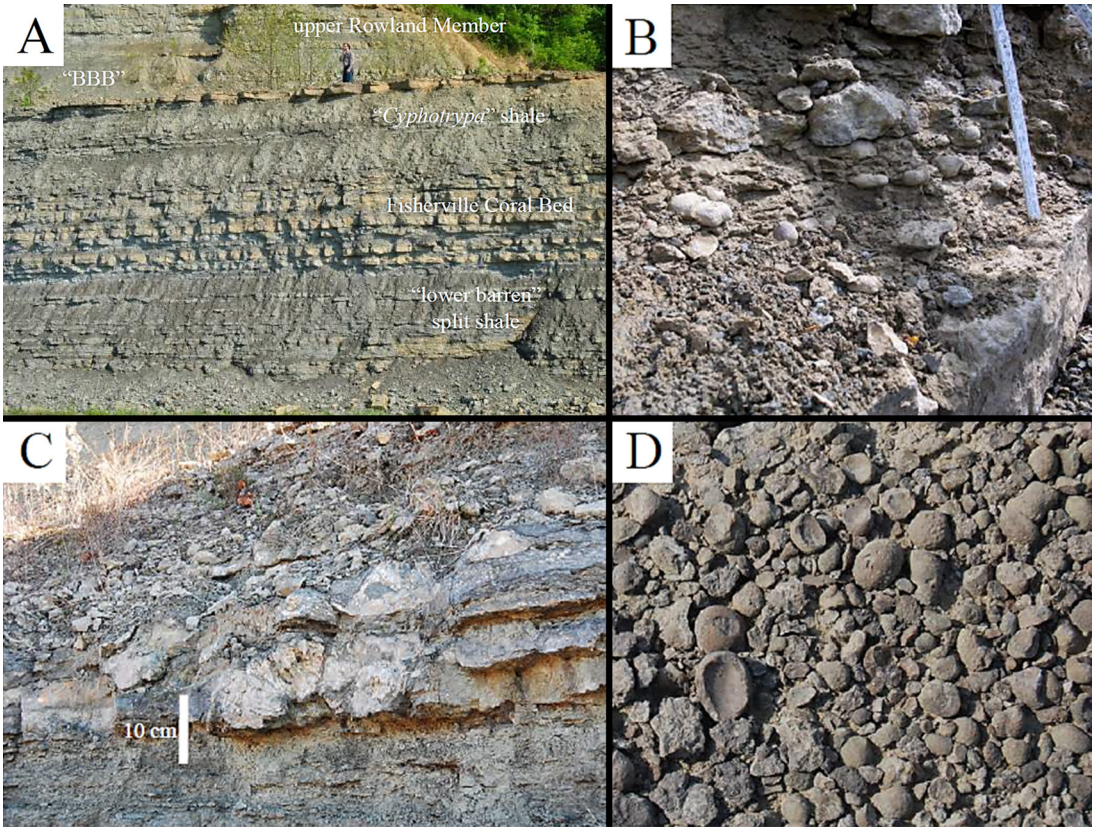


Fig. 6. Details of the upper Bull Fork Formation in the vicinity of Owingsville, Kentucky (see Fig. 1A). (A) View of outcrop on I-64, at exit 123 onto US Rte. 60, showing the sequence boundary above the *Cyphotrypa* shale; the immediately overlying bed is remarkably rich in round *Cyphotrypa* colonies (BBB = "ball bryozoan bed"), as shown in (D). (B and C) Basal upper Rowland bed showing abundant vuggy stromatoporoids and corals; image in (B) is from the same locality as (A), and image in (C) is from a nearby roadside outcrop. (D) Close-up of dense *Cyphotrypa* concentration at the base of the upper Rowland Member-equivalent; from the same locality as that shown in (A).

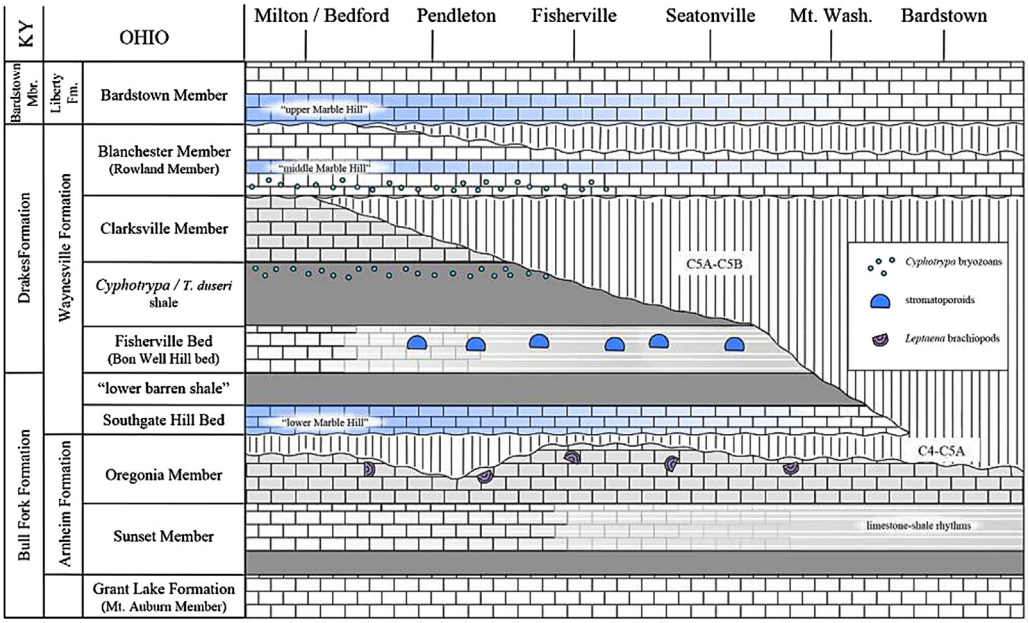


Fig. 7. Schematic cross-section along western side of Cincinnati Arch from Milton, Kentucky in the north to Bardstown, Kentucky in the south (see Fig. 1A). This cross-section, approximately 120 km in distance, shows a southward truncation of the *Cyphotrypa* shale, Fisherville bed, "lower barren" shale, and Southgate Hill-lower Marble Hill bed below the basal upper Rowland Member, at a regionally angular unconformity. The "C4-C5A" and "C5A-C5B" labels are associated with unconformities (designated by vertical striping) that serve as the boundaries between third-order stratigraphic sequences defined and named by Holland and Patzkowsky (2007) and modified slightly by Brett et al. (2012).

we have documented on the northwest side of the Cincinnati Arch.

### 2.4.1. Basal succession and "barren shales"

The base of the lower Rowland/Fort Ancient-equivalent succession is not as clearly defined in all outcrops, but appears to be represented at Mt. Sterling, Kentucky by four or five highly fossiliferous packstone beds totaling approximately 1.6 m (Figs. 2 and 7). However, cuts along exit 123 from I-64 east of Owingsville show a distinctive channelized set of grainstones that appear to fill a channel several tens of meters across and at least a meter deep (see Weir et al., 1984). Even more dramatically, at large roadcuts on KY-111 northeast of Owingsville, the apparently correlative interval is represented by a channel-fill succession, up to three meters thick, of coarse, cross-bedded grainstones that laterally pinches to a 40 cm grainstone within a few tens of meters laterally.

In all localities, the grainstone is overlain by 1–1.7 m of pale-gray, thinly nodular, sparsely fossiliferous olive gray to dark brownish-gray mudstone, rich in dasycladacean algae with a medial band rich in *Hebertella*, *Platystrophia*, and ramose bryozoans (Fig. 5). These beds appear to be the equivalent of the barren algae-rich shales and cherty calcisiltites of the western side of the Cincinnati Arch, but have not yielded chert nodules at any outcrop on the eastern side.

### 2.4.2. Fisherville coral beds-equivalents

The sparsely fossiliferous mudstone interval is abruptly overlain by a distinctly rhythmic succession of ten to twelve micritic, sub-concretionary wackestones interbedded with very dark brownish-gray, carbonaceous shales (Figs. 2, 5 and 6A). This interval is very well exposed at mile markers 115 and 117 on I-64 near Preston, Kentucky. It appears to correlate with the rhythmic limestone-dark shale succession of the Fisherville interval on the west side of the Cincinnati Arch. This interval thins to about a meter to the north on both sides of the Cincinnati Arch and has fewer rhythmic beds, perhaps due to the amalgamation of layers. These outcrops also contain a very similar fauna to the Fisherville beds, including abundant modiolopsid bivalves, ramose and hemispheroidal bryozoans, and notably common *Hebertella* brachiopods, especially near the base of the unit. In these sections, however, colonial corals and small stromatoporoids are relatively uncommon and restricted to one or two beds near the base.

### 2.4.3. Cyphotrypa *shale*

At sections from Howards Mill, east of Mt. Sterling, to just east of Owingsville, rhythmic carbonates and coral biostromes of the Fisherville interval are overlain by one to two meters of olive-gray, silty shale that is exceptionally rich in small (1–3 cm in diameter) hemispheroidal colonies of the bryozoan *Cyphotrypa clarksvillensis* (Figs. 2 and 6D). This shaly interval is again very similar to the *Cyphotrypa* shale of the west side of the Cincinnati Arch, more than 150 km to the west and was almost certainly coextensive with this shale prior to erosion of the Cincinnati Arch (see Figs. 7 and 8).

### 2.4.4. Upper Bull Fork succession

In sections between Mt. Sterling and Owingsville, the upper bed of the *Cyphotrypa* shale interval is overlain by a 15–20 cm

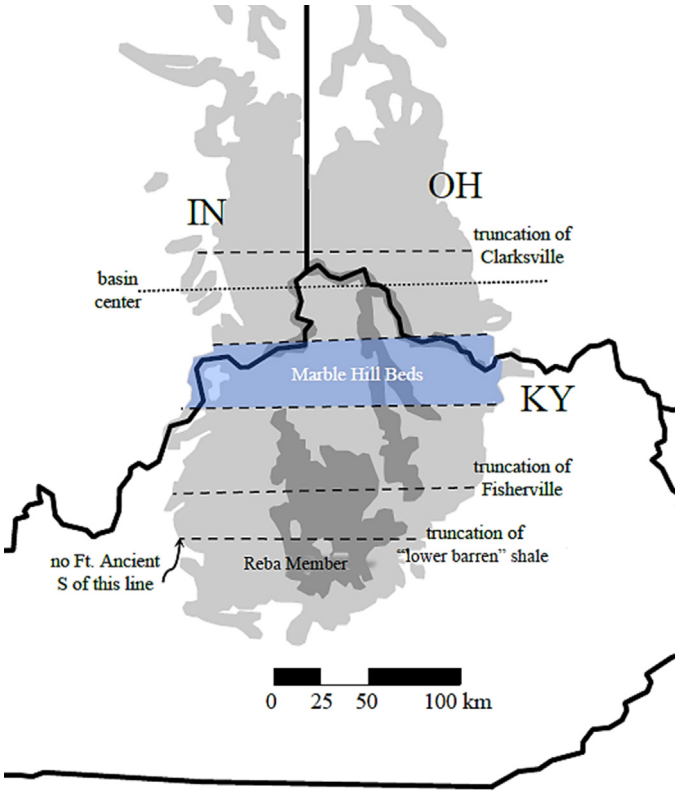


Fig. 8. Paleogeologic, subcrop map extrapolated across the Cincinnati Arch. Cincinnatian outcrop area is shown in pale gray with older Ordovician strata in darker gray. This map shows how units are intercepted and truncated beneath regionally angular unconformity at the base of the upper Rowland Member.

ledge-forming packstone, the upper surface of which is nearly completely covered by *C. clarksvillensis*. This so-called "ball bryozoan bed" forms a prominent local marker (Fig. 6A and D) in these outcrops and has been the subject of detailed taphonomic investigation (Schwalbach et al., 2014). In all of these sections, bryozoans are most commonly attached to bivalves (*Modiolopsis*), which appear as external molds on the flattened basal surfaces of the colonies. This bed is overlain by a poorly exposed slightly dolomitic mudstone interval, rich in the brachiopod *Hebertella* and bryozoans.

This succession is exceptionally well developed in outcrops near I-64 exits 121 and 123 at Owingsville, Kentucky, where it becomes highly fossiliferous and sharply overlies the "*Cyphotrypa* shales" at an apparent sequence boundary (Fig. 6A). The base of the interval, equivalent to the "ball bryozoan bed", is represented by a relatively compact, phosphatic, oncolitic grainstone, rich in *Cyphotrypa*, about twenty to fifty centimeters thick. Locally, this basal bed contains abundant colonial corals, including *Cyathophylloides*, *Tetradium*, and small stromatoporoids. This basal limestone and the overlying one to two meter fossiliferous mudrock and packstone interval is also exceptionally rich in large, robust individuals of the brachiopod *Hebertella occidentalis*, representing a proliferation epibole for this taxon. The upper half of this interval culminates in two thicker beds extremely rich in large, pink stromatoporoids (*Labechia* sp.) and corals (*Cyathophylloides*, *Tetradium*). Although the color of stromatoporoid colonies is not a diagnostic, time-specific feature of this thin interval and pink stromatoporoids are known from other intervals of the greater Cincinnati Arch region, the coloration is nevertheless consistent across the study area and allows these faunal elements to stand out sharply from surrounding matrix sediments. In contrast, most stromatoporoids from the older Sunset Member of the lower part of the Arnheim Formation are typically a brownish color.

Again, as on the west side of the arch, careful mapping starting with the work of Robert Weir (USGS) revealed a pattern of abrupt southward thinning of the Bull Fork Formation (Fig. 7). Our work shows that this results in part from successive southwestward truncation of the *Cyphotrypa* Shale, Fisherville, and basal beds down to a level within the lower Arnheim. This erosion takes place within the length of two quadrangle maps and is analogous to the rapid removal of units between Seatonville and Mount Washington on the west side of the Arch. The underlying *Cyphotrypa* shale interval is removed southwest of Howards Mill; eventually, the "ball bryozoan bed", typically with vuggy stromatoporoids, marking the base of the middle Rowland comes to overlie a thin remnant of the lower Bull Fork Formation, equivalent to the *Leptaena-Rynchotrema* beds of the lower Arnheim Formation, again termed the Reba Member of the Ashlock Formation, southwest of Mount Sterling. Hence, as on the western side of the Cincinnati Arch, the base of the middle Rowland appears to represent a regionally angular unconformity that removes the entire "lower Rowland" succession and several meters of underlying material. Indeed, this is the same unconformity that removes the lower Rowland near Bardstown on the opposite side of the Cincinnati Arch, 150 km to the west.

## 3. Discussion

Despite separation by up to 270 km owing to post-Paleozoic erosional removal, the succession of distinctive epiboles within the so-called "lower Rowland" interval of the western side of the Cincinnati Arch very closely matches that of an interval of the Bull Fork Formation on the eastern side (Figs. 7 and 8). This provides strong evidence that these successions record a correlative interval and preserve a persistent pattern of strata along depositional strike (see also Brett et al., 2007). The underlying causes of widespread epiboles and related time-specific facies remain to be conclusively determined. However, we may make some tentative hypotheses as to their significance.

The Fisherville coral beds record the first appearance of *Cyathophylloides* corals in the Cincinnati Arch region. The occurrence of these taxa and their persistence into higher stratigraphic levels seemingly records the incursion of warm-water fauna from lower latitudes near the beginning of the "Richmondian invasion" (Holland and Patzkowsky, 2007). *Cyathophylloides*, as well as *Tetradium* and stromatoporoids, occur in the putatively equivalent middle Fort Ancient Member of the Waynesville Formation to the north, in Ohio. In this case, the *Cyathophylloides* epibole of the Fisherville bed may be linked to incursion of warm, nutrient-rich waters during a major paleoceanographic event. It is notable that *Cyathophylloides*, *Tetradium*, and small stromatoporoids also first occur in the apparently equivalent Fort Ancient shales in Ohio

(Frey, 1987); hence, this incursion epibole is regional and somewhat facies cross-cutting. Furthermore, the incursion of these coral and sponge taxa is associated with a major late-Katian sea-level highstand and a positive carbon isotope excursion (the Waynesville excursion of Bergström et al., 2010). It is particularly notable that this aspect of the Richmondian invasion in shallow water facies occurs earlier than the incursion of deeper brachiopod, coral, and other taxa in offshore shale-rich facies, which occurs in the overlying Clarksville interval in Ohio and Indiana. Perhaps not surprisingly, the influx of warm water masses affected shallow water areas before deeper portions of the basin, which retained a more typical lower Cincinnatian *Rafinesquina* and dalmanellid-brachiopod dominated fauna through deposition of the Fort Ancient Member.

The association of this coral incursion epibole with rhythmic wackestone-shale facies is analogous to associations of stromatoporoid-*Tetradium* biostromes in several older units; these include the Mt. Auburn and Sunset Members of the Grant Lake Formation and the Stamping Ground and Strodes Creek Members of the Lexington Limestone (Young et al., 2013). In all cases, the depositional system appears to have been poised between two end-members: (1) an organic-rich clay-bottom setting that favored non-calcified algae, and (2) a carbonate mud setting with abundant corals, mollusks, and ostracods. Abundant dasyclads indicate shallow water depths, probably less than fifteen meters, and may also suggest eutrophic conditions (Brett et al., 1993, in press). In addition, the abundance of chert in the immediately underlying beds seemingly reflects an incursion of nutrient-rich waters (Pope, 2004), which may have fostered an abundance of siliceous sponges. Elevated nutrient levels are also supported by the vast accumulations of high-spired gastropods (*Loxoplocus*) in grainstone facies (Marble Hill beds) recording a shallow-water shoal-bar complex (Swadley, 1979) in laterally equivalent sediments to the north.

The proliferation of *Cyphotrypa clarksvillensis* appears to be coupled with this distinctive faunal change. This small, hemispherical bryozoan shows a pattern suggestive of an opportunistic taxon, similar to *Prasopora* (Brett and Brookfield, 1984; Cuffey, 1997), that is well-adapted to muddy, shallow water facies because of its growth form and ability to rapidly colonize locally abundant bivalve shells (Schwalbach et al., 2014). This bryozoan extends into more offshore facies further north, though it is not as abundant.

Regardless of cause, these marker beds provide an excellent framework that permits characterization and high-resolution correlations of a critical, previously unrecognized stratigraphic interval. Further, mapping of these markers (Figs. 7 and 8) provides evidence for a previously unrecognized erosion surface with implications of gentle regional tilting. Progressive southward removal of these persistent marker units along an erosive contact at the sharp base of a distinctive, prominent glauconitic, bioturbated coral-bryozoan bed ("*Skolithos* bed-ball bryozoan bed"), highlights the significance of this surface as a regionally angular unconformity. This "mid-Richmondian unconformity" was predicted by Ross and Ross (2002, 2004), but its exact position and extent remained unclear prior to the recent detailed correlations.

## 4. Conclusions

The Upper Ordovician (Katian: lower Richmondian) of north-central Kentucky records deposition along a gently sloping ramp in the Taconic foreland basin. Although an integrated study of this temporal interval throughout the region has been complicated by uplift and erosion of the Cincinnati Arch and application of a plethora of lithostratigraphic terms, distinctive faunal markers — epiboles — nevertheless serve as important tools for high-resolution correlation. We recognize a consistent succession of epiboles and associated lithologic units (the "lower Rowland succession") that persist from the southeastern Cincinnati Arch to the northwestern Cincinnati Arch, and, in turn, into southwestern Ohio and southeastern Indiana. These faunal markers, which had been largely discounted by many previous workers as local phenomena without biostratigraphic utility, permit recognition of near "layer cake" stratigraphy over a broad geographic area. Further, progressive removal of these persistent units underneath an erosive contact (the base of the "mid-Rowland succession") highlights the significance of this surface as a regionally angular unconformity (Figs. 2 and 7).

Although the exact underlying causes of certain of these epiboles remain to be conclusively determined, some may be linked to incursion of nutrient-rich waters during a major paleoceanographic event, whereas others reflect an opportunistic life strategy and capacity to utilize specific, locally abundant substrata. In a broader sense, this study demonstrates the value of faunal epiboles and associated stratigraphic markers in regional correlation and high-resolution sequence and event stratigraphy; ongoing and future work of a similar nature shows considerable promise for further resolving stratigraphic relationships in the type Cincinnatian.

## Acknowledgments

This research was supported by NSF-EAR 0819820 to CEB and Dry Dredgers Paleontological Research Awards to JRT and CDA. Discussions with Patrick I. McLaughlin (Wisconsin Geological and Natural History Survey), Benjamin F. Dattilo (Indiana University-Purdue University-Fort Wayne), Thomas J. Schramm (Louisiana State University), and Kyle R. Hartshorn (Dry Dredgers) improved the quality of this study. Earlier versions of this article were improved by the constructive reviews provided by Rebecca L. Freeman (University of Kentucky) and Jisuo Jin (University of Western Ontario). This is a contribution to the International Geoscience Programme (IGCP) Project No. 591 — The Early to Middle Paleozoic Revolution.

## References

Allmon, W.D., 1992. Role of temperature and nutrients in extinction of turretelline gastropods: Cenozoic of the northwestern Atlantic and northeastern Pacific. Palaeogeography, Palaeoclimatology, Palaeoecology 92 (1), 41–54.

Aucoin, C.D., Brett, C.E., Dattilo, B., 2014. Evidence for a Mid-Richmondian Unconformity in the Upper Ordovician (Katian) Strata along the Cincinnati Arch, USA. Proceedings of the 4th IGCP 591 Meeting, p. 13.

Beaumont, C., Quinlan, G., Hamilton, J., 1988. Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America. Tectonics 7 (3), 389–416.

Bergström, S.M., Young, S.A., Schmitz, B., 2010. Katian (Upper Ordovician) $\delta^{13}C$ chemostratigraphy and sequence stratigraphy in the United States and Baltoscandia: A regional comparison. Palaeogeography, Palaeoclimatology, Palaeoecology 296 (3–4), 217–234.

Brett, C.E., 2000. A slice of the "layer cake": The paradox of "frosting continuity". Palaios 15 (6), 495–498.

Brett, C.E., Baird, G.C., 1997. Epiboles, outages, and ecological evolutionary bioevents: Taphonomic, ecological, and biogeographic factors. In: Brett, C.E., Baird, G.C. (Eds.), Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications. Columbia University Press, New York, pp. 249–284.

Brett, C.E., Brookfield, M.E., 1984. Morphology, faunas and genesis of Ordovician hardgrounds from southern Ontario, Canada. Palaeogeography, Palaeoclimatology, Palaeoecology 46 (4), 233–290.

Brett, C.E., Goodman, W.M., LoDuca, S.T., 1990. Sequences, cycles, and basin dynamics in the Silurian of the Appalachian Foreland Basin. Sedimentary Geology 69 (3–4), 191–244.

Brett, C.E., Boucot, A.J., Jones, B., 1993. Absolute depths of Silurian benthic assemblages. Lethaia 26 (1), 25–40.

Brett, C.E., Algeo, T.J., McLaughlin, P.I., 2003. Use of event beds and sedimentary cycles in high-resolution stratigraphic correlation of lithologically repetitive successions: The Upper Ordovician Kope Formation of northern Kentucky and southern Ohio. In: Harries, P.J. (Ed.), High-Resolution Approaches in Stratigraphic Paleontology. Springer, New York, pp. 315–350.

Brett, C.E., McLaughlin, P.I., Baird, G.C., 2007. Eo-Ulrichian to Neo-Ulrichian views: The renaissance of "layer cake stratigraphy". Stratigraphy 4 (2–3), 201–215.

Brett, C.E., McLaughlin, P.I., Sullivan, N.B., Thomka, J.R., 2012. Middle Paleozoic sequence stratigraphy and paleontology of the Cincinnati Arch. In: Brett, C.E., Cramer, B.D., Gerke, T.L. (Eds.), Middle Paleozoic Sequence Stratigraphy and Paleontology of the Cincinnati Arch, Part 1: Central Kentucky and Southern Ohio. International Geoscience Programme Project 591 2nd Annual Meeting and 1st Foerste Symposium Field Trip Guidebook, pp. 1–54.

Brett, C.E., Malgieri, T.J., Thomka, J.R., Aucoin, C.D., Dattilo, B.F., Schwalbach, C.E., in press. Calibrating water depths of Ordovician communities: Lithological and ecological controls on depositional gradients in Upper Ordovician strata of southern Ohio and north-central Kentucky, USA. Estonian Journal of Earth Sciences 64 (1).

Brown, R.G., 1964. The coral horizons and stratigraphy of the upper Richmond Group in Kentucky west of the Cincinnati Arch. Journal of Paleontology 38, 385–392.

Butts, C., 1915. Geology and Mineral Resources of Jefferson County, Kentucky. Kentucky Geological Survey, Series 4, Volume 3 (Pt. 2), 270 pp.

Cuffey, R.J., 1997. *Prasopora*-bearing event beds in the Coburn Limestone (Bryozoa; Ordovician; Pennsylvania). In: Brett, C.E., Baird, G.C. (Eds.), Paleontological Events: Stratigraphic, Ecological, and Evolutionary Implications. Columbia University Press, New York, pp. 110–130.

Cuffey, R.J., 1998. An introduction to the type-Cincinnatian. In: Davis, R.A., Cuffey, R.J. (Eds.), Sampling the Layer Cake that Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian. Ohio Division of Geological Survey Guidebook 13, pp. 2–9.

Davis, R.A., Cuffey, R.J., 1998. Sampling the Layer Cake that Isn't: The Stratigraphy and Paleontology of the Type-Cincinnatian. Ohio Division of Geological Survey Guidebook 13, 194 pp.

Elias, R.J., 1983. Middle and Late Ordovician Solitary Rugose Corals of the Cincinnati Arch Region. United States Geological Survey Profession Paper 1066-N, 13 pp.

Ettensohn, F.R., 2008. The Appalachian foreland basin in eastern United States. In: Miall, A.D. (Ed.), The Sedimentary Basins of the United States and Canada. Elsevier, Amsterdam, pp. 105–179.

Foerste, A.F., 1903. The Richmond Group along the western side of the Cincinnati Anticline in Indiana and Kentucky. American Geologist 31 (1), 333–364.

Foerste, A.F., 1912. The Arnheim Formation within the areas traversed by the Cincinnati Geanticline. The Ohio Naturalist 12 (1), 429–453.

Frey, R.C., 1987. The paleoecology of a Late Ordovician shale unit from southwest Ohio and southeastern Indiana. Journal of Paleontology 61 (2), 242–267.

Holland, S.M., Patzkowsky, M.E., 2007. Gradient ecology of a biotic invasion: Biofacies of the type Cincinnatian Series (Upper Ordovician), Cincinnati, Ohio region, USA. Palaios 22 (4), 392–407.

Kepferle, R.C., 1976. Geologic map of the Fisherville quadrangle, north-central Kentucky. United States Geological Survey Geological Quadrangle Map GQ-1321.

Kolata, D.R., Huff, W.D., Bergström, S.M., 2001. The Ordovician Sebree Trough: An oceanic passage to the Midcontinent United States. Geological Society of America Bulletin 113 (8), 1067–1078.

McLaughlin, P.I., Brett, C.E., 2007. Signatures of sea-level rise on the carbonate margin of a Late Ordovician foreland basin: A case study from the Cincinnati Arch, USA. Palaios 22 (3), 245–267.

Pope, M.C., 2004. Cherty carbonate facies of the Montoya Group, southern New Mexico and western Texas and its regional correlatives: A record of Late Ordovician paleoceanography on southern Laurentia. Palaeogeography, Palaeoclimatology, Palaeoecology 210 (2–4), 367–384.

Ross, J.R.P., Ross, C.A., 2002. Bryozoans in Ordovician depositional sequences, Cincinnati Arch region, USA. In: Wyse Jackson, P.N., Buttler, C.J., Spencer Jones, M.E. (Eds.), Bryozoan Studies 2001. A.A. Balkema, Lisse, pp. 261–274.

Ross, J.R.P., Ross, C.A., 2004. Bryozoans and stratigraphy, upper Richmondian (Cincinnatian, Ordovician). In: Moyano, G.H.I., Cancino, J.M., Wyse Jackson, P.N. (Eds.), Bryozoan Studies 2004. Taylor and Francis, London, pp. 245–256.

Schwalbach, C.E., Thomka, J.R., Brett, C.E., Malgieri, T.J., 2014. Reciprocal time-averaging and taphonomic feedback in a composite bivalve-bryozoan concentration from the Upper Ordovician of Kentucky. Geological Society of America, Abstracts with Programs 46 (4), 2.

Swadley, W.C., 1979. The Marble Hill Bed: An Offshore Bar-tidal Channel Complex in the Upper Ordovician Drakes Formation of Kentucky. United States Geological Survey Professional Paper 1126-D, 8 pp.

Weir, G.W., Petersen, W.L., Swadley, W.C., 1984. Lithostratigraphy of Upper Ordovician Strata Exposed in Kentucky. United States Geological Survey Professional Paper 1151-E, 121 pp.

Young, A.L., Reis, A., Brett, C.E., 2013. Sequence stratigraphy and biotic patterns of an unusual interval in the Upper Ordovician Lexington Formation, central Kentucky. Geological Society of America Abstracts with Programs 45 (7), 131.