International Geoscience Programme Project 653 Third Annual Meeting - Athens, Ohio, USA

Field Trip Guidebook

THE CLASSIC UPPER ORDOVICIAN STRATIGRAPHY AND PALEONTOLOGY OF THE EASTERN CINCINNATI ARCH

Carlton E. Brett – Kyle R. Hartshorn – Allison L. Young – Cameron E. Schwalbach – Alycia L. Stigall

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FOREWORD

We are field geologists, first, foremost, and forever. At first glance, this may seem odd, centered as we are in the heartland of America, a region better known for farmland than extensive geological exposures. There are no mountains, badlands, or sea cliffs within many hundreds of kilometers. Yet the continental interior of North America is sheathed in Paleozoic strata ranging from the Cambrian to the Permian and every period in between. In particular, the tri-state area of Ohio, Kentucky, and Indiana is a world-class natural laboratory for Ordovician stratigraphy and paleontology. Thanks to ever-expanding urban development and the generous contributions of taxpayers and civil engineers, the low hills of the countryside are riddled with an astounding array of roadcuts, some fresh, others decades old.

This is our field area. We have spent the better part of twenty years driving the byroads of these states on the hunt for roadcuts new and old, many long days of obsessively measuring the strata and collecting the fossils, often past sunset. This extensive research has helped to usher in a new renaissance in high resolution stratigraphy, building on the strong foundations laid by many generations of geologists past. We couple modern tools such as carbon isotope chemostratigraphy with the concepts of sequence stratigraphy and century-old traditions of macrofossil correlation. But always, always, always we return to the field.

Rocks don't lie; they are only misunderstood. Human abstractions of those same rocks can easily introduce further confusion and opacity. Although useful and necessary, no strat column, measurement log, photograph, 3D model, database, or museum collection will ever replace getting out into the field. One must see the strata in situ, noting how they change (or stay the same) from outcrop to outcrop, identifying patterns in time and space. Only then can one build a robust model and start to make predictions. Then those predictions must be rigorously tested by applying the model to more outcrops and verifying (or falsifying) their validity. *This* brachiopod will appear in *that* bed; *those* limestones will transition into *that* shale; phosphate will be found at *that* horizon. The raw data are in the field; it is up to us to interpret it.

This guidebook and its accompanying field trips will provide a brief but extensive overview of the Upper Ordovician stratigraphy and paleontology of Kentucky, the epicenter of the Ordovician outcrop belt in the eastern midcontinent. They are a contribution to International Geoscience Programme (IGCP) 653 ("The onset of the Great Ordovician Biodiversification Event"), prepared for the IGCP 653 Third Annual Meeting, hosted in Athens, Ohio. While a full examination of these rocks requires a lifetime of fieldwork, the highlights can be distilled into a few days and a couple hundred kilometers of travel. Localities will include strata ranging from the upper Sandbian to the Lower Silurian (Rhuddanian-Aeronian), a composite section spanning about 10 million years. There is no shortage of outcrops, so we have chosen those that enable us to tell the most interesting stories as we interpret the rock record and review the local faunas. Where possible, we have attempted to organize stops in a stratigraphic order, oldest to youngest. However, to our deep and inexpressible shame, the cruel limitations of time and geography have forced us to put the younger (Cincinnatian) strata first and the older (Mohawkian) strata second.

The following text incorporates updated content based on several previous field trip guides. Firstly, we fondly refer back to a volume published a decade ago by the Cincinnati Museum Center: "Stratigraphic Renaissance in the Cincinnati Arch: Implications for Upper Ordovician Paleontology and Paleoecology" (McLaughlin et al., 2008b, especially McLaughlin et al., 2008a and Brett et al., 2008b therein). Secondly, we draw upon the guidebooks produced for the 2012 annual meeting of the International Geoscience Programme 591 ("The Early to Middle Paleozoic Revolution"; ancestor of IGCP 653), held in Cincinnati, Ohio and featuring two field trips focused on the Ordovician and Silurian of the Cincinnati Arch, one to the west side (Indiana and Kentucky; Brett et al., 2012b) and another on the east (Ohio and Kentucky; Brett et al., 2012c). Finally, we include material created for a series of field trips put together for a 2016 Cincinnati "mini conference" organized by the FOSSIL Project (Hartshorn et al., 2016), a National Science Foundation (NSF) funded project to bring together professional and amateur/avocational paleontologists for the benefit of both groups. We have synthesized these field trips into two new ones (mid and post meeting), revising the itinerary, updating the text with new findings, correcting embarrassing old mistakes, adding embarrassing new mistakes, and generally retargeting the guide for the interests of the IGCP 653 audience.

Welcome to the Cincinnati Arch.

INTRODUCTION

The Cincinnati Arch

The Cincinnati Arch is a large-scale structural upwarping which runs north-northeast from Tennessee up to northern Ohio, there splitting into the Kankakee Arch to the west and the Findlay Arch to the east (Figure 1C). The Arch is important regional feature, dividing the Illinois Basin on the west from the Appalachian Basin on the east. The current Cincinnati Arch (i.e. the Cincinnati Arch *sensu stricto*) is an eroded forebulge of Carboniferous or Permian age, a result of the Alleghenian orogeny. However, the Arch has a long and complex geological history, with possible antecedents in the Ordovician (Pope et al., 2009), and a more definite origin in the Middle to Late Paleozoic in the Acadian and Alleghenian orogenic events.

Hundreds of millions of years of erosion have beveled off the upper strata of the Arch, revealing a stratigraphic section of Ordovician through Pennsylvanian rock that represents a timespan of about 150 million years. The oldest rock, Late Ordovician in age (Sandbian - Katian; approximately 455 to 445 million years old), is exposed in the center of the Arch, located within (and responsible for) the Bluegrass physiographic region of central Kentucky. The primary Ordovician outcrop region of Kentucky ranges from Mount Washington on the west to Hillsboro on the east and from Covington in the north (just south of Cincinnati, Ohio) to Stanford in the south. The outer "belt" of this region exposes the Cincinnatian (mid to late Katian), whereas older Mohawkian strata crop out in a more limited region in the middle, forming the carbonate-dominate succession that gives rise to the so called Inner Bluegrass Region. This area, characterized by a pitted karst plain with gently rolling fields and lush grazing pastures including the nominal grass, *Poa*. The fertile soils of this region owe their existence to weathering of phosphate rich limestones of the Lexington Formation (giving rise to its typical name, the Lexington Limestone). These rocks are well exposed in the cliffs along the deeply entrenched Kentucky River and its tributaries near the cities of Lexington and Frankfort, the capital of Kentucky.

This region is encircled by progressively younger strata: Silurian, Devonian, Mississippian, and Pennsylvanian. However, the succession is discontinuous, with numerous unconformities of varying durations. Most relevantly, the Ordovician-Silurian boundary is represented by the Cherokee unconformity, with the uppermost Katian and entire Hirnantian Stage missing. These unconformities may also "telescope" onto one another. For example, in southern Kentucky one may find Upper Devonian black shales resting directly on Upper Ordovician dolosiltites, with the Silurian cut out entirely (or not deposited in the first place). Astoundingly, the combined intervals of these gaps represent more time than the rock itself.

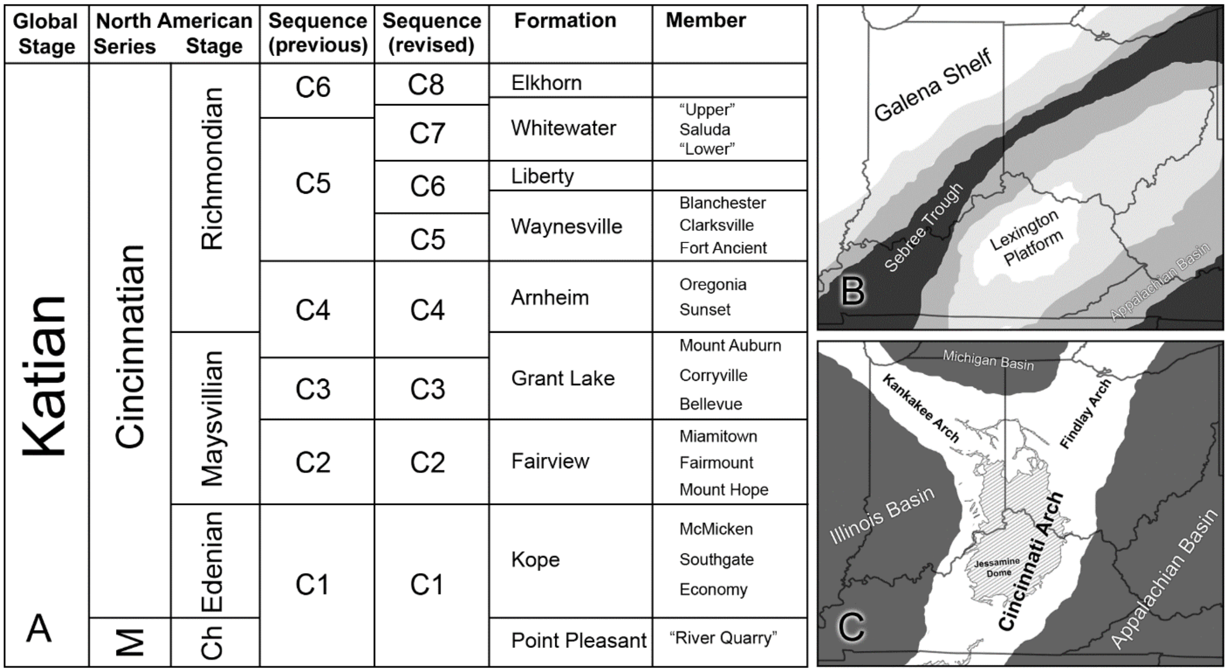

Figure 1. *A, generalized stratigraphic column showing the litho- and sequence stratigraphy of the Cincinnatian Series (Ohio style nomenclature); B, map showing the rough paleogeography of the Cincinnati depositional area during the Late Ordovician; C, map showing the present-day position of the Cincinnati, Kankakee, and Findlay Arches, as well as the Illinois, Michigan, and Appalachian Basins, and the Jessamine Dome; the crosshatched region in the center represents the Ordovician outcrop area. (Modified from Hartshorn et al., 2016, figure 1.)*

Historical Study

The Ordovician geology of the Cincinnati Arch region has been studied for over 150 years, in no small part due to the abundance of fossils weathering out of the local limestones and shales. The term "Cincinnati Group" was first introduced by Meek and Worthen (1865), later becoming the "Cincinnatian Series" (Clarke and Schuchert, 1899; Nickles, 1902; Wilmarth, 1925), a North American chronostratigraphic term still in use today.

Few of the early students of Cincinnatian fossils and strata were professional geologists. Rather, like many 19th century naturalists, they were dedicated amateurs, pursuing a passion for geology on the side. Admirably, they presented their detailed findings in local self-published journals, such as the Journal of the Cincinnati Society of Natural History, the Cincinnati Quarterly Journal of Science, or The Paleontologist. These early publications are a treasure trove of geological information and are still useful today. The individuals responsible would come to be informally known as the "Cincinnati School of Paleontology". The local hill quarries and stream cuts would forge many a budding paleontologist, some of whom would later go on to illustrious careers, including Ray S. Bassler, August F. Foerste, John M. Nickles, Charles Schuchert, and Edward O. Ulrich. See Meyer and Davis (2009) for an extensive review of Cincinnatian paleontologists and their stories. A great deal of new study of sequence stratigraphy, paleontology and evolutionary paleoecology has been carried out since the mid-1900s especially since the 1980s, which has brought about a renaissance in understanding of the strata, basin dynamics and faunas; this research is summarized in sections below.

This tradition of the publishing amateur continues today. The Dry Dredgers, an association of amateur geologists and fossil collectors, work closely with the Department of Geology at the University of Cincinnati (UC). The organization was founded in 1942 with the aid of UC geology professor Kenneth Caster; it is the oldest continuously operating group of its kind in the United States. Dry Dredgers have a strong tradition of volunteering at museums, donating specimens, participating in conferences, assisting in field work, and co-authoring publications. Similarly, the Kentucky Paleontological Society (KPS) of Lexington, Kentucky has a good relationship with the University of Kentucky and researchers at the Kentucky Geological Survey

Research continued throughout the 20th century, with varying degrees of intensity. The modern epoch of Cincinnatian study began in the 1990s with a resurgence in the interest in the paleontology and stratigraphy of the region. These contributions were largely led by "local" researchers, particularly the faculty and students working out of the University of Cincinnati (Benjamin F. Dattilo, Warren D. Huff, David L. Meyer, Arnold I. Miller, and many others, including some of the present authors), the University of Chicago (especially Steven M. Holland and Mark E. Patzkowksy), and other midwestern institutions. Another pulse of interest came in the past two decades, with an onslaught of new chemostratigraphic research by Stig M. Bergström, Matthew R. Saltzman, Seth A. Young, and colleagues, more cohorts of University of Cincinnati graduate students (e.g., Patrick I. McLaughlin), and the establishment of the Stigall Lab at Ohio University (Alycia L. Stigall and students). The work of these researchers, heavily cited below, is of critical importance to the understanding of the Late Ordovician earth system, not only in the Cincinnati Arch region but also globally.

Late Ordovician Tectonic and Paleoenvironmental Setting

The strata of the Cincinnati area were deposited about 455 to 445 million years ago, during the Sandbian to Katian Age of the Late Ordovician Period. In North America, this interval is also called the Cincinnatian Epoch, named for the deposits in this very region. At time of deposition, a shallow epicontinental sea covered much of the paleocontinent Laurentia (the core of modern North America). What is now the Cincinnati region was situated south of the equator, in the southern subtropics, with a warm, semi-arid climate comparable to the modern Bahamas (Figure 2). As in modern subtropical seas, the waters teemed with life, and innumerable shelly organisms lived and died to form the limestones that make up much of the bedrock. The Mohawkian and Cincinnatian record the final phase of the Great Ordovician Biodiversification Event (GOBE), an episode in the history of life that saw widespread diversification and evolution of marine organisms.

During the Middle and Late Ordovician, the southeastern margin of Laurentia (some 400 km distant from the Cincinnati region, at closest) was being subducted beneath an overthrust accreted wedge of deep ocean sedimentary and igneous rocks as a result of collisions with a series of island arcs or microcontinent slivers (Rowley and Kidd, 1981; Stanley and Ratcliff, 1985; Bradley and Kidd, 1991). This mountain building event, the Taconian (or Taconic) Orogeny, consisted of at least two and probably three tectophases (Ettensohn, 1992; Ettensohn and Brett, 1998) that lasted through the end of the Ordovician and likely into the Silurian (Ettensohn and Brett, 2002).

The Middle Ordovician Blountian phase primarily affected areas in the present southern Appalachians and had little effect on the Cincinnati region, which remained a carbonate platform with little topographic relief throughout late Sandbian (Turinian) time (Cressman, 1973; Cressman and Noger, 1976; Keith, 1988; Kolata et al., 2001; Ettensohn et al., 2002; Brett et al., 2004).

The second (Taconic) tectophase commenced in the late Sandbian to early Katian (Chatfieldian; about 453 million years ago), heralded by a series of huge volcanic eruptions (Huff et al., 1992). The fallout from these eruptions is preserved as lithified ash beds: K-bentonites. These tuff deposits are critical time markers that may be traced for thousands of square kilometers. Moreover, some contain minerals such as zircons with traces of uranium that may be analyzed to provide absolute dates using U/Pb radioactive decay parent/daughter ratios. A pair of widespread and well-studied K-bentonites, the Deicke and Millbrig, are roughly coincident with the North American Turinian-Chatfieldian stage boundary, providing excellent age constraints (Sell et al., 2015).

This increased volcanic activity may have been associated with reversal of subduction in the Taconic orogeny from eastward dipping subduction of the Laurentian plate beneath a Taconic or Shelburn Falls Arc in present day Vermont, to westward Andean style subduction forming the Bronson Hill magmatic arc outboard of the Taconic arc in present day central New England. This event also transformed the Taconic from a peripheral to retroarc foreland basin coincident with broad lateral migration of Utica black shale facies (Indian Castle Formation in New York State) to the continental interior and Sebree Trough (Point Pleasant-upper Utica and Kope and Clays Ferry Formations of Ohio and Kentucky, respectively).

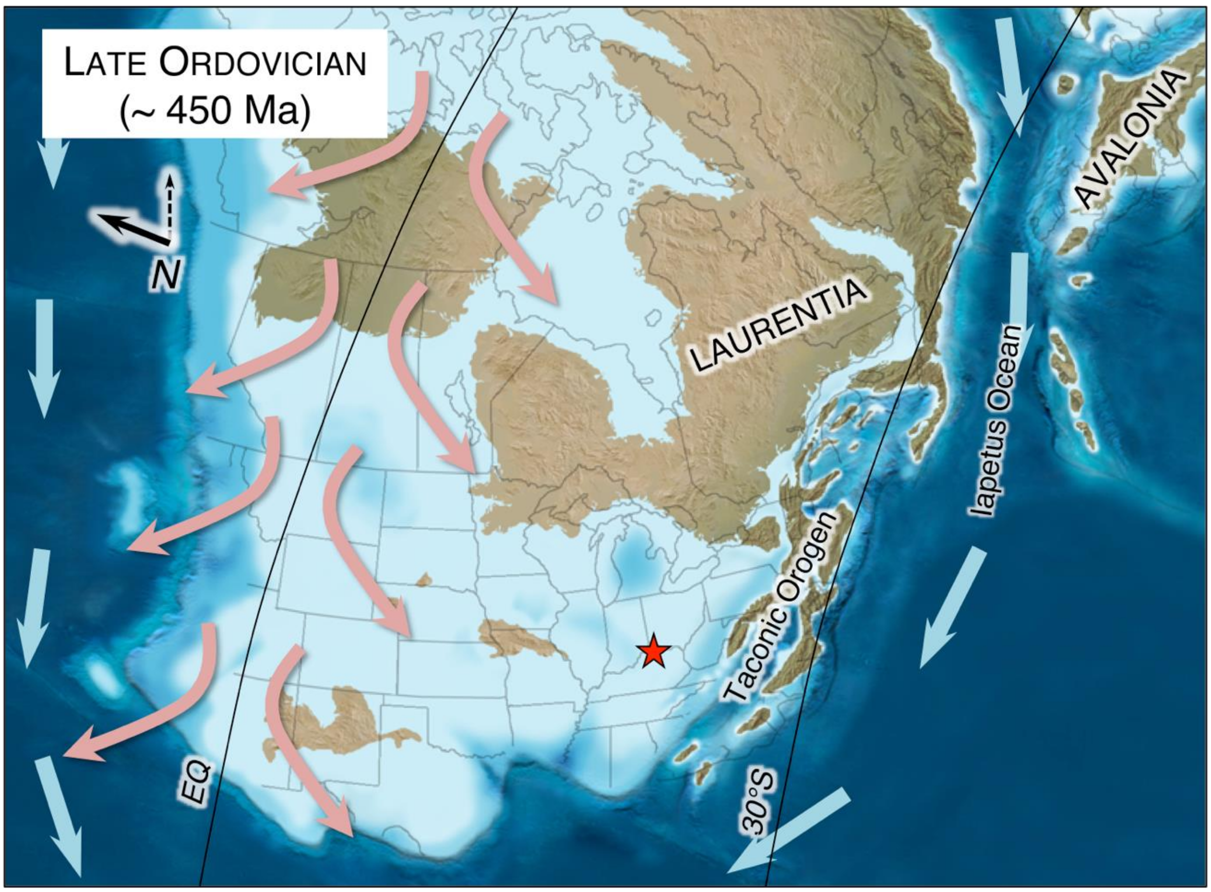

Figure 2*. Paleogeographic map of Laurentia during the Late Ordovician. Approximate borders of present-day US states shown in gray lines. Pink arrows indicate storm tracks. Blue arrows indicate ocean currents. Red star indicates position of the Cincinnati Arch region. Solid black arrow indicates paleomagnetic North, dashed black arrow indicates present-day North (modified from Ron Blakey, NAU Geology).*

A major lithologic change occurs just above this contact: micritic facies, which typify much of the Mohawkian up to this point, change abruptly to mixed skeletal limestones and shale, a motif that endures throughout the remainder of the Ordovician. This shift in lithology has been attributed to a switch from tropical- to temperate-style carbonate production, induced by increased differentiation of the carbonate platform into a series of basins and arches (resulting in increased upwelling), increased turbidity, and sea level rise (Holland and Patzkowsky, 1996; Pope and Read, 1997). Regional studies (Cressman, 1973; McLaughlin et al., 2004; Brett et al., 2004) provide strong evidence for widespread probably eustatic cycles of relative sea level rise and fall. Facies mapping within individual Chatfieldian-Edenian unconformity-bounded depositional sequences throughout broad portions of eastern North America suggest the presence of a peripheral foreland basin on the southern margin of Laurentia, but otherwise little differentiation of the craton during early Chatfieldian time.

Throughout the remaining Chatfieldian, differential subsidence and uplift owing to stresses in the Laurentian crust occurred in areas defined by older basement faults (Black and Haney, 1975), resulting in development of a number of related topographic depressions and swells. One such feature was the Sebree Trough, a narrow southwest-northeast oriented basin that extended from modern day western Tennessee to western Pennsylvania (Figure 1C; Kolata et al., 2001; Ettensohn et al., 2002), where it eventually connected with the Taconic foreland basin during Edenian time (McLaughlin et al., 2004). Passing just to the northwest of present-day city of Cincinnati, the Sebree Trough probably resulted from subsidence along deep basement faults associated with the ancient Reelfoot Rift, which appears to have been reactivated by far field stresses from the Taconic Orogeny (Ettensohn, 1991; 2008).

The Sebree Trough remained prominent into the early Cincinnatian (middle Katian) during the deposition of the Kope Formation. Edenian rock shows a strong facies change from shallow mixed carbonate pack- and grainstones and siliciclastics typically assigned to the upper Clays Ferry Formation in the Jessamine Dome area to typical shale/mudstone dominated Kope Formation of the Cincinnati region, to dark shales commonly referred to as “Utica Shale” some 50 kilometers (30 miles) northwest of Cincinnati. However, the Trough appears to have become largely infilled during the Edenian such that facies of the upper Kope and Fairview Formations are more uniform from south to north, although the pattern of increasing shale content to the north persists through the Maysvillian Stage (Katian, Ka2), suggesting a continued gentle depression to the north-northwest.

For much of the Early and Middle Ordovician, tidal flats, shallow lagoons, and carbonate shoals stretched for thousands of square kilometers across the continent: the majestic Great American Carbonate Bank. Not particularly fossiliferous, these massive, micritic limestones form the upper part of the Knox Group of Tennessee and equivalent parts of the Beekmantown Group in Virginia, Maryland, Pennsylvania, and New York. On the Cincinnati Arch, these units are only found in the subsurface, though the lower Upper Ordovician (Sandbian) High Bridge Group records a relatively similar tropical carbonate bank environment. As the Late Ordovician progressed, increasing volumes of mud and silt were exported from the Taconic Mountains to the southeast. The Cincinnatian strata show an intriguing mix of these extrabasinal sediments mixed with "homegrown" carbonates. The interplay of these two systems is manifested in numerous meter-scale and larger cycles that may record the sedimentary response to sea level oscillations.

Late phases of erosion in the Taconian orogen produced the extensive Juniata-Queenston deltaic wedge over much of eastern Laurentia, overfilling the foreland basin. This reddish marginal marine to non-marine strata extended as far west as eastern Ohio and Kentucky, where it is known as the Preachersville Member of the Drakes Formation (upper Richmondian, apparently equivalent to the Liberty, Whitewater, and

Elkhorn Formations of traditional Ohio usage). This voluminous sediment supply, coupled with the global sea level drawdown resulting from the major Hirnantian glaciation events, meant that parts of the Cincinnati region were almost certainly dry land by the end of the Ordovician. However, this emergence did not last more than a few million years, and the area returned to normal marine conditions along with rising sea levels during the Early Silurian (Llandovery, Rhuddanian), as recorded by the crinoidal grainstones of the Brassfield Formation.

STRATIGRAPHIC OVERVIEW

The Upper Ordovician strata exposed on Cincinnati Arch comprise a wide range of carbonate litho- and biofacies. Below we briefly address the facies, fossils, depositional environments, and stratigraphy of the High Bridge Group, Lexington Limestone, and particularly the "Cincinnati Group". This strata comprises the Mohawkian and Cincinnatian of this region. Note that while older publications often refer to the Mohawkian as "Middle Ordovician", advances in global correlation in recent decades have shown that it is indeed Late Ordovician (Sandbian-Katian).

Much of the original work done on the local Ordovician used faunal occurrences to define rock units (see, e.g., Nickles, 1902). However, work in the later 20th century, particularly by the United States Geological Survey and state geological surveys, shifted over to a paradigm of lithostratigraphy, characterizing units based on their primary rock constituents (e.g., shale versus limestone, etc.). However, this latter practice has its own issues, as the region's wide variety of depositional environments and diverse lithofacies have resulted in a proliferation of different but time-equivalent stratigraphic nomenclatures, obfuscating lateral relationships and hindering correlation. Additional complications are introduced by the differing philosophies and practices of three independent state geological surveys. Thus, the nomenclature of Ohio, Indiana, and Kentucky differ from each other to various degrees, and the nomenclature of northern Kentucky is markedly different from that in central and southern Kentucky. Most Cincinnatian units have at least two, and typically three or four names, as well as historical variations and recombinations.

This arcane nomenclature can be quite confusing to the uninitiated and a full treatment of this subject could fill entire reports (and has; see, e.g., Wiess and Norman, 1960; Tobin, 1982). Herein, we attempt to use a synthesized terminology largely based on the traditional unit names, but with reference to newer and other nomenclatures. Extensive field study has shown that the boundaries of traditional, faunally-defined units often closely approximate lithological changes that can be used to delimit modern lithostratigraphic units and we feel that the preservation of older names, properly redefined and modernized, is preferable to the introduction of yet another slate of mostly-equivalent-but-new names. However, we also recognize that some newer names are so commonplace that they should be used regardless of historical preference. For example, we use the Grant Lake Formation instead of its older but less well-defined equivalent, the McMillan Formation. At the same time, we reapply the members of the McMillan—Bellevue, Corryville, and Mount Auburn—as members of the Grant Lake. We also promote the introduction of named subunits (members, submembers, beds) for laterally extensive stratal packages that may aid in high resolution correlation (decameter scale, sometimes even down to meter scale).

General Model of Sequence Stratigraphy

The arrival or extinction/extirpation of fauna noted by older workers was often coincident with relative sea level changes that are the basis for sequence stratigraphy, an extremely useful model that interprets sedimentation patterns in the context of (often cyclic) relative sea level rise and fall. See Catuneaunu (2016), Coe (2003), Embry (2009), Galloway (1989), Sloss (1963), and Vail et al. (1977a,b,c) for background on this stratigraphic paradigm. The principles of sequence stratigraphy have been applied to the Upper Ordovician strata of the Cincinnati region by a number of workers, especially Holland (1993), Holland and Patzkowsky (1996, etc.), and Ross and Ross (2001, 2002). More recently, Brett et al. (2003, 2004, 2012, 2015, 2016), McLaughlin et al. (2004a,b; 2008b and several papers therein) and Aucoin and Brett (2016). These studies are leading to a new synthesis and better understanding of regional and perhaps global patterns of sea level and climate change as well as syndepositional tectonics.

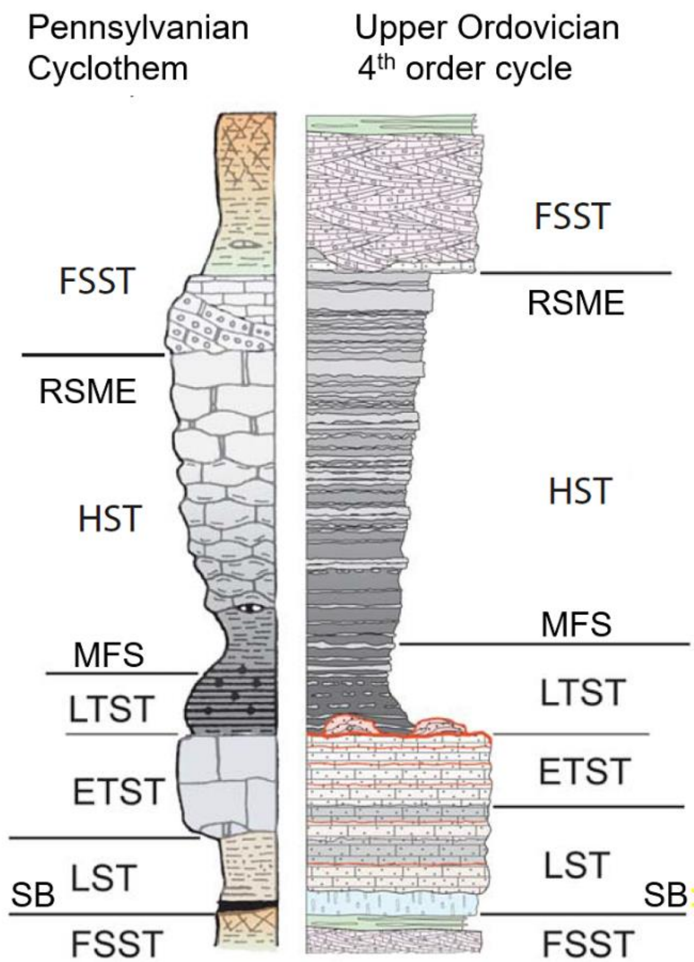

Figure 3. *Comparison of an idealized sequence of a mid-continent Pennsylvanian cyclothem versus a typical Upper Ordovician 4th order cycle, showing many analogous aspects of the systems tracts. Acronyms: ETST: early transgressive systems tract, FSST: falling stage systems tract; HST: highstand systems tract; LST: lowstand systems tract; LTST: late transgressive systems tract; MFS: maximum flooding surface; RSME: regressive surface of marine erosion. Modified after McLaughlin et al. (2008).*

Sequence stratigraphy allows predictions based on the recognition of distinct "surfaces" that separate the rock record into depositional *sequences*, each starting with a basal unconformity (or its correlative conformity in deep water) known as a *sequence boundary*, from which relative sea level rises, forming a *transgressive systems tract* (TST) deposit until it reaches its maximum extent, recorded in the strata as a *maximum flooding surface* (or maximum flooding zone). From there, sea level holds steady to produce a *highstand systems tract* (HST) until it undergoes a period of regression, or relative sea level fall, which produces erosion during a *falling stage systems tract* (FSST) and the cycle begins anew with another unconformity/sequence boundary. These sequences are fractal in nature, with many self-similar sequences of varying orders of magnitude repeated throughout the rock record (e.g. a small-scale transgression may occur within a more prominent, longer-lasting highstand). Figure 3 compares the surfaces and systems tracts of a typical Ordovician sequence with those of an idealized midcontinent cyclothem.

In the Ordovician Appalachian Basin and its neighboring depositional regions, sea level rise resulted in the siliciclastic sediments from the Taconian orogeny becoming sequestered closer to their source, in rivers and estuaries to the (modern) east and southeast, far from the Cincinnati region. Consequently, transgressive deposits are often limestone-rich, condensed units that typically lack large amounts of siliciclastic sediments (they are clastic starved or "clean"), with mineralized (pyritic or phosphatic) hardgrounds at their major flooding surfaces. In contrast, units that represent highstands are usually very shale rich, formed as sea level stabilized and an offshore sediment transport regime returned. Falling stage deposits are not always evident, as they are sometimes truncated by the overlying sequence boundary, but where present they often contain large amounts of silt and coarser particles, sometimes deposited in channel fill structures.

Although not universally applicable, this sequence stratigraphic model has great predictive power within the Cincinnati Arch region, for paleontology as well as stratigraphy. Within the contexts of the sequence stratigraphic model, there are predictive patterns of distribution of fossils and their preservation (Brett, 1995). For example, flooding surface hardgrounds may contain encrusting organisms such as crinoids and edrioasteroids; conversely, the shaly highstands can preserve smothered, fully articulated fossils such as trilobites and crinoids (e.g., Aucoin and Brett, 2016), and silty falling stage deposits may contain well preserved trace fossils (as in the Taylor Mill submember at the top of the Kope Formation).

Sequence Nomenclature

This guidebook follows the Upper Ordovician depositional sequence nomenclature established by Steven Holland and Mark Patzkowsky (e.g., Holland, 1993; Holland and Patzkowsky, 1996), with numbered 3rd order sequences prefixed with a letter to indicate their regional stage (i.e. Mohawkian sequences prefixed with "M" and Cincinnatian sequences prefixed with "C"). However, our usage differs from this tradition in several key regards.

Firstly, based on two decades of field study, we have revised the position of several sequence boundaries and introduced others, splitting existing sequences into two or more new sequences that are then renumbered as appropriate. For example, we have split the former C5 into three new sequences, C5 (revised), C6 (revised), and C7 (new). In turn, the former C6 has been renamed C8. We readily admit that this has the potential to introduce confusion, as it requires readers to be aware of which version of nomenclature that an author is using. However, this situation is no different from that of other stratigraphic units (as noted herein, the boundaries and names of many formations have been revised and re-revised many times over the years). In addition, this sequence splitting process has precedent, as Holland and Patzkowsky (1996) themselves split their original five sequences into six in much the same fashion.

Secondly, we have introduced a 4th order sequence nomenclature, subordinate to the 3rd order sequences, using letter suffixes: A for the first (i.e. oldest) 4th order sequence within a 3rd order sequence, B for the next, and so on. For example, we use C5A for the basal subsequence of the C5 sequence. Preliminary but not entirely identical versions of this usage were put forward by Aucoin and Brett (2016) and Hartshorn et al. (2016). This letter-based subsequence nomenclature has also been applied to Mohawkian strata (e.g., McLaughlin et al., 2004).

See Figures 4 and 12 for diagrams of our revised interpretations of Mohawkian and Cincinnatian sequence stratigraphy (respectively). As always, these interpretations are subject to revision based on fresh rocks, fresh data, and fresh eyes. We are eager to hear what conference and field trip attendees will have to say once they have seen these strata firsthand.

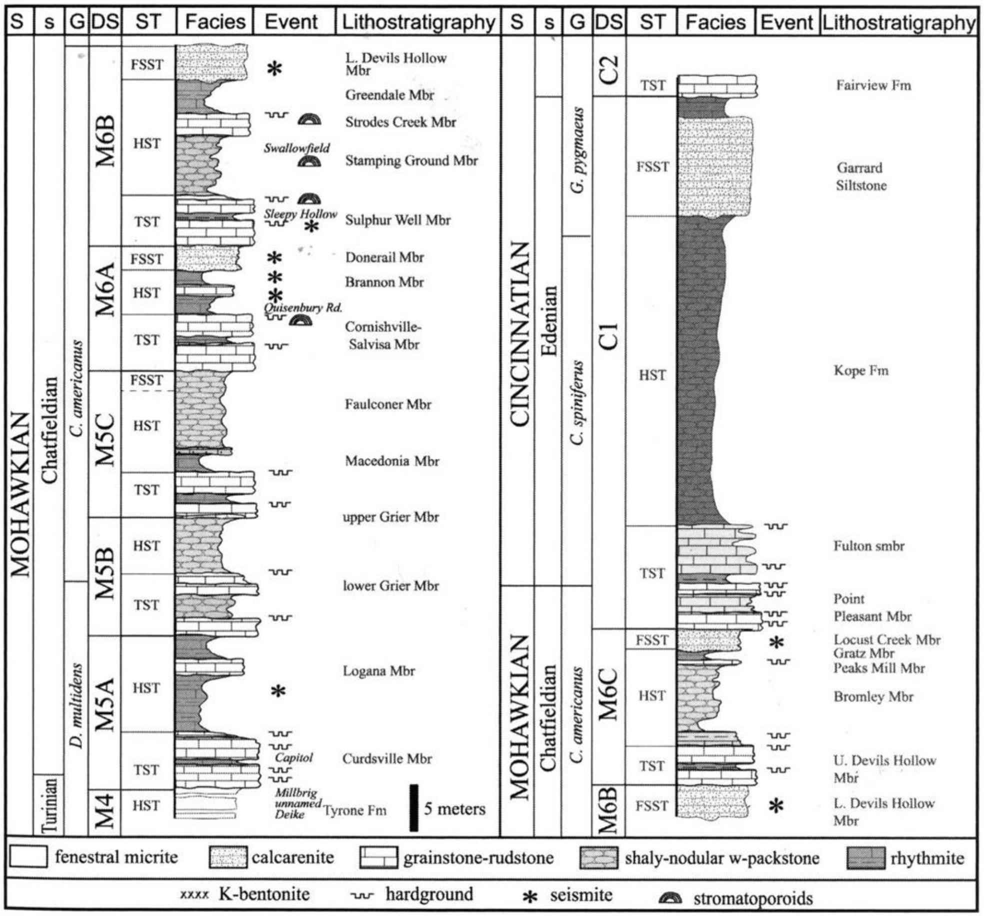

Figure 4. *Generalized litho- and sequence stratigraphic terminology for the Mohawkian to lower Cincinnatian strata of Cincinnati Arch. From McLaughlin et al. (2008).*

The Mohawkian Series

Named for exposures in the Mohawk River valley of New York, the Mohawkian Series represents the lower Upper Ordovician of North America. Long considered Middle Ordovician, the Mohawkian is now recognized to include only Sandbian and lower Katian strata, and thus is purely Upper Ordovician. Holland and Patzkowsky (1996) subdivided the Mohawkian into six 3rd order depositional sequences (M1 to M6), which we follow herein. The Mohawkian comprises lower (Turinian) and upper (Chatfieldian) stages, split at the Millbrig K-bentonite (typically near the M4-M5 sequence boundary).

Sequences M1? - M3: Camp Nelson Formation and Oregon Formation

The oldest rocks exposed on the Cincinnati Arch, middle to upper Sandbian (Mohawkian, Turinian) in age, crop out around the Jessamine Dome in central Kentucky and belong to the High Bridge Group. The Camp Nelson and Oregon Formations are a succession of massive limestones is known from outcrops around the Kentucky River, including the picturesque "Palisades of the Kentucky River" south of Lexington, where limestone cliffs tower over 60 meters (~200 feet) above the river below. The unit is also "exposed" in cement mines around the Ohio River area. The High Bridge Group is assigned to the North American Turinian Stage (Blackriverian of older usage) and corresponds to the upper Sandbian Stage. The age of the lower Camp Nelson is poorly constrained and may comprise M1 or M2 strata.

Sequence M4: Tyrone Formation

The Tyrone Formation, the upper unit of the High Bridge Group, consists of about 25 to 30 meters of strongly micritic limestones, commonly with fenestral fabrics and their accompanying "birdseye" features. The basal portion comprises fossiliferous wackestones with abundant fossils including, *Tetradium*, leperditians, and gastropods. The Tyrone represents sequence M4 of Holland and Patzkowsky (1996), but as with other successions it is probably divisible into smaller scale subsequences.

The Tyrone is also notable for its K-bentonite beds, perhaps as many as 19 or 20 (Conkin and Conkin, 1983), including two of the most widespread ash beds in the geologic record, the Deicke and Millbrig K-bentonites (Kolata et al., 1996). The latter is typically at or near the top of the Tyrone, though locally removed by erosion at the M4-M5 sequence boundary below the base of the Curdsville Member of the Lexington Limestone. This critical K-bentonite has been used to establish the base of the Chatfieldian Stage and U/Pb radiometric dating of its zircons indicates an age of 453 to 454 million years old (Huff et al., 1992). Refined apatite trace-element dating by Sell et al. (2015) revised this range to 452.86 +/- 0.29 Ma.

The M4-M5 Sequence Boundary: Base of the Lexington Formation

The latest Sandbian to early Katian age Lexington Formation (Lexington Limestone) rests upon a major regional unconformity, which separates it from the underlying Tyrone Formation (Figure 5). This sharp, slightly wavy surface demonstrably cuts out several meters of the upper Tyrone (Cressman and Noger, 1976), locally removing the Millbrig K-bentonite.

Above, the Lexington consists of about 100 m of fossiliferous, gray nodular limestones, massive cross-bedded grainstones, and a few distinctive intervals of dark shales and calcisiltites. It is divided into over a dozen members, two 3rd order sequences (M5 and M6), and approximately six 4th order sequences (M5A, M5B, M5C, M6A, M6B, M6C), each consisting of a lower interval of clean carbonates (often light weathering grainstones) overlain by a package of more argillaceous strata (nodular packstones and shales). See Figure 4 for a complete breakdown of the Lexington sequences and rough lithostratigraphy.

Figure 5. *The M4-M5 sequence boundary (at pen). The pale, fenestral micrite of the upper Tyrone Formation is sharply overlain by the darker gray skeletal grainstones of the Curdsville member of lower Lexington Limestone. US Highway 127 north of the junction with US Highway 421, north of Frankfort, Kentucky ("Frankfort North").*

Sequence M5A: Curdsville and Logana Members of the Lexington Limestone

The Curdsville Member comprises coarse crinoidal limestone at the base of the Lexington Limestone (Figures 4, 5, 6). It contains multiple hardground surfaces with a diverse and well-preserved echinoderm fauna (see Sumrall and Deline, 2009), trilobites, and, locally, the large and unusual hexactinellid sponge *Brachiospongia*. A shaly, bentonitic zone known as the Capitol Bed (named for exposures near the Kentucky state capitol in Frankfort) is present around the middle of the unit. The upper contact of the Curdsville is marked by about a meter of densely packed dalmanellid brachiopods (*Heterorthina*) overlain by the shales and thin, chalky weathering, rhythmically bedded calcisiltites and thin dalmanellid shell beds of the Logana Member. The regional distribution of these facies suggests a widespread deepening event. This pair of units is roughly coincident with the boundary between the international Sandbian and Katian Stages. The interval is closely associated with a major positive isotope excursion, regarded by Bergström *et al.* (2010) as the lower portion of the well-known Guttenberg isotopic carbon excursion or GICE. Herein we term this peak the Logana Excursion, as it appears to be well separated from a younger, somewhat lesser peak or series of peaks of δ13C in the Grier (the Macedonia Excursion; see below). The precise correlation of the basal-Katian carbon isotope excursions on the Cincinnati Arch to the type GICE is still under study.

Sequence M5B: Grier Member of the Lexington Limestone (in part)

The Grier Member consists of a thick interval of packstones and calcarenites (Figures 4, 6). The lower Grier is a brachiopod-rich, grainstone-dominated interval that lies disconformably upon the upper Logana. This unit is sharply overlain by the middle Grier, an interval of shaly nodular *Prasopora*-rich packstones that exhibits well developed small-scale cyclicity. A distinctive occurrence of large, round crinoid columnals (*Archaeocrinus* sp?) may be found in the Grier approximately 3 to 5 m below the overlying Macedonia (Cressman, 1973). Intriguingly, this epibole is at almost precisely the same stratigraphic position as the so-called “crinoid beds” of the upper Kirkfield Formation (or upper Bobcaygeon Formation) near Lake Simcoe in Ontario. This zone, also assigned to sequence M5B, is about 3 to 5 m below a positive kick in the carbon isotope signature that may represent the Macedonia Excursion (Paton, 2017). Similar occurrences of these *Archaeocrinus* columnals may be found in the Lexington-equivalent “Trenton Limestone” (for lack of a better term) exposed near Tazewell, Tennessee.

Sequence M5C: Upper Grier and Macedonia Member of the Lexington Limestone

The upper Grier is dominated by skeletal grainstone facies and sharply overlain by the shales and calcisiltites of the Macedonia Member (or Macedonia Bed) at a mineralized hardground interpreted as a sediment starved surface. The Macedonia often contains large, gumdrop-shaped *Prasopora* bryozoan colonies. This shaly zone and the immediately underlying grainstones show a distinctive series of positive C isotopic peaks (Bergström et al., 2010) termed the Macedonia Excursion by Young et al. (2016).

The Macedonia shaly interval is overlain by a variable package of fossiliferous, *Prasopora* bearing pack and grainstones and nodular beds commonly very rich in the brachiopod *Rhynchotrema increbescens*. These beds in part have been referred to the lower or Faulconer submember of the Perryville Member. We interpret the Faulconer as the falling stage deposits of M5C.

Figure 6. *Section showing the M5 sequence (uppermost Sandbian to lower Katian) on US Highway 127 north of Frankfort, Kentucky, exposing the Curdsville, Logana, Grier, and Macedonia members of the Lexington Limestone. The Sandbian-Katian boundary is thought to be within sequence M5A.*

Figure 7. *Corroded firmground with let down of phosphatic sand at a starvation surface in the upper part of the Perryville Member of the Lexington Limestone (Cornishville submember), showing irregular relief dictated by* Thalassinoides *type burrow galleries in fine grained grainstone. Note skeletal lag bed overlying the contact (at tip of hammer). Exposure on US Highway 421 near Harrodsburg, Kentucky.*

Sequence M6A: Perryville, Brannon, and Donerail Members of the Lexington Limestone

The M6 interval of Holland and Patzkowsky (1996) comprises the upper Lexington and Point Pleasant Formations. The M5-M6 sequence boundary is placed within the Perryville Member of the Lexington Limestone, beneath the Salvisa submember (Figure 4). Much of the M6 sequence, commencing with the distinctly argillaceous Brannon Member, have been assigned to the Point Pleasant Formation in northern Kentucky and Ohio, and in subcrop to the north and east (A. Young et al., 2016).

The Perryville Member of the Lexington Limestone comprises three submembers: the lower, grainstone-rich Faulconer, the micritic Salvisa, and the Cornishville, a nodular, fossiliferous calcisiltite. The Salvisa rests on an erosion surface that truncates a few meters of the underlying Faulconer beds or Grier Member in south-central Kentucky. The pale fenestral micrites of the Salvisa reflect a shallow water depositional environment, likely representing the early TST of the M6 sequence. The Cornishville is interpreted as a late TST, with the heavily mineralized hardground at or near its upper contact being a maximum starvation surface (Figure 7).

The calcisiltites and shales of the overlying Brannon form a thin but very distinctive interval in the Lexington area; these beds include very widespread deformed strata (Figures 8 and 9) that have been interpreted as seismites (Ettensohn et al., 2002; McLaughlin and Brett, 2004). Locally, the Brannon is overlain sharply to conformably by thin, rhythmically laminated, fine grained rusty weathering grainstone informally assigned to the Donerail member (McLaughlin et al., 2004; Figure 8). The Brannon shales are interpreted as highstand deposits, while those of the Donerail as regressive or falling stage. The Brannon or Donerail are sharply overlain by the Sulphur Well Member (lower middle Tanglewood) at a disconformity that forms the M6A-M6B sequence boundary.

Figure 8. *The M6A sequence on Bluegrass Parkway west of the Kentucky River. The upper Perryville (Cornishville submember) is abruptly overlain by shale and calcisiltites of the Brannon Member; the latter is sharply incised by small scale erosional channel with deformed channel fill (center); and at the top, bedded rudstones of the Sulphur Well Member overlie the Donerail member with angular discordance at the sub-Sulphur Well unconformity.*

***Figure 9**. The sequence M6B early transgressive systems tract: the Sulphur Well Member of Lexington Limestone. Here the lower part of the Sulphur Well shows a basal white grainstone bed overlain by rhythmic (tidally?) laminated fine grainstone reddish partings. This package showing overturned folds (presumably a seismite) truncated by an overlying grainstone, clearly illustrating the chronological relationship between the deformation and deposition of the overlying strata. Long roadcut on I-75 south of Elkhorn Creek, near Georgetown, Kentucky.*

Sequence M6B: Sulphur Well, Stamping Ground/Strodes Creek, and lower Devils Hollow Members of the Lexington Limestone

The Sulphur Well Member (also known as the lower middle tongue of Tanglewood Member; however, we regard the Tanglewood as an overly-broad lithofacies-based name that is not particularly useful for widespread correlation) is a massive, coarse, bryozoan and crinoidal rudstone/grainstone capped by a series of closely spaced, commonly pyrite coated (rusty weathering) horizons. Clustering of these hardgrounds near the top of the unit indicates a condensed section associated with sediment starvation (Figure 10). The overlying Stamping Ground Member is more argillaceous and forms the beginning of a complex, fossil-rich succession. The Stamping Ground, "unnamed" (see below), and Greendale members are commonly mapped as the Millersburg Member of the Lexington Limestone, named for typical outcrops of shaly, rubbly limestone exposed near Millersburg, Kentucky. Like the Tanglewood, the Millersburg is more useful for lithofacies mapping than correlation. However, a series of new roadcuts on US Highway 68 west and south of Millersburg have recently enabled a comprehensive review of the type Millersburg and clarified its relationship to the Sulphur Well and Strodes Creek Members.

These units are locally very rich in fossils, with the lower Stamping Ground (Millersburg facies) typified by an abundance of small brachiopods (*Rafinesquina*, *Rhynchotrema*, *Vinlandostrophia*). Near Swallowfield, Kentucky, this unit has yielded common small trilobites (including enrolled *Flexicalymene*), delicate crinoids, and the small mitrate stylophoran *Enoploura*. Along the eastern side of the Lexington platform, the lower Stamping Ground is also host to a major, regionally extensive stromatoporoid biostrome. Large specimens of *Labechia huronensis* are extraordinarily packed in some beds, together with solenoporids (probably chaetetid sponges; Riding, 2004) and less common *Tetradium* and colonial rugosans (*Cyathophylloides*?; formerly *Columnaria*). The Strodes Creek Member, a distinctive unit of interbedded grey micrites and dark shales with stromatoporoids, corals, and *Solenopora* (Black and Cuppels, 1973), is equivalent to the upper part of the Stamping Ground interval and may be best considered a submember.

The upper (5^{th} order?) subsequence of M6B, as presently construed, starts with an unnamed 2-3 m thick massive skeletal grainstones (informally referred to as the "unnamed member" pending the selection of a worthy type locality) that are sharply set off above the stromatoporoid-rich Strodes Creek submember below. These beds pass upward, in some cases with a distinct, ferruginous hardground, into a thin (0-4 m thick) medium gray shaly nodular packstone-shale interval believed to be equivalent to the type Greendale Member. McLaughlin et al. (2004) traced this interval widely on both sides of the Jessamine Dome, in contrast to statements of Cressman (1972) that the Greendale is merely a local lenticular unit. The overlying calcarenites of the lower Devils Hollow Member are interpreted as the M6B falling stage.

Figure 10. *Lower-middle M6B on a long roadcut along I-75 south of Georgetown, Kentucky. Here the Sulphur Well Member is sharply overlain by the shaly, nodular Stamping Ground Member at a corroded hardground surface interpreted as a major flooding surface.*

Sequence M6C: Upper Devils Hollow and Bromley Members of the Lexington Limestone

The uppermost part of the Lexington Formation, as presently defined, was formerly assigned to the Cynthiana Formation. The widespread skeletal grainstones of the upper Devils Hollow Member (sometimes mapped as the upper or Nicholas tongue of the Tanglewood Member) record a complex of shoal, tidal bar and local lagoonal sediments.

At nearly all outcrops the Devils Hollow or upper Nicholas interval rest sharply on the underlying "Millersburg facies" of the Greendale and locally, in Nicholas County, this sharp erosive surface (M6B-M6C sequence boundary) cuts out the underlying Greendale and stacks the Devils Hollow on massive "unnamed" grainstones to form the e massive Nicholas Member. Recent inspection of the Nicholas type locality indicates that, contrary to some reports, this unit is not overlain by Edenian strata. Rather, it is overlain by the Bromley-equivalent part of the Clays Ferry. Near Frankfort, the lower Devils Hollow interval shows large dune-forms composed almost entirely of high-spired gastropod shells (cf. *Loxoplocus*). The mineralized hardgrounds at the top of the Devils Hollow are interpreted as slow deposition associated with rapid sea level rise.

The overlying Bromley Shale or Bromley Member (locally mapped as a lower part of the Clays Ferry Formation or an upper tongue of the Millersburg Member of the Lexington Limestone; sometimes informally considered the base of the Point Pleasant Formation) consists of medium gray, shaly nodular limestones and thin shales recording deeper, more offshore environments than the underlying Devils Hollow. Fossils are abundant though mainly fragmentary. Small brachiopods (*Zygospira,* little *Vinlandostrophia,* and *Rafinesquina*) are common, as are mollusk beds very rich in gastropods, bivalve molds, and small nautiloids. However, the most distinctive aspect of this interval are limestone beds packed with fragmentary remains of the trilobite *Isotelus*.

The upper part of this succession is ambiguously assigned to the uppermost Lexington Formation or Point Pleasant Formation; the latter predominates in informal usage. This package of fine calcarenites with distinctive laminations with dark gray and red partings (“pinstriping”, possibly of tidal origin) is the Locust Creek submember or Locust Creek beds, named for exposures along Locust Creek in Bracken County, Kentucky. The grainstones are interbedded with thin calcareous mudstones and nearly all exposures of this 1 to 2 m thick interval show extensive deformation in at least three levels. These deformed beds have been discussed in detail by McLaughlin and Brett (2004) and are interpreted as seismites. Presumably, the loading of rapidly deposited carbonate sands and silts onto mud layers produced latent instabilities, such that seismic shocks deformed the layers into ball and pillow to saucer-like masses separated by thin, breccia filled, muddy diapirs. Many of the deformed layers are truncated at submarine erosion surfaces, some of which are bored hardgrounds, proving that the deformation of the sediments was penecontemporaneous with deformation and probably occurred on the seafloor. Similarly deformed beds appear characteristic of falling stage deposits in many sequences (e.g. the Donerail of the M6A) but they are best developed in the Locust Creek interval.

The Point Pleasant Problem

The Point Pleasant Formation was named for limestones and shales found in extensive quarry exposures in and around the town of Point Pleasant, on the Ohio River between Cincinnati and Maysville (Orton, 1873). The term has been used intermittently for the carbonate-rich strata immediately subjacent to the Cincinnatian Series, i.e. below the Kope Formation of present usage. However, the unit is poorly defined, as the type exposures are now degraded or inaccessible. In addition, extensive oil and gas exploration in

Figure 11. *M6B FSST, M6-C1 sequence boundary, and C1 TST in the Point Pleasant Formation. The deformed, wavy laminated (“pinstriped”, perhaps tidally bedded) Locust Creek beds are erosionally truncated and draped by fossiliferous rudstone/grainstone at base of “River Quarry” beds at a rusty, possibly karstic unconformity. US Highway 127 near BP gas station northwest of Peaks Mill, Kentucky.*

the Appalachian Basin has resulted in the widespread use of the term “Point Pleasant” for a package of dark calcareous shale with thin silty limestones beneath the dark “Utica Shale”. This “Point Pleasant” of drillers can be used quite differently from the way the same terminology is applied in outcrop, such that the subsurface unit may not be correlative to its surficial counterpart. In general, the subsurface “Point Pleasant” represents a much broader interval than the Point Pleasant sensu stricto, which is often restricted to the uppermost package of limestones just beneath the Kope Formation and its equivalents (for example, see usage by McLaughlin et al., 2004, who place the entire Point Pleasant above the Bromley). However, surface studies can also be ambiguous, and some workers have historically included have included a substantial thickness of strata in the Point Pleasant, including the Bromley and sometimes even below (see plate 1 of Weiss and Norman, 1960 for examples of this variability).

Core and outcrop studies by Young et al. (2016) show that the “Point Pleasant” of drillers appears to represent the entire Point Pleasant *sensu stricto*, as well as the upper Lexington (down to the Brannon, more or less, almost the entire M6 sequence). Intriguingly, this concept of a “greater Point Pleasant” or Point Pleasant *sensu lato* is not dissimilar from the older Cynthiana Formation (although the term Point Pleasant has historical priority). In addition, it closely matches the extent of the Point Pleasant used by Sweet et al. (1974), Bergström et al. (2010), and Coates et al. (2010, figure 4). Therefore, in an effort to bring surface and subsurface terminology into alignment, an argument can be made to increase the scope of the Point Pleasant to include units currently belonging to the upper Lexington (Brannon, Sulphur Well, Stamping Ground/Strodes Creek/Millersburg, “unnamed”, Greendale, Devils Hollow, and Bromley Members), reassigning them and thus removing them from the Lexington. While tempting, these major revisions may be too ambitious for the scope of this field trip guidebook, as its purpose is to provide an introduction to these strata, not foment stratigraphic upheaval (for the most part). Ongoing study and future publications will continue to clarify and refine the stratigraphy and nomenclature of this interval.

The Type Cincinnatian Series

The Upper Ordovician Cincinnatian Series strata exposed on the Cincinnati Arch comprise mixed shales, minor siltstones, shelly limestones and argillaceous dolostones. These strata are famed for their invertebrate fossil record, including diverse and spectacularly preserved corals, bryozoans, brachiopods, mollusks, trilobites and echinoderms (Meyer and Davis, 2009), which constitute a major component of the sedimentary rocks. Although reefs (*sensu stricto*) are lacking, biostromes of bryozoans, colonial corals, and stromatoporoids are well developed at many levels. Time-averaged, phosphate-rich shell beds are exceptionally common in much of the succession, and are seen as evidence for sediment starvation

The Cincinnatian is split into a trio of stages: the Edenian Stage, Maysvillian Stage, and Richmondian Stage. Some workers (e.g. Lattman, 1954) favored extending the definition of the Cincinnatian down to include the Cynthiana Formation, though modern usage considers these rocks to be a part of the Mohawkian Series (and assigned to the upper Lexington Limestone or Point Pleasant Formation). More recently, the Cincinnatian has been divided into six 3rd order depositional sequences, the C1-C6 of Holland and Patzkowsky (1996).

Recent study by the present authors has revealed a need for re-definition of certain sequences and their boundaries (Figure 12). Moreover, the documentation of regional disconformities points to the need for further subdivision of small and larger sequences. In several instances, sequences can be further subdivided into distinct smaller scale (i.e. 4th order) depositional sequences, which are herein provisionally labelled with letter designations (A, B, C, etc.) pending formal reconsideration of sequence nomenclature.

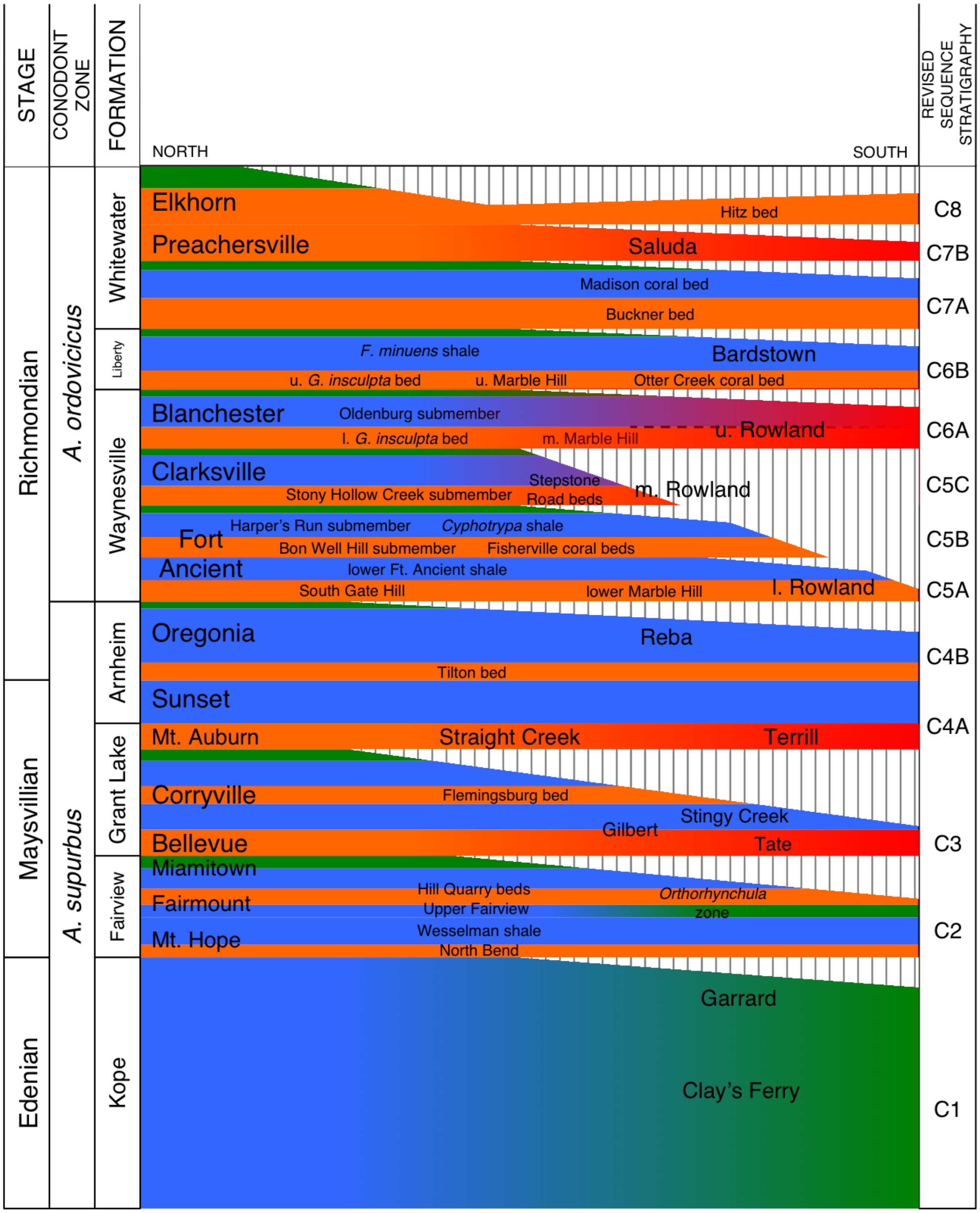

Figure 12. *Revised sequence stratigraphy of the upper Katian (Cincinnatian) of the Cincinnati Arch area. Orange represents limestones, typically interpreted as transgressive systems tracts; red represents shallow-water micrites or dolosiltites; blue represents shaly strata usually interpreted as highstands; green represents silts associated with late highstand or falling stage deposits; vertical hashmarks indicate the presence of an unconformity. Vertical scale approximate.*

Sequence C1: River Quarry beds and Kope Formation

The transgressive systems tract of sequence C1 (uppermost Chatfieldian-Edenian, i.e. basal Cincinnatian; middle Katian, Ka1? - Ka2) is represented by the upper grainstone of the Point Pleasant Formation (also called the uppermost tongue of Tanglewood or the Point Pleasant tongue of the Clays Ferry Formation by Kentucky mappers). Once termed the "River Quarry beds" or the Rogers Gap (in part; Foerste, 1914), this 5 to 10 m package of skeletal grainstone was first described from quarries and exposures at Point Pleasant, Ohio. Much of this limestone is composed of crinoid columnals, including the smooth cylindrical stems of *Merocrinus*. Other fossils include abundant ramose bryozoans and, near Cincinnati, the first appearance of the distinctive "lace collar" trilobite *Cryptolithus*. The River Quarry beds rests sharply upon the underlying Locust Creek grainstones at a surface we interpret as an important erosion surface (Figure 11). Note that some previous authors, such as McLaughlin et al. (2004, 2005), refer to the "Point Pleasant" in a restricted sense, as the upper limestone beds exposed at the type section near Point Pleasant, Ohio. Although the upper Point Pleasant is often listed as uppermost Mohawkian, we include it as the base of the Cincinnatian as it seems to be genetically and faunally related to the overlying Kope Formation. We also point out that the Point Pleasant was at one time exposed in the vicinity of Cincinnati itself, before dams on the Ohio River raised the local water level and inundated the outcrops. However, many previous workers assigned the Point Pleasant to the Cynthiana or Lexington Formations, and have included varying amounts of strata within it.

The canonical Cincinnatian Series begins with the Edenian Stage, named for now-covered exposures near Eden Park east of Cincinnati. In Ohio, Indiana, and northern Kentucky, the blueish gray shales, siltstones, and limestones of the Kope Formation are synonymous with the Edenian. The soft Kope shales erode easily; they form the steep hills and valleys of the Outer Bluegrass region surrounding Cincinnati and adjacent northern Kentucky. Up to 80 meters thick, the Kope has been subdivided into the Economy, Southgate, and McMicken Members, which in turn have been subdivided into a series of submembers on the basis of clustered limestones alternating with distinct of thicker shales (the "Big Shales" of Brett and Algeo, 2001; Brett et al., 2008; McLaughlin et al. eds, 2008).

The basal unit of the Kope Formation is the Fulton submember (Figure 13). This distinctive interval shows a deepening upward pattern with about five small-scale cycles of limestone and dark gray shale. The shale includes some of the only occurrences of the deep-water trilobite *Triarthrus* in the outcrop belt as well as abundant *Cryptolithus, Merocrinus*, gastropods, bivalves, and other diverse fossils. Also notable is the occurrence of the rhombiferan cystoid *Cheirocystis fultonensis*, a rare but geographically widespread species known only from a thin zone less than a meter above the base of the unit.

The remaining interval of the Kope has been subdivided the Brent, Pioneer Valley, Snag Creek, Grand View, Grand Avenue, and Taylor Mill submembers (Brett and Algeo, 2001). These units and their component meter-scale limestone-shale cycles (numbered 1-40 following Holland et al., 1997) have proved to be widely traceable and they are interpreted as 4^{th} order cycles (Brett et al., 2008a; Dattilo et al., 2008). This cyclicity has been extensively studied in terms of depositional environments and paleoecology, particularly gradient analysis (Holland et al., 2001; Miller et al., 2001). Overall, the Kope Formation may actually represent two large-scale cycles, with the transgressive systems tract of the second cycle represented by the limestone-rich Grand View submember. The overlying shale and siltstone-dominated Taylor Mill submember is interpreted as representing a strong shallowing forced by sea level drop.

The upper Clays Ferry Formation of central Kentucky is in part equivalent to the Kope Formation (Weir and Greene, 1965). However, as noted above, the Clays Ferry also includes older strata, equivalent to some units of the Point Pleasant and upper Lexington Formations (e.g. the Bromley), and thus should not be

Figure 13. *The C1 sequence MFS on top of the "River Quarry" beds of Point Pleasant Formation; a major flooding surface into distal dysoxic shales of the basal Kope Formation, Fulton submember. Roadcut on US Highway 52 near Asbury, Ohio.*

Figure 14. *The C1-C2 sequence boundary; uppermost Kope Formation (the silty Taylor Mill submember) is sharply overlain by the "Z bed" (at a regional erosion surface) at the base of the Mount Hope Member of the Fairview Formation. This is followed by the "2-Foot shale" (possible lowstand deposit?). Together, these two marker beds form an excellent method of identifying the Kope-Fairview contact throughout northern Kentucky and surrounding areas. In turn, the shale is sharply overlain by a smaller scale (4th order) subsequence boundary at the base of the* Strophomena-*rich North Bend submember of the Mount Hope Member. Cut on the east side of Kentucky Route 11 south of Taylor Mill road, just south of Maysville, Kentucky.*

considered completely correlative to the Kope. The uppermost Kope (Taylor Mill submember) is laterally equivalent to the Garrard Siltstone. This unit with large ball and pillow structures, overlies the Clays Ferry, including excellent outcrops in the Clays Ferry type area, near the I-75 Clays Ferry Bridge over the Kentucky River.

In the subsurface to the north, east, and west, the Kope grades into black "Utica Shale", a term borrowed from New York. As with the "Point Pleasant", the usage of "Utica" by drillers to refer to subsurface Ordovician black shales may be problematic, as the subsurface units may not be correlative to the true Utica of New York or the Kope Formation. However, parts of the New York Utica (i.e. the Indian Castle Shale) are indeed correlative to the Kope, so this name is not entirely misleading.

Sequence C2: Fairview Formation / Calloway Creek Formation and Miamitown Shale

Whereas the Edenian Stage is mostly shale, the Maysvillian Stage is mostly limestone. Near Cincinnati, Maysvillian strata are represented by the Fairview Formation, the Miamitown Shale, and the overlying Grant Lake Formation. In central Kentucky, this same succession is represented by the Fairview-equivalent Calloway Creek Limestone and the partially Grant Lake equivalent Ashlock Formation (Weir et al., 1965); Miamitown-equivalent strata is lacking, apparently chopped out underneath an unconformity at the base of the Grant Lake (i.e. the C2-C3 sequence boundary).

The lower interval of the Fairview is typified by tabular, bryozoan- and *Rafinesquina*-dominated packstones, commonly with edgewise brachiopod coquinas interbedded with thin shales and siltstones. These strata were originally assigned to sequence C2 by Holland and Patzkowsky (1996). However, the litho- and sequence stratigraphy of the Maysvillian were thoroughly revised by Schramm (2011), who subdivided the Fairview succession into three subsequences. The first sequence includes the lower portion of the Fairview Formation (Mount Hope Member) and it is construed as having a lower transgressive package comprised of compact skeletal limestones (the "Z bed") and a very widespread 60 cm shale (informally known as the "2-Foot shale"; Figure 14). This is overlain by compact brachiopod and or bryozoan rich stacked limestones (packstone or grainstone) assigned to the North Bend Submember. At Maysville this interval contains a flaky coquina densely packed with *Strophomena* brachiopods. Overlying units include the shaly Wesselman Submember and, above that, a presently unnamed submember.

The upper member of Fairview is named the Fairmount for exposures on the west side of Cincinnati. The Fairmount Member consists of siltstones and compact skeletal grainstones. Certain siltstone packages high in the unit were assigned by Schramm (2011) to the Hooke-Gillespie submember, locally exhibit thickened lenticular structures that are thought to be infilled submarine channels. These same siltstones have been deformed into bulbous, contorted ball and pillow structures in at least three widespread intervals. These heavily deformed beds, beautifully exposed at many roadcuts near Maysville, are interpreted as seismites, like those of the Locust Creek deformed zone mentioned above. These beds are overlain by compact skeletal grainstones containing the brachiopod *Strophomena* and, rarely but importantly, the rhynchonellid *Orthorhynchula linneyi*; this is the Lawrenceburg Submember of Schramm (2011). Finally, the highest beds of the Fairview are informally known as the "Hill Quarry" beds, in reference to their historical prominence in the quarries dug into hills surrounding Cincinnati. They form a series of compact 30 to 50 cm limestones separated by soft gray shales. At Maysville, these beds have famously yielded masses of completely articulated crinoids (*Glyptocrinus decadactylus;* Milam et al., 2017) which are prominently displayed at the Cincinnati Museum.

In south-central Kentucky Fairview-equivalent strata is known as the Calloway Creek Limestone. Although the precise correlation requires additional study, the unit appears to be nearly completely equivalent to the type Fairview. The Calloway Creek is well exposed near Richmond, Kentucky, including on fresh roadcuts on Kentucky Route 52 north of the town of Paint Lick. There the unit contains an abundance of *Orthorhynchula linneyi*, as well as small, well-preserved cyrtoconic nautiloid cephalopods.

The Miamitown Shale is a package of greenish-gray silty mudstone and siltstone overlying the Fairmount. Although it contains scattered shells of brachiopods (e.g. small *Rafinesquina)*, the Miamitown is particularly rich in mollusks including beds of gastropods and modiomorphoid clams, some of which show attached edrioasteroid echinoderms. The Miamitown Shale is well developed in southeastern Indiana and southern Ohio (Holland, 1993; Dattilo, 1998; Holland and Patzkowsky, 2007), found in localities such as Trammel Fossil Park north of Sharonville, Ohio. However, it is lacking in much of Kentucky (including the field trip area), where it has apparently been cut out by an unconformity below the Bellevue Member of the Grant Lake Formation: the C2-C3 sequence boundary.

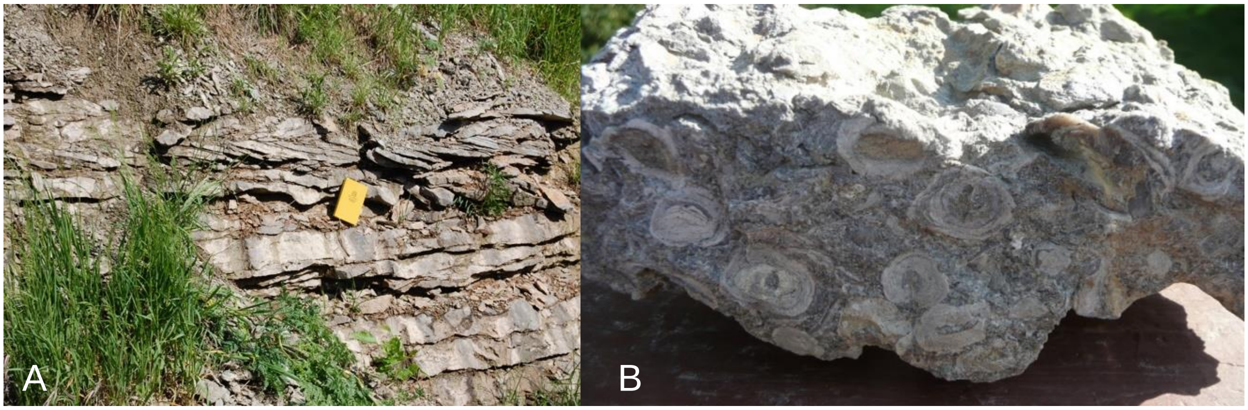

Figure 15. *C3 basal transgressive facies, the Bellevue Member of the Grant Lake Formation. A, basal bimodally crossbedded skeletal grainstone (yellow field notebook for scale); B, oncolitic packstone of transitional condensed facies. From exposures on I-71 at the Trimble/Henry County line, near Campbellsburg, Kentucky.*

Sequence C3: Bellevue and Corryville Members of the Grant Lake Formation

Unconformably overlying the Fairmount Member of the Fairview Formation or, where present, the Miamitown Shale is the Grant Lake Formation. This limestone-rich unit consists of three members: the thin, wavy nodular bedded fossil fragmental limestones and minor shales of the Bellevue Member, the shales and thin-bedded brachiopod packstones of the Corryville Member, and the nodular pack- and grainstones of the Mount Auburn Member. Previous workers have regarded three units as members of the old McMillan Formation, or even formations in their own right.

The basal unit, the Bellevue, crinoidal grainstones may show herringbone cross bedding and oncolites (Figure 15) and thin-bedded packstones stuffed with the large brachiopods *Rafinesquina*, *Vinlandostrophia ponderosa*, and *Hebertella*, and is believed to represent the initial transgression of sequence C3. The overlying unit, the Corryville Member, is a shaly, often with thin-bedded nodular packstones; it is the C3 highstand. The Corryville Member is also full of brachiopods, and complete, geodized *Vinlandostrophia ponderosa* are extremely common south of Maysville, Kentucky. A locally biostromal grainstone package in the middle of the Corryville is termed the Flemingsburg Bed for exposures near Flemingsburg, Kentucky and interpreted as a 4th order transgressive package, splitting the C3 into lower (C3A; Bellevue and lower Corryville) and upper (C3B; Flemingsburg and upper Corryville) subsequences.

In the southern Cincinnati Arch region, the Bellevue appears to pass laterally into greenish laminated and rarely desiccation cracked dolomitic siltstones of the Tate Member of Ashlock Formation (Weir et al., 1965), interpreted as a peritidal facies. This unit shows a deepening into nodular, shaly and brachiopod-rich facies, assigned to the Gilbert Member of the Ashlock and the latter locally passes upward into distinctively rhythmic, tabular-bedded pale gray micritic wackestones and alternating dark gray shales referred to as the Stingy Creek Member of the Ashlock Formation. These middle Ashlock units are believed to be correlated to the Corryville Member of the Grant Lake, though the precise relationship is still ambiguous. We caution that the lithostratigraphic nature of many of the Kentucky units can cause problems for those attempting to use a more allostratigraphic paradigm. For example, the Tate Member can be included in either the Grant Lake Limestone or the Ashlock Formation (see Weir et al, 1965), yet in some regions the Grant Lake is reduced in rank to a member of the Ashlock Formation (also Weir et al., 1965), at least partially equivalent to the Gilbert and separate from the Tate. We discourage the use of this restricted “Grant Lake Member”.

Sequence C4: Mount Auburn Member of the Grant Lake Formation and Arnheim Formation

Holland and Patzkowsky (1996) assigned a single unit, the Arnheim Formation, to sequence C4. However, reconsideration of the stratigraphy by Schramm (2011), Malgieri (2015), Hartshorn et al. (2016), and the present authors indicates that the sequence should include both the Arnheim *and* the underlying Mount Auburn Member of the Grant Lake Formation (and its equivalents); it is tentatively divisible into at least two subsequences (C4A and C4B). Malgieri (2015) indicated that the coarse Straight Creek facies of the Mount Auburn Member sharply overlie a regionally angular disconformity that truncates the upper Corryville down to or below the level of a distinctive stromatoporoid-*Tetradium* biostrome here termed the Flemingsburg bed (Figure 17). Near Cincinnati, the Mount Auburn is a series of nodular to concretionary, rubbly packstones rich in small phosphatic granules and containing an abundance of the brachiopod *Vinlandostrophia ponderosa (*including the particularly inflated *V. ponderosa auburnensi*s) as well as cephalopods and other mollusks. Farther to the southeast this interval exhibits at least two small scale cycles, with grainstones alternating with nodular, shaly biostromal wackestones. These beds locally yield abundant *Solenopora* (putative chaetetid sponges) and large stromatoporoids. Still farther to the south, these beds give way to the pale olive gray laminated and desiccation cracked Terrill Member of the Ashlock Formation (Weir et al., 1965; Figure 18). Lithologically analogous to the older Tate, the Terrill is interpreted as having been deposited in shallow lagoon to tidal flat environments. We consider the Mount Auburn and its equivalents to form the lowstand to transgressive systems tract of the revised C4 sequence.

The Arnheim Formation comprises 21 to 30 m of interbedded medium dark greenish gray shale and skeletal pack- and grainstone that pass upward into nodular calcisiltites and calcareous shale. The Arnheim is interpreted as the highstand systems tract of sequence C4, deepening upward from the Mount Auburn Member of the Grant Lake Formation. In its type area near Fleming County, Kentucky, the lower Arnheim Sunset Member consists of sparsely fossiliferous thin-bedded pale gray muddy limestones with scattered bryozoans and stromatoporoids, interbedded with organic-rich black shales containing carbonized algae (the HST of C4A). The overlying Oregonia Member (and laterally equivalent Reba Member of the Ashlock Formation) is fossil rich and shows the first incursion of several typical Richmondian brachiopods, including *Leptaena richmondensis* (Figure 45C), *Rhynchotrema dentatum*, and the rare but important *Retrosirostra carleyi* (see Holland and Patzkowsky, 2007). However, these occurrences are often merely thin (a few centimeters to a meter or slightly more) epiboles above which these taxa abruptly disappear, only to return much higher in the section. The base of the Oregonia is locally marked by the prominent Tilton bed, which is interpreted as the C4B TST. The upper portion is a nodular argillaceous limestone and shale (the C4B HST) containing abundant bryozoans such as *Constellaria* and *Hallopora subnodosa*.

The Arnheim Formation is typically considered the basal unit of the Richmondian Stage, the final major division of the Cincinnatian Series. Named for exposures near Richmond, Indiana, the Richmondian commences with gray, silty shales and thin limestones of the Arnheim and Waynesville Formations, apparently representing a major transgression. These units are often assigned to the Bull Fork Formation in northern Kentucky, where they consist of medium gray, brownish-weathering shale and brachiopod packstones. South of Louisville, Kentucky, the Arnheim Formation may be mapped as an upper part of the Grant Lake Formation, due to its lithological similarity to the Grant Lake in that region. There the Grant Lake is capped by the pale green dolosiltites of the Rowland Member of the Drakes Formation. Note that Holland and Patzkowsky (1996) included the Rowland in their C4 sequence as a correlative to the upper Arnheim Formation (i.e. Oregonia Member). We do not believe this is the case, as typical Oregonia and its distinctive brachiopod fauna may be traced far into Kentucky, including in regions where the Rowland is exposed. Rather, as elaborated upon below, we correlate the Rowland to the Waynesville Formation.

Figure 16. *Detail of the C3-C4 sequence boundary between laminated dark fine grained grainstone (uppermost Corryville Member of the Grant Lake Formation; likely FSST deposits) and pinkish gray rudstone of the basal Mount Auburn Member of the Grant Lake Formation (Straight Creek facies). Sharp contact just above head of hammer is apparently erosional. Roadcut on Kentucky Route 11 near Tilton, Kentucky.*

Figure 17. *Uppermost C3 and lower C4 sequences along Kentucky Route 11 near Tilton, Kentucky. Stromatoporoid-rich rudstone overlies "pinstriped" grainstone at the base of Mount Auburn Member of the Grant Lake Formation; also note flooding surface atop the Mount Auburn, transitioning into the shaly Sunset Member of the Arnheim Formation (basal Richmondian).*

Figure 18. *The C3-C4 sequence boundary and TST in peritidal facies along Kentucky Route 52 near Lake Reba at Richmond, Kentucky. The dark shaly Stingy Creek Member of the Ashlock Formation (upper Corryville equivalent) is sharply and disconformably overlain by the pale olive dolomicrites and laminated dolomitic shales of the Terrill Member of the Ashlock Formation, recording early transgressive or lowstand deposits.*

***Figure 19**. The basal Waynesville Formation exposed along Roaring Brook, near the Caesar Creek Dam spillway east of Waynesville, Ohio. This interval shows a major flooding surface and backstepping pattern of nodular limestones and shales; at the bottom is the compact, nodular South Gate Hill bed overlain by the lower Fort Ancient Member of the Waynesville Formation, which represents the C5A maximum flooding zone. Christopher Aucoin for scale.*

Sequence C5: Lower to Middle Waynesville Formation

Holland (1993) originally assigned the Waynesville, Liberty, and lower Whitewater units to a single depositional sequence, what is currently termed C5. However, we propose that this strata is over-lumped and should be split into three 3rd order sequences, C5 (revised), C6 (revised), and C7 (in part), each with their own lettered 4th order subsequences. Sequence C5 consists of the lower and middle members of the Waynesville Formation, the Fort Ancient and Clarksville Members (respectively).

Sequence C5A: Fort Ancient Member of the Waynesville Formation

The basal Fort Ancient Member of the Waynesville Formation, similar in aspect to the Kope Formation, is divisible into two cycles, each with a thick interval of soft clay shale ("butter shale" of collectors), separated by a thin cluster of limestones collectors). The base of the Waynesville Formation records a globally important transgression and faunal change (Holland, 2009). Where typically developed in Ohio and Indiana, a compact, *Cincinnetina*-rich grainstone separates the Waynesville from the underlying Arnheim. This bed or package of beds, dubbed the South Gate Hill submember by Aucoin et al. (2016; Figure 19), has been interpreted to represent a highly condensed transgressive unit. It is overlain by mostly barren lower Fort Ancient shale (Figures 19 and 20), which is in turn is overlain by the ledgy Bon Well Hill beds. The upper Fort Ancient is separated by a thin cluster of limestones typically rich in the brachiopod *Cincinnetina meeki*. The upper Fort Ancient shale (the Harpers Branch Submember of Aucoin et al., 2016)

Figure 20. *Base of sequence C5 in central Kentucky, just off of I-64 exit 123 east of Owingsville, Kentucky; Bull Fork or lower Rowland Member; basal channel-fill grainstones equivalent to South Gate Hill submember overlain by dark shale and thin, nodular wackestone*

is a fossiliferous “butter shale” that was termed the *Treptoceras duseri* shale by Frey (1987), in recognition of the abundance of this nautiloid cephalopod. This “butter shale” is exceptionally rich in articulated specimens of the trilobites *Flexicalymene meeki* and *Isotelus gigas*, and thus very popular with fossil collectors. In Kentucky, the Fort Ancient is a rubbly limestone mapped as a part of the Bull Fork Formation or lower part of the Rowland Member of the Drakes Formation.

Sequence C5B: Clarksville Member of the Waynesville Formation

The middle or Clarksville Member of the Waynesville Formation consists of about 6 m of richly fossiliferous shaly limestones. Its base rests unconformably on underlying "butter shale” and mainly consists of stacked pack- and grainstone beds exceedingly rich in *Cincinnetina*. This is locally the first abundant appearances of the brachiopods *Eochonetes clarksvillensis*, *Strophomena planumbona*, and *Hiscobeccus capax* (Figure 45G), the solitary rugose corals *Grewingkia* (Figure 45A) and *Streptelasma*, and the encrusting heliolitid coral *Protaraea* as well as typical Richmondian bryozoans and mollusks (Shideler in Marak, 1992) further evidence of the Richmondian Invasion. The Clarksville fauna persists into Kentucky, where it forms a notable horn coral zone within the Bull Fork Formation (Schilling and

Peck, 1967). However, it becomes less distinctive as the unit transitions southward into the middle Rowland Member of the Drakes Formation.

The middle to upper Waynesville fauna records a first return of many coral genera following prolonged outage of perhaps 5 to 6 million years (late Chatfieldian to early Cincinnatian, though note that Harris et al., 2018, recently reported corals from the Edenian Kope Formation, as have amateur collectors [Ron Fine, personal communication, 2018]). This may record a warming trend that ushered in the so-called Richmondian Invasion (Holland, 1997; Patzkowsky and Holland, 1996; Holland and Patzkowsky, 2007). It is now apparent that the middle (Clarksville) and upper (Blanchester) divisions of the Waynesville represent unconformity bounded sequences in their own right (Brett et al., 2015b; Aucoin and Brett, 2016).

The C5-C6 Sequence Boundary: The mid Richmondian unconformity

Recent work has demonstrated the existence of a regionally angular unconformity (the "mid-Richmondian unconformity") at the base of the upper Rowland submember, apparently correlative to the Blanchester Member in Ohio (Aucoin et al., 2015). This erosion surface apparently cuts down into the underlying Clarksville, Fort Ancient, and even Arnheim as one heads southward into central Kentucky.

Sequence C6: Upper Waynesville and Liberty Formations

The revised C6 comprises the Blanchester Member of the Waynesville Formation and the overlying Liberty Formation. However, we admit that this sequence is somewhat anomalous. Unlike many of the other 3rd order sequences, it does not begin with a conspicuous grainstone package. The "Lower *Glyptorthis* Beds" that mark the base of the sequence are more limestone rich than the surrounding shales, but particularly notable save for their unique fauna. Upramp correlatives (i.e. the Owingsville coral bed; Figure 21) are more prominent, with biostromes of stromatoporoids and corals. Yet even these are nowhere near the magnitude of the River Quarry beds, Bellevue, Mount Auburn, or even the basal Waynesville South Gate Hill beds. In contrast, the upper part of C6, the Liberty Formation and correlative Bardstown Member of the Drakes Formation, is significantly more limestone-rich than the Blanchester. Thus, unlike most of the other sequences described herein, C6 starts with a shaly package and ends with a carbonate. Regardless, the presence of a major unconformity means that there is a major sequence boundary by definition. Either the evidence for the regional unconformity is misleading, or this is indeed a sequence boundary. We currently believe the latter but continue to look for an explanation that matches the data on hand.

Another anomalous aspect of this sequence is an odd reversal in the expected depth gradients between the Waynesville and the Liberty from north to south. The northern Waynesville of Ohio and Indiana comprises shales, siltstones, and minor limestones, an offshore facies similar to the Kope Formation. Yet, unlike the Kope, its equivalent in central Kentucky (the Rowland), is a shallow-water unit of dolosiltites and massive micrites, potentially peritidal in many areas. Conversely, the type Liberty Formation comprises tabular fossiliferous limestones and shales, likely a deep subtidal to offshore depositional environment; its southern equivalent (the Bardstown) is a brown-weathering, fossiliferous rubbly packstone, still with a normal marine fauna of corals and sponges, likely a shallow subtidal depositional environment. Thus, the lithofacies of these units suggest that the downramp Waynesville is offshore and the upramp Waynesville is intertidal, while the downramp Liberty is deep subtidal and the upramp Liberty is only shallow subtidal, an unexpectedly less significant gradient. We do not yet have a perfect explanation for these observations, though perhaps the shales of the Waynesville are more of a signal of clastic sedimentation than water depth.

Figure 21. *The C5-C6 sequence boundary along I-64 exit 123 east of Owingsville, Kentucky. Here the Owingsville coral bed in the upper Rowland Member of the Drakes Formation sharply overlies shaly "*Hebertella *beds" (upper middle Rowland) at an apparent regionally angular erosion surface, the mid-Richmondian unconformity.*

Figure 22. *The C5-C6 boundary near I-71 mile 30, Pendleton, Kentucky, on the west side of the Cincinnati Arch. Base is lower Fort Ancient equivalent; middle limestones are Fisherville beds (corresponding to Bon Well Hill beds of Indiana) and overlying* Cyphotrypa *shale is thought to be equivalent to the Harpers Run (*Treptoceras duseri*) shale of Ohio. Note sharp contact of yellowish weathering dolomitic wackestone on underlying shale.*

Sequence C6A: Blanchester Member of the Waynesville Formation / upper Rowland Member of the Drakes Formation

The mid-Richmondian erosion surface is overlain by a distinct interval of compact skeletal limestones termed the "Lower *Glyptorthis* Beds" in earlier literature. This condensed transgressive bed not only records the first appearance of the distinctive brachiopod *Glyptorthis insculpta* (Figure 45C), but also hosts the rarer *Catazyga headyi* and *Retrosirostra carleyi.* To the south, near Owingsville, Kentucky, this bed becomes a major biostrome of stromatoporoids and corals (the Owingsville coral bed; Figure 21) but further to the southeast the horizon is a thick vuggy dolostone bed with occasional stromatoporoids and *Tetradium*. It is this bed that oversteps various unit above the mid-Richmondian unconformity.

The upper Blanchester Member again is subdivisible into a duo of trilobite-rich "butter shales" separated by a limestone bundle rich in *Rafinesquina, Strophomena,* and other brachiopods. These Waynesville subdivisions are thought to be of approximately the same order of magnitude as the submembers of the Kope Formation. The lower shale is termed the Oldenburg submember for exposures near Oldenburg, Indiana; the upper is named the Roaring Brook submember for exposures along the creek near the emergency spillway at Caesar Creek State park in southwestern Ohio (Aucoin and Brett, 2016).

These subdivisions of the Waynesville appear to be well traceable from northern Kentucky and southern Indiana on the west side of the Cincinnati Arch through south central Ohio (e.g. the well-known outcrops at Caesar Creek State Park in the Waynesville type area) and eastward to the Maysville-Flemingsburg region of Kentucky, where they are mapped as part of the Bull Fork Formation. Farther south, the differentiation of the Waynesville members and submembers is less clear cut as the interval passes into the sparsely fossiliferous dolomitic mudstones and argillaceous dolostones of the upper Rowland Member (Figure 22). Ongoing research is attempting to provide better correlation in this region.

Sequence C6B: Liberty Formation / Bardstown Member of the Drakes Formation

The Liberty Formation of Indiana and Ohio (middle Richmondian; Katian, Ka3?) consists of 11 to 15 m of tabular, somewhat argillaceous limestones overflowing with strophomenid brachiopods such as *Eochonetes, Leptaena, Rafinesquina, Strophomena,* as well as the orthids *Hebertella* and *Vinlandostrophi*a, and the globular rhynchonellid *Hiscobeccus capax* (Figure 45D). Locally, the base of the Liberty contains a thick package of limestones full of the distinctive brachiopod *Glyptorthis insculpta* (Figure 45B): these are the Middle and Upper *Glyptorthis* Beds. South of Louisville, Kentucky, this same horizon contains colonial corals such as *Cyathophylloides* and *Tetradium*: the so-called "Bardstown reef" at the base of the Liberty-equivalent Bardstown Member of the Drakes Formation (Figure 23). A zone rich in rugose corals recognized in the Maysville area may be an eastern representation of this unit, though the horn corals *Grewingkia* and *Streptelasma* are also locally abundant elsewhere. This diverse fauna records a strong pulse of the Richmondian Invasion (Holland, 1997; Holland and Patzkowsky, 2007).

Near Louisville, these shell-rich beds give way to blocky dolomitic mudstones in the upper part of the Liberty/Bardstown. This zone sometimes considered a part of the lower Whitewater Formation, but we suggest that these are the silty highstand and falling stage deposits of the Liberty, and thus more genetically linked to that unit. Though rich in trace fossils (*Planolites*, *Chondrites*), this unit is sparse in shelly fauna. Bivalves are moderately common and typically preserved as dark carbonaceous films. This horizon may be correlated to the silty, bioturbated "Turkey Track" beds of the upper Liberty in Indiana and Ohio.

Figure 23. *The C6B TST, the Otter Creek limestone beds (basal Bardstown Member of the Drakes Formation) showing backstepping pattern into overlying shale with the Bardstown coral biostromes passing up into highstand shale. Note abundant coral heads in transition zone. US Highway 150 near Fredericktown, Kentucky.*

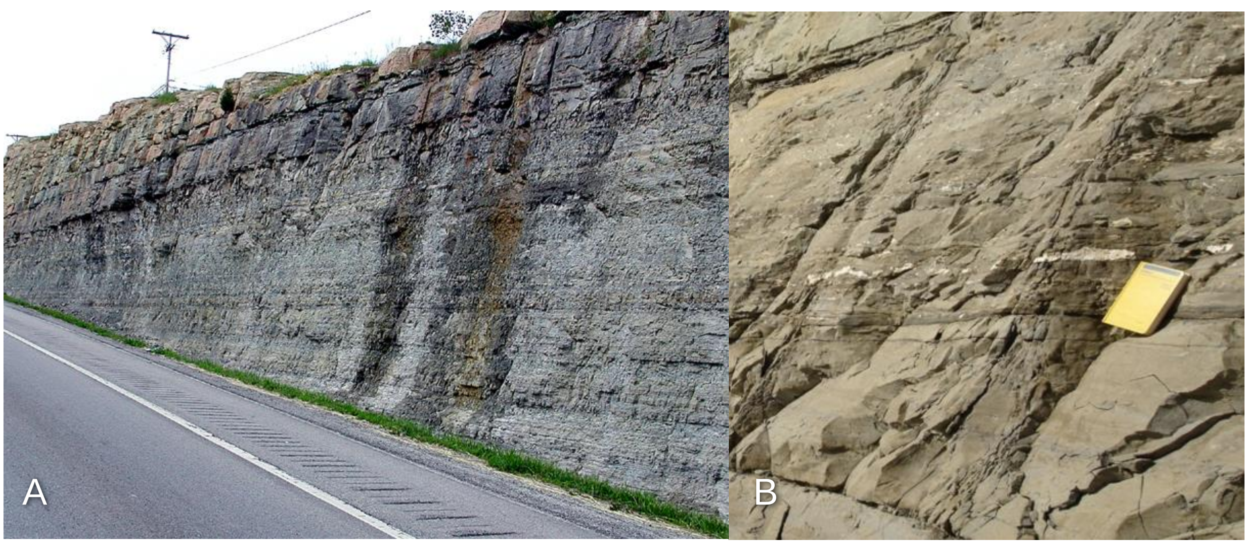

Figure 24. *The C6-C7 sequence boundary on the west side of the Cincinnati Arch. A, the upper Bardstown silty dolostones (falling stage) are sharply and erosionally overlain by the bryozoan and coral bearing dolomitic grainstones of the Buckner bed/submember of the lower Whitewater Formation; B, enlargement shows contact (sequence boundary) at yellow notebook. Kentucky Route 393 at Buckner, Kentucky.*

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Sequence C7: Whitewater Formation / Preachersville Member of the Drakes Formation

The Whitewater Formation of Ohio and Indiana (upper Richmondian; Katian, Ka3-Ka4) is a fossiliferous limestone unit that overlies the Liberty Formation. It is often broken into two semi-formal members, the Lower Whitewater and Upper Whitewater, locally with a major dolostone package, the Saluda, in between. In central Kentucky, this strata changes radically into the unfossiliferous greenish dolomitic shales of the Preachersville Member of the Drakes Formation. (However, note that the type Preachersville likely also includes strata equivalent to the Elkhorn Formation, so it best thought of as C7 through C8.) Our new sequence C7 is equivalent to most of the Whitewater Formation, with the possible exception of some of the uppermost Upper Whitewater, which may form the transgressive systems tract of sequence C8.

Sequence C7A: Lower Whitewater Formation

Along the west side of the Cincinnati Arch, the lower Saluda Member (informal designation; the lower Whitewater Formation in Indiana, in part) is sharply set off from the underlying dolomitic mudstones by a surface interpreted as a sequence boundary. A distinct package of dolostones full of orange-weathering, recrystallized bryozoans, named the Buckner Bed for excellent exposures at Buckner, Kentucky, is interpreted as a transgressive section (Figure 24). This is overlain by two or more closely spaced colonial coral biostromes known as the "Madison reef" for widespread occurrences near Madison, Indiana. These contain massive (sometimes over 1 m) heads of the coral *Cyathophylloides stellata* (formerly *Columnaria* or *Favistella alveolata*); *Tetradium* is also present in certain layers, particularly near the top. The sponge *Dystactospongia madisonensis* is found in some of these beds. These fossiliferous beds have sometimes been included in the Saluda Member of the Whitewater Formation. We informally refer to them as the "lower Saluda", whereas the massive "upper Saluda" (or "true Saluda") forms the bulk of the unfossiliferous or sparsely fossiliferous dolostone that is iconic of the member.

In turn, these biostromes are overlain by a thin, widespread thin dark shale and dolostone succession interpreted as the highstand deposits (sometimes containing black strap-like remains, possibly algae); the latter may be truncated by an overlying erosion surface beneath the "upper Saluda". Recent fieldwork in the region of Richmond and Waco, Kentucky at well-exposed sections near Drowning Creek has led to recognition of possible eastern equivalents of the Buckner bed, as bryozoan-rich dolomitic limestones beneath the green-gray shales and mudstones assigned to the Preachersville Member of the Drakes Formation.

Sequence C7B: Saluda and Upper Whitewater Formation (in part)

From Madison, Indiana to the western flank of the Cincinnati Arch, the informal "upper" submember of the Saluda consists of massive, rhythmically-laminated, desiccation cracked pale orange-buff weathering silty dolostones up to about 12 meters thick. The sharp base of this unit is interpreted as major sequence boundary, as it appears to truncate the top of the "lower Saluda" further to the south (e.g. near Buckner, Kentucky). Meanwhile, we interpret the massive dolostones of the Saluda to represent the lowstand or early transgressive systems tract of the C7B cycle. This laminated dolostone facies does not persist to the east side of the Cincinnati Arch. However, the uppermost ~5 m of Drakes Formation near Richmond, Kentucky, appear to record lithology transitional between "upper Saluda"-like thick dolosiltites and the greenish gray shaly facies typical generally assigned to the Preachersville Member of the Drakes Formation. These beds appear to overlie a bryozoan-rich interval possibly correlative with the Buckner Bed.

The corresponding highstand of the C7B sequence is represented in the rubbly packstones of the Upper Whitewater Formation. The typical expression of these beds are exposed near Richmond, Indiana, and adjacent Ohio. They are intensely fossiliferous, with superabundant bryozoans, brachiopods (e.g. *Vinlandostrophia acutilirata*, *Rhynchotrema dentatum*, *Hebertella*), bivalves, cephalopods, and gastropods, some coral or bryozoan-encrusted. Southward, this unit thins and becomes more dolomitic, apparently transitioning into the somewhat less fossiliferous Hitz Member of the Whitewater Formation, as exposed near Madison, Indiana and east of Louisville, Kentucky.

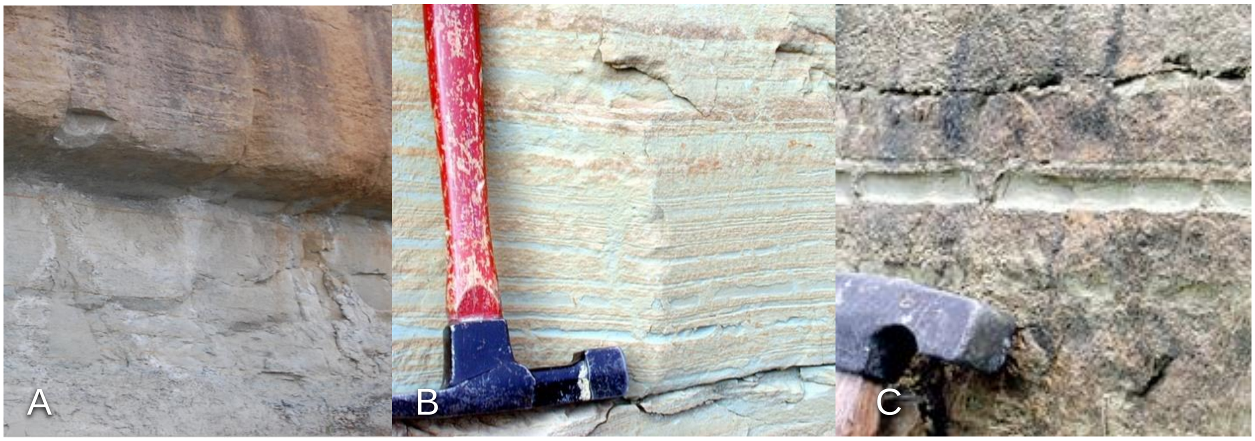

Figure 25. *The C7A-C7B sequence boundary in the Saluda Member of the Whitewater Formation. A, long view of blocky mudstones sharply, erosively overlain by massive, laminated dolostones of the "true" Saluda Member (of the Drakes Formation when mapped in Kentucky; US Highway 150 near Fredericktown, Kentucky); B, detail of laminated facies of the upper Saluda showing rhythmic, millimeter-scale laminae; C, small desiccation cracks are common in the Saluda (B and C from Kentucky Route 393 near Buckner, Kentucky).*

Sequence C8: Uppermost Whitewater Formation and Elkhorn Formation

The final sequence of the Cincinnatian, the former C6, now revised to C8, comprises the uppermost limestones of the Whitewater Formation and the Elkhorn Formation. The upper Whitewater is locally somewhat more tabular than the rubbly underlying strata, and the Whitewater-Elkhorn boundary interval shows several faunal changes, including the appearance of common and large *Tentaculites*, a recurrence of Leptaena, and a zone containing the rare rhombiferan *Lepadocystis moorei.*

The Elkhorn Formation, named for Elkhorn Creek southeast of Richmond, Indiana, is a poorly exposed unit of blue-gray shales and limestones that overlies the Upper Whitewater Formation. The Richmondian invasion fauna is relatively rare in the Elkhorn, with only sporadic occurrences of horn corals and typical Richmondian brachiopods. Rather, the unit is locally dominated by cosmopolitan taxa such as ramose bryozoans, *Rafinesquina*, *Isotelus*, *Vinlandostrophia moritura*, and *Hebertella*. In Ohio, green and maroon mudstones formerly termed Elkhorn are currently mapped as the Preachersville Member of the Drakes Formation, though it is unclear whether they are truly equivalent to the type Preachersville in south-central Kentucky (likely only the uppermost part, with the lower Preachersville being Whitewater-equivalent). These maroon horizons pass laterally into the major Queenston-Juniata redbed succession of the Appalachian foreland basin to the east. A stromatoporoid-*Tetradium* reef is locally present just below the greenish Preachersville facies (for example, in the vicinity of Springboro and Centerville in Ohio).

North of Dayton, Ohio the uppermost Ordovician consists of bluish-gray, sometimes brownish barren shales that appear to overly the greenish Preachersville-type shales. In the subsurface, this succession may merge into the upper part of the Maquoketa Shale in the Illinois Basin to the west.

Overlying Strata

The uppermost Cincinnatian strata are typically overlain by the Brassfield Formation, of Early Silurian age (Llandovery, Rhuddanian – Aeronian; Figure 26), at the Cherokee unconformity that marks the Ordovician-Silurian boundary. This contact is widely exposed in Kentucky, Ohio, and Indiana, with the Saluda or Preachersville usually representing the Ordovician below. Brassfield is locally fossiliferous, with a diverse fauna of corals, bryozoans, stromatoporoids, brachiopods, trilobites, and echinoderms, including asteroids, rhombiferans, and especially crinoids (see numerous works by Ausich, most recently Ausich et al., 2015). The unit is distinctly regional, with several different facies in its type area on the east side of the Cincinnati Arch (typical Brassfield near Richmond, Kentucky and up to Adams County, Ohio) versus the west (the "golden Brassfield" near Louisville, Kentucky and southeastern Indiana) versus the north (the "red" and "white Brassfield" near Dayton, Ohio) versus the south (the "cherty Brassfield" near Bardstown, Kentucky and northern Tennessee). The correlation between these different "versions" of the Brassfield is still somewhat ambiguous, but it appears that the northern and western Brassfield is slightly younger than the unit in its type region, with some indications that the red and golden Brassfield may be properly correlated to the slightly younger (latest Aeronian) Oldham Limestone (Sullivan et al., 2016).

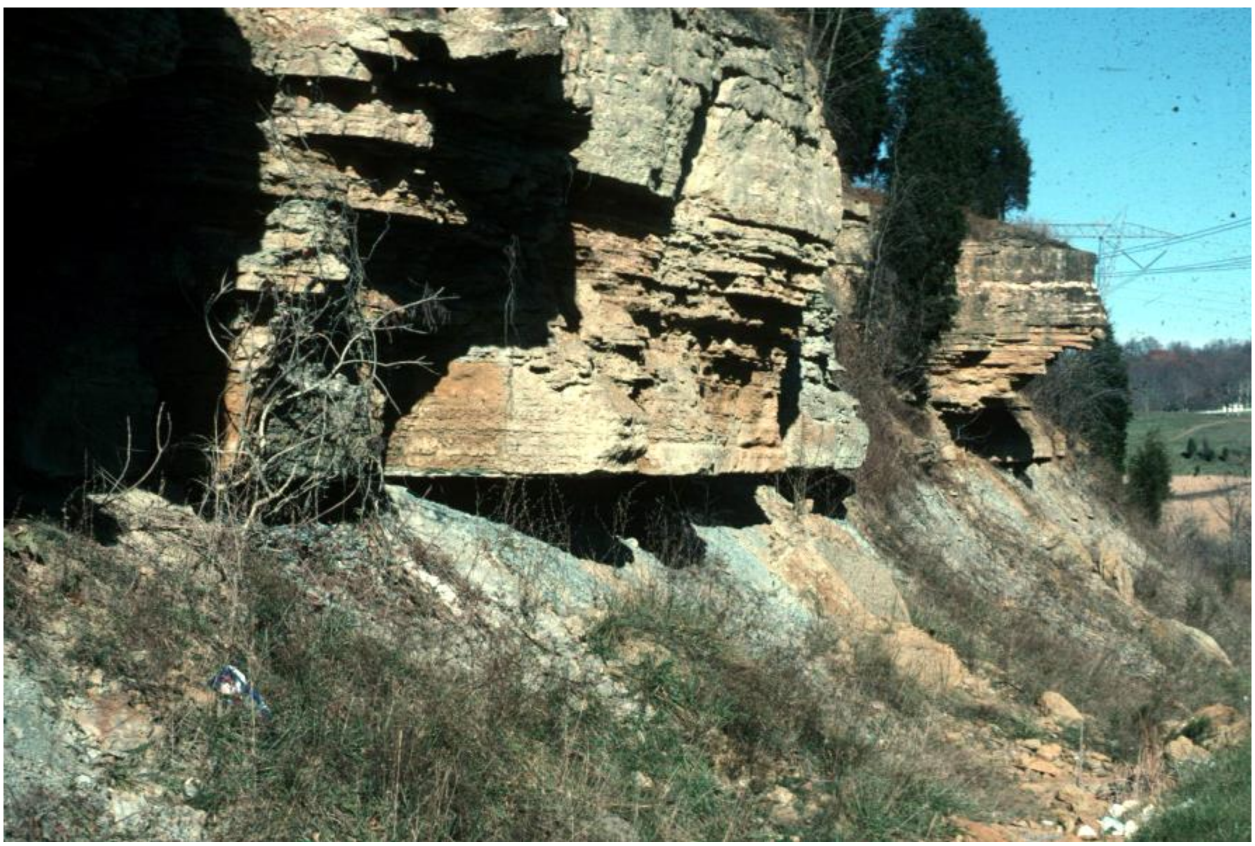

Figure 26. *The Lower Silurian (Llandovery, Rhuddanian?) Belfast Member of Brassfield Formation sharply overhanging the soft greenish gray shales of the Preachersville Member of the Drakes Formation. This contact is the Cherokee unconformity near the Ordovician-Silurian boundary. The Belfast is overlain by the cherty "Lower Massive Member" of the Brassfield Formation. Outcrop on Kentucky Route 10 west of Cabin Creek near Tollesboro, Kentucky.*

In south central Kentucky, along the southern rim of the main Ordovician outcrop belt, the Ordovician is capped by Devonian rock. The Middle Devonian Boyle Formation (or perhaps Sellersburg Formation) overlies the Rowland Member of the Drakes Formation near Lebanon, Kentucky. South of Stanford, in Lincoln County, the New Albany Shale sits atop the Preachersville Member of the Drakes Formation, forming a magnificent rust-stained erosional contact that represents a stratigraphic gap of over 70 million years. Similarly, the Gassaway Member of the Chattanooga Shale overlies the Drakes Formation near Liberty, in Casey County (Over, 2002), and in Cumberland County the Chattanooga Shale is often in contact with the Cumberland Formation, a unit of massive dolosiltites of Maysvillian to Richmondian age that locally crops out south of the main Ordovician outcrop area.

A far younger "unconformity" of sorts truncates the bedrock to the north in Ohio and Indiana. The Illinoian and Wisconsin ice sheets plowed their way across the Canada and the northern United States during the Pleistocene, flattening the topography of the northern parts of those states before stopping at the very outskirts of Cincinnati. Some localities in Butler County, Ohio and vicinity expose glacial deposits directly atop Ordovician bedrock (e.g. along Collins Creek in Peffer Park south of Oxford, Ohio). Foreign metamorphic and sedimentary glacial erratics, ranging in size from pebbles to boulders up to boulder size, are common in Ohio rivers and creeks, their well-rounded forms juxtaposed with gray slabs of local limestone. Very rarely, Silurian and Devonian fossils may be found in these erratics.

Chemostratigraphic Approaches

Alternative approaches to correlation have also been applied to the Upper Ordovician rocks of the Cincinnati region. These include chemical fingerprinting, as well as radiometric dating of prominent K-bentonites (altered volcanic ash or tephra layers), primarily in the upper Sandbian to lower Katian interval. Of these the Diecke and Millbrig bentonites (also called Pencil Cave and Mud Cave; Cressman, 1973), both occurring in the upper Tyrone Formation in Kentucky, are the most widespread (Kolata et al., 1996; Sell et al., 2015). These permit precise correlation of the M4-M5 sequence boundary (locally, the Tyrone-Lexington contact) over much of eastern North America (Figure 27).

In addition, relatively recent application of whole rock carbon isotopic data has provided a very important additional constraint on biostratigraphic correlations. The Late Ordovician Period included several major, globally recognizable carbon cycle perturbations that have been identified using whole rock carbon isotope analysis (Bergström et al., 2010). The source of these isotopic excursions is still debated (Pancost et al., 2013), but they are often attributed to times of increased primary productivity and deposition of ^{12}C-enriched organic matter, thus removing it from the global carbon cycle (Kump and Arthur, 1999). The carbonate that makes up the limestones being sampled is precipitated in equilibrium with the dissolved inorganic carbon (DIC) isotopic ratio of the ocean in which it was formed. This value is fairly steady through much of the study interval. However, these values show major perturbations to the system at isochronous horizons. Sandbian - Katian carbon isotope excursions appear to coincide with major sea level transgressive events, noted as widely recognized highstands, time intervals for which temperature reconstructions from oxygen isotopes suggest warming (Buggisch et al., 2010; Elrick et al., 2013).

The Guttenberg Isotopic Carbon Excursion (GICE), first recognized by Hatch et al. (1987) in the Guttenberg Member of the Decorah Formation in Iowa, is now recognized to be of global extent (Bergström et al., 2010). The GICE is bounded below with the prominent Millbrig (452.86 +/- 0.29 Ma of Sell et al., 2015 and Deicke (453.74 +/- 0.20 Ma of Sell et al., 2015) bentonites and above with several other K-bentonite horizons, which constrain the age of the excursion to be of less than a million years in duration (Kolata et al., 1996; Sell et al., 2013; Sell et al., 2015).

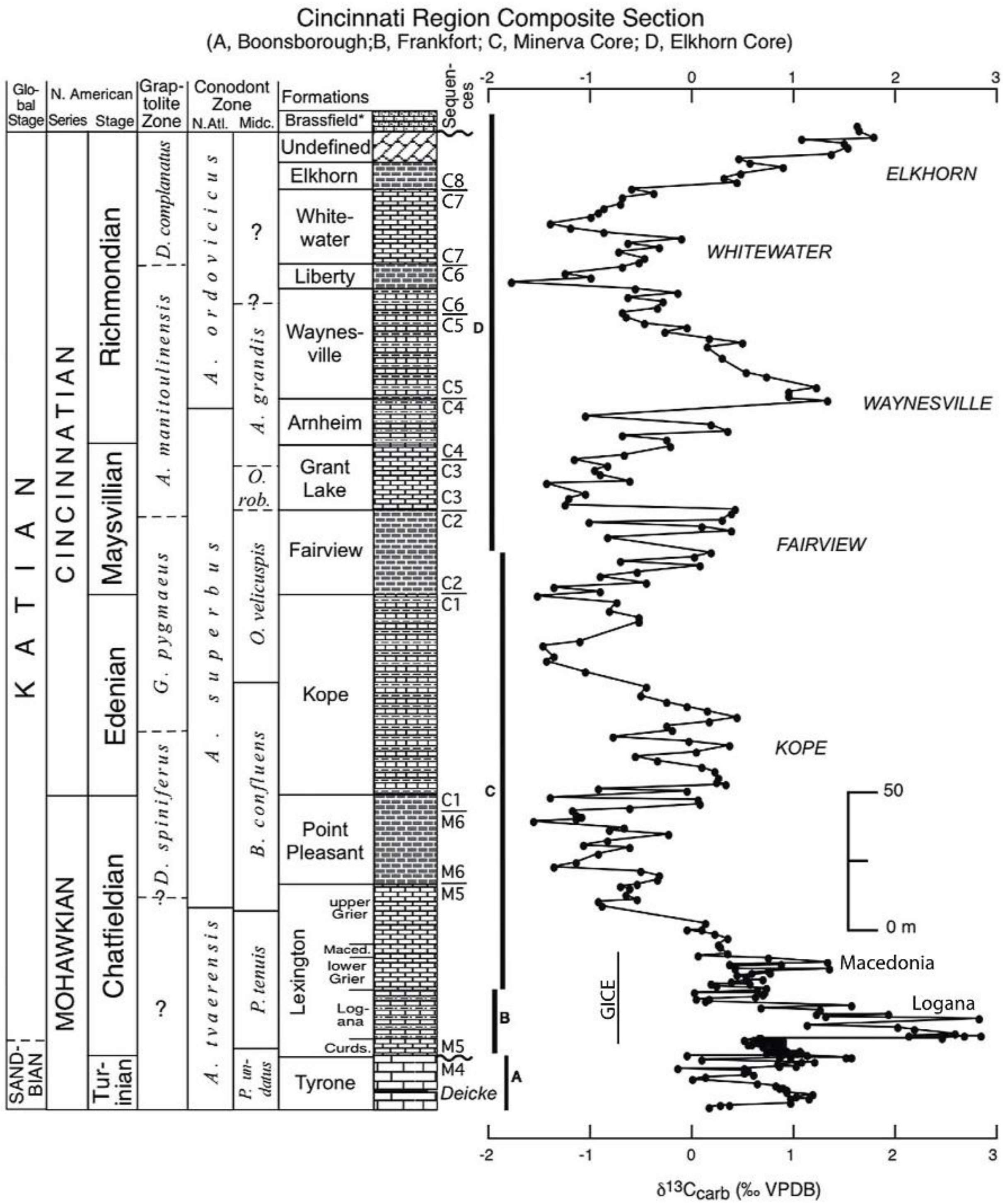

Figure 27. *Diagram showing biostratigraphy, revised sequence stratigraphy (per this report), and carbon isotope chemostratigraphy of the Katian of the Cincinnati Arch region based on data composited from four sections in Kentucky and Ohio. Modified from Bergström et al. (2010); reprinted with permission.*

While the exact cause of the GICE is unknown, the large magnitude of organic carbon burial may also have had a profound impact on the lowering of pCO_2 levels during this pre-Hirnantian Glaciation time and may have induced ice build-up (Kump et al., 1995; Saltzman and Young, 2005; Pancost et al., 2013; Pope and Steffen, 2003). Consistency in the identification of the GICE has been inhibited by its apparent change in structure regionally, likely due to preservation of different phases of the GICE in different paleogeographic regions and depositional settings. This has led to the issue of an apparently prolonged GICE interval in Appalachian Basin sections, and complete truncation of the GICE event in other studies (Quinton et al., 2016).

Recent high resolution analysis of the GICE interval on the Lexington Platform has confirmed that the record of this carbon cycle perturbation is not facies dependent. With sufficiently high resolution sampling, the internal structure of the GICE may offer a more detailed correlation tool of at least regional extent in the complex facies transitions of the Lexington Limestone (Coates et al., 2010). Locally in Kentucky and Ohio, two divisions of the GICE excursion have been recognized and used for a more refined correlation of the lower Lexington Formation (A. Young et al., 2016, Coates et al., 2010). Young et al., (2016) named the lower of the two isotopic events that comprise the GICE as the Logana Excursion, and the upper isotopic event as the Macedonia excursion. Recognition that these are separate events is a consideration of at least regional importance, especially when tracing units into the Sebree Trough where one or both of the events appear to be missing.

The whole rock carbon isotope record of the Lexington-Cincinnatian interval (including the Point Pleasant - Utica interval in the subsurface, approximately equivalent to the upper Lexington plus lower Cincinnatian) preserves several regional carbon isotopic events including the previously discussed well-known global excursions (GICE and Kope Excursion). Bergström et al. (2010) provided a critical summary of both Chatfieldian and Cincinnatian isotopic excursions in the classic Cincinnati Arch region and elsewhere. In addition to the Kope Excursion, these researchers identified four higher positive isotopic excursions in the higher Cincinnatian (upper Katian), which were also observed elsewhere and correlated on the basis of conodont biostratigraphy. A relatively minor excursion, the Fairview Excursion, occurs in the lower Maysvillian (*O. velucuspis* Zone) and is separated by low values in the upper Maysvillian to lowest Richmondian from a strong (>+2‰) and multi-pronged Waynesville Excursion in the lower Waynesville Formation (lower middle Richmondian). Significantly, the Waynesville Excursion is approximately coincident with the widely recognized *A. superbus*-*A. ordovicicus* conodont zonal boundary (Bergström et al., 2010; see section on biostratigraphy). Very negative values in the overlying Liberty Formation (informally known as the "Liberty Low") are followed by a minor Whitewater positive excursion and finally a very strong Elkhorn excursion (up to +2‰) in the highest Cincinnatian beds. Combined with other techniques, this series of excursions provides an exceptional new tool for refining stratigraphic correlations.

Finally, it should be noted that studies of astrochronology, utilizing mainly magnetic susceptibility (MS) measurements as a proxy for climatic changes, provide evidence for a hierarchy of periodic oscillations in terrigenous sedimentation that may be related to Milankovitch band cyclicity. Time series analysis of more than 1000 MS samples taken at 5-cm intervals from the Edenian Kope Formation demonstrated a hierarchical pattern of oscillations of terrigenous influx. Comparisons with visual cycles in outcrop suggest a predominance of eccentricity related decameter-scale cycles and obliquity related meter-scale cycles, with some evidence of precessional cycles (Ellwood et al., 2012). These patterns hold promise for the development of an astrochronological time scale for the Late Ordovician and further work is in progress (M. Sinneasael, personal communication).

Biostratigraphy of the Upper Ordovician of the Cincinnati Arch

The Upper Ordovician strata of the Cincinnati Arch have been subject to a number of biostratigraphic studies. Although earlier workers such as Bassler, Foerste, and Ulrich successfully used a variety of index fossil taxa, especially bryozoans and brachiopods, to subdivide and locally correlate these rocks, later research has focused primarily on two groups, conodonts and, to lesser extent, graptolites in an attempt to place these strata into an international framework of biostratigraphy (Figure 27). North American Midcontinent conodont zones in the study interval include, in ascending order, the *Phragmodus undatus*, *Plectodina tenuis*, and *Belodina confluens, Oulodus velicuspis, Oulodus robustus, and Amorphognathus grandis* zones (Sweet, 1984). The alternative, or North Atlantic conodont zonation, which was established in samples from about 500-ft (152 m) in the Middletown core, near Middletown in southwest Ohio, as well as outcrop sampling near Frankfort, Kentucky, places the Lexington Formation and Cincinnatian into just three zones in a single genus lineage: the *Amorphognathus tvaerensis*, *A. superbus*, and *A. ordovicicus* zones (Richardson and Bergström, 2003) with the *A. tvaerensis-A. superbus* boundary occurring close to the base of the Perryville Salvisa beds (the M5-M6 sequence boundary). The *P. tenuis* and *B. confluens* boundary of the Midcontinent zonation occurs just slightly lower, within the upper Grier Member well above the Macedonia Bed (Richardson and Bergström, 2003; Bergström et al., 2010), and the *B. confluens* Zone ranges the entire remainder of the Lexington and approximately halfway through the overlying Kope Formation.

From the standpoint of conodont biostratigraphy, the Cincinnatian Series rocks (“Cincinnati Group”) have been subdivided into just two North Atlantic conodont zones with a single significant boundary: the *A. superbus-A. ordovicicus* zonal boundary has been established near C4-C5 sequence boundary or near the lithostratigraphic boundary of the Arnheim and Waynesville Formation; the zone extends to the top of the Cincinnatian. As noted, the *Belodina confluens* zonal boundary is placed within the Edenian. Upper Edenian and lower Maysvillian (Fairview) strata are assigned to the *Oulodus velicuspis* Zone, while the upper Maysvillian—roughly equivalent to the Grant Lake Formation (sequence C3)—encompasses the *O. robustus* and the lower portion of *Aphelognathus grandis* Zone. The latter extends upward into the lower to mid Richmondian (Arnheim through Waynesville formations; sequences C4-C6 in present classification). Higher portions of the Cincinnatian are presently un-zoned.

There are six graptolite zonal boundaries of potential interest in the study interval, primarily because they are abundant in the dark Point Pleasant and Utica shale facies of the Ohio subsurface, as well as the laterally equivalent Kope Formation. Stratigraphically important graptolites are rare in the higher Cincinnatian. The *Climacograptus bicornis – Corynoides americanus* boundary occurs within the upper Sandbian and should be present within beds equivalent to the lower Curdsville Member. The *C. americanus – Orthograptus ruedemanni* zone boundary occurs very close to the level of the *P. tenuis-B. confluens* conodont boundary, and thus should be equivalent to beds of the upper Grier (or Perryville Member). This position is not well established in the graptolitic shales of the Sebree Trough northwest of Cincinnati but may occur at ~525 ft (~160 m) in the Middletown core. The *O. ruedemanni–D. spiniferus* boundary has been tentatively identified based on graptolites in the Sebree Trough (Mitchell and Bergström, 1991) just below 500-ft (~152 m) or about 25 m below the base of the Kope Formation in the Middletown core (although there is some question as to whether this is correct). This boundary has not been established on the platform though it is extrapolated to the upper Perryville Member within the Cornishville submember (Bergström et al., 2010; Sell et al., 2015). The *D. spiniferus-Geniculograptus pygmaeus* Zonal boundary occurs within the middle Kope Formation in outcrop (in the Snag Creek submember of the Southgate Member) and in the Middletown core.

While the position of the *C. americanus – O. ruedemanni* zonal boundary is tightly constrained to the base of the Chatfieldian (Shermanian) Dolgeville Formation in New York, its precise position locally is ambiguously placed within the "lower Lexington Limestone" (Sell et al., 2015). Sell et al. (2015) also recently correlated the Haldane-Manheim K-bentonite from near the top of the Dolgeville Member in New York, near the *O. ruedemanni-D. spiniferus* boundary, with a bentonite in the Perryville Member of Kentucky and the Paradise Road K-bentonite of the lower Utica Shale (*D. spiniferus* Zone) in New York with the Brannon K-bentonite in the middle Lexington Brannon Member. By implication, this suggests a position low in the *Diplacanthograptus spiniferus* Zone near the middle of the Lexington Formation. However, there are still a number of uncertainties. Thus, the lowest dark shales of the Sebree Trough are as yet undated by graptolites, the occurrences of *O. ruedemanni* reported previously (Mitchell and Bergström, 1991) are questionable and finally the position of the lowest occurrence of *D. spiniferus* on the platform has not been well established (personal communication C. Mitchell, 2016). Work in collaboration with Charles Mitchell (SUNY Buffalo) is aimed at resolving these issues. In 2016, new graptolites were obtained by Allison Young from upper Lexington Formation beds, which may clarify the oldest known position of *D. spiniferus* zone on the platform (C. Mitchell, personal communication, 2016).

Surprisingly, the chitinozoan fauna of the Cincinnati Arch has been little studied. However, recent sampling has proven these enigmatic flask-shaped microfossils to be abundant in some Cincinnatian shales and have received preliminary study (Miller, 1976) and a study by Grahn and Bergstrom (1985) identified chitinozoans in the high Cincinnatian and overlying Belfast Member of the Lower Silurian and suggested a stratigraphic gap equivalent to about four graptolite zones based on the differences. Additional study would surely yield insights into biostratigraphy and correlation.

In addition, trilobite and bryozoan biostratigraphic markers are present in the Lexington Formation. The trilobite *Triarthrus beckii*, typical of dark shale facies and found abundantly in some drill cores, shows a transition in cephalon morphology that may be a useful indicator of the approximate *O. ruedemanni - D. spiniferus* boundary (C. Mitchell personal communication, 2016). As yet this feature has not been systematically studied but drill cores showing series of abundant *Triarthrus* exist and are under study.

CINCINNATIAN PALEOECOLOGY AND PALEOBIOLOGY

The exquisite preservation of many Cincinnatian fossils provides crucial details about the lives of Ordovician organisms (Meyer and Davis, 2009). Some assemblages are preserved in near life position, virtual snapshots of an ancient seafloor. This direct evidence from fossils and their surrounding sediments enables paleoecological interpretation by allowing comparison to the biology of closely related living organisms, as well as studies of functional morphology that use inferences based on anatomical structure.

Ecosystems can be thought of as consumptive networks: starting with an energy source (generally sunlight) that is used by primary producers (autotrophs such as photosynthetic algae), which are eaten by primary consumers (herbivorous animals), which may in turn be devoured by second order (or higher) consumers (predators, scavengers, etc.). Finally, decomposers (primarily bacteria) degrade organic matter and recycle its contained nutrients. Such consumption-based relationships are called trophic systems, and in many cases they contain far more interlinkages than the simplified description above would suggest.

In the case of marine systems, common trophic modes include removal of suspended planktonic algae, zooplankton, or organic detritus from seawater. This may entail passive *suspension feeding*, as in crinoids, which rely upon external currents in seawater to bring food particles to sticky feeding surfaces, or active *filter feeding* in which organisms create their own feeding currents using movements of flagella (as in sponges), cilia (as in brachiopods and bryozoans) or whole limbs (as in certain arthropods). Infaunal organisms, termed *deposit feeders*, live in the substrate and actively ingest sediment, from which they extract residual nutrients. Other organisms are *scavengers*, feeding off the dead, or *grazers*, rasping or scraping up organic matter, typically algae. Still others are *predators*, mainly active swimming or crawling forms that kill and consume other animals for food.

By far the most abundantly represented trophic group in Late Ordovician benthic communities is that of suspension feeders. This category encompasses a wide array of filter feeders, including the varied sponges, brachiopods and bryozoans and probably also the graptolites, as well as passive suspension feeders, such as crinoids. Attached epifaunal suspension feeders may show *tiering*, that is, feeding at different levels above the sediment surface. Low-level organisms occupy a zone of abundant suspended food particles 1 to 2 cm above the seafloor. Intermediate level suspension feeders such as many bryozoans and some crinoids are elevated about 5 to 15 cm above the bottom, while some long-stemmed crinoids may feed at heights exceeding a meter.

The Late Ordovician Fauna of the Cincinnati Arch

A brief review of major groups is presented below.

Algae

The primary producers of Late Ordovician oceans are poorly represented in the fossil record. However, given the incredible abundance and diversity of suspension feeding organisms, we must presume that swarms of phytoplanktonic algae provided the basis for the food web, as they do today. Certain acritarchs, some of which may be the remains of planktonic algae, are present in the shales of the Cincinnatian (Jacobson, 1978).

Ordovician macroalgae are marginally better known. The discoidal to spheroidal *Cyclocrinite*s, *Lepidolites* and *Anomaloides*, uncannily resembling flattened golf balls, may be the plated thalli of calcified green algae. The cyanobacteria *Girvanella* forms whitish micritic coatings on skeletal grains and centimeter-scale spherical oncolites in shoal facies. Black, branching strap-like fossils, often attributed to the problematic dendroid graptolite *Inocaulis*, are extremely common in some shallow water dark shales. These are thought to be the carbonized remains of soft dasyclad algae. All of these algal fossils are critical depth indicators because as algae are photoautotrophic and thus restricted to the relatively shallow photic zone (roughly, less than 50 meters depth, though this is dependent on other factors such as turbidity).

In addition, a number of boring microalgal groups as well as cyanobacteria, termed microendoliths, are recorded in Cincinnatian as minute trace fossils in the form of etchings in shells, that were excavated as dwelling structures by these organisms. The tiny trace fossils have been studied by carefully cleaning shells and injecting them with epoxy, dissolving the shells and observing the artificial casts of these microborings. Vogel and Brett (2009) documented microendoliths in shells from a variety of different facies within the Cincinnatian. Remarkably, these included a number of traces nearly identical to those found in modern subtropical marine environments. Moreover, today these organisms include forms that are highly sensitive to light level. Thus, by identifying assemblages of these microendoliths in Ordovician shells it is possible to assign facies to particular light levels. Thus, for example, the Kope yielded very few microendoliths except for etchings made by fungi; this suggests that at least some Kope sediments were deposited under very murky dysphotic conditions. In contrast, shells from the Fairview yielded microendoliths from deeper euphotic assemblages by comparison with modern, and those from the Grant Lake and Waynesville in part yielded evidence for a shallow euphotic zone indicating depths of a few tens of meters at most.

Figure 28. *A pair of specimens of the solitary rugose coral* Grewingkia canadensis *(up to ~10 cm long); Clarksville Member of the Waynesville Formation near West Union, Ohio.*

Figure 29. *A large specimen of the stromatoporoid* Labechia *showing prominent mamelons; lower Rowland Member of the Drakes Formation near Owingsville, Kentucky.*

Cnidarians

Corals of two major groups, rugosans and tabulates, are common in some shallow water facies, particularly in the mid Lexington and Richmondian strata of the Cincinnati area (but see Harris et al., 2018 for an anomalous example from the Kope Formation). Their massive skeletons, together with stromatoporoids and in some cases, solenoporids, formed local thickets or biostromes but in the Cincinnati region there were no true reefs. These form a special trophic category: not true suspension feeders, they utilize stinging tentacles to actively capture food particles including larvae and adult small invertebrates and not producing feeding currents. What is not clear at this time is whether any of the Ordovician corals possessed symbiotic zooxanthellae in their tissues, as do modern corals. There is some circumstantial evidence based on growth banding in certain Ordovician corals (and also stromatoporoids) that these colonies had growth rates comparable to those of living zooxanthellate corals in which secretion of the skeleton is strongly aided by the photosynthetic activities of their mutualistic symbionts.

The small solitary rugosan horn coral *Grewingkia* (Figure 28) and the solitary to weakly colonial *Streptelasma* occurred in vast numbers in some seafloors of the late Cincinnatian; presumably with an iceberg strategy (Thayer, 1974) in which the heavy conical skeleton was partially sunken in soft sediment though Elias and Butler (1986) has argued that curvature in the plane of bilateral symmetry may have been an adaptation to maintaining an orientation parallel to prevailing water currents. These corals were apparently invaders from more tropical waters to the paleo-north and form an important component of the so-called Richmondian invasion appearing first in abundance in the middle or Clarksville member of the Waynesville Formation (Holland and Patzkowsky, 2009).

Sponges

Sponges are an underappreciated component of the Late Ordovician fauna on the Cincinnati Arch. They are locally represented by a variety of forms, including skeletonized demosponges like

Dystactospongia, Heterospongia, and the large tuberous *Brachiospongia*. The small, round *Hindia* is found in certain beds. Far more numerous, in shallow water facies of the mid Lexington and upper Cincinnatian are massive, heavily calcified stromatoporoids such as *Labechia*, with hemispheroidal coenostea up to a meter across and the chaetetids, perhaps closely allied with living sclerosponges, including *Solenopora*, formerly regarded as a red alga (Riding, 2004; Kallmeyer et al., 2018), which formed pinkish, brain-like masses that are especially common in the Strodes Creek Member of the Lexington Formation near Winchester, Kentucky and the Grant Lake Formation near Flemingsburg, Kentucky. By analogy with living sponges these extinct forms probably filtered sea water by generation of their own feeding currents, using specialized flagellated cells termed choanocytes. Tuberosities of demosponges and small elevated mounds on the colony surfaces, mamelons of stromatoporoid sponges (Figure 29) may have promoted water flow off the colony surface to prevent stagnation.

Bryozoans

The lophophorates, bryozoans and brachiopods, were true filter feeders, that generated feeding currents using ciliated tentacles on their looped or coiled lophophores that produce rhythmic beats that propel water and suspended particles. Many of these organisms also have morphological adaptations that may have aided in water flow. The small bumpy monticules on the surfaces of many bryozoans (e.g. *Monticulopora*, *Constellaria*) may have served a Venturi function analogous to the mamelons of stromatoporoids.

Bryozoans form the majority of bioclasts in many Upper Ordovician limestones on the Cincinnati Arch. Some, such as *Parvohallopora*, *Dekayia*, *Constellaria* (Figure 38A) and others, were capable of surviving in relatively muddy environments not only because of active filter pumping but also via growing portions of their colonies up above the seafloor. Their slender branching shapes, adaptive for low energy environments, may also have helped in shedding sediment from the surfaces of colonies. However, most living bryozoans are sensitive to high turbidity, probably because suspended silt may clog their delicate filtration meshes.

Other bryozoans appear to have behaved opportunistically, encrusting surfaces and even other organisms. The hemispherical "gumdrop" bryozoan *Prasopora* may have initially attached to hard substrates: some specimens in the Lexington Limestone show scars of conical hyolithid shells on their undersurfaces of their colonies. However, as mature colonies these organisms had a broad flat base providing a large bearing surface on soft substrates. Large *Prasopora* are exceptionally common in the lower Lexington Formation (particularly the Grier Member) and form an epibole of regional extent that has been used in correlation with rocks of New York, Pennsylvania and the upper Mississippi Valley. An analogous bryozoan, *Cyphotrypa,* occurred in vast numbers in rather sparsely inhabited muddy lagoonal sediments in the Rowland Member of the Drakes Formation in north-central Kentucky. These bryozoans initially attached to shells and the imprints of bivalve shells preserved in the bases of their colonies provide the only record of aragonitic shellfish that are otherwise lost from the fossil record.

Brachiopods

Alongside bryozoans, brachiopods dominated the Cincinnatian seas. Many larval brachiopods may have initially settled on various hard substrates, but adults were more often free-resting on the seafloor. The large, broad surface area of shells in strophomenids like *Rafinesquina, Sowerbyella,* and *Strophomena* (Figure 30) is thought to have helped to distribute the weight of the free-resting brachiopods to prevent them sinking into soft muds, akin to a snowshoe (Thayer, 1975). The concentric growth rings or rugae of *Leptaena* not only provided increased frictional contact with the substrate but may have strengthened the shell against physical damage or possibly predation by nautiloid cephalopods. These flattened forms and the small dalmanellids like *Cincinnetina* (Figure 30; formerly *Dalmanella* or *Onniella*; see Jin, 2012) may have been an opportunistic, thriving in somewhat stressed low energy and perhaps low oxygen environments. Rhynchonellids (e.g. *Rhynchotrema*) were attached by pedicle stalks and typically were affixed to shell fragments or other hard substrates for at least part of their life history.

Some brachiopod taxa (e.g. *Orthorhynchula linneyi*, *Catazyga headyi*, *Glyptorthis insculpta*) are widespread yet stratigraphically restricted, making them excellent index fossils. Their broad distribution is likely a result of drifting planktonic larvae, though it is not entirely clear where these taxa originated or why their chronological range is so limited. They may have been opportunistic, capable of brief but spectacular bursts of abundance when conditions were temporarily favorable.

As with bryozoans, many Ordovician brachiopods produced structures that promoted water flow for efficient filter feeding. For example, the groove at the center of the valves (fold and sulcus) in *Vinlandostrophia* (formerly *Platystrophia*; see Zuykov and Harper, 2007), *Rhynchotrema*, and *Hiscobeccus* (Figure 45G), served to funnel the wastewater away from the lateral incurrent streams and may have induced a Venturi effect to promote water flow.

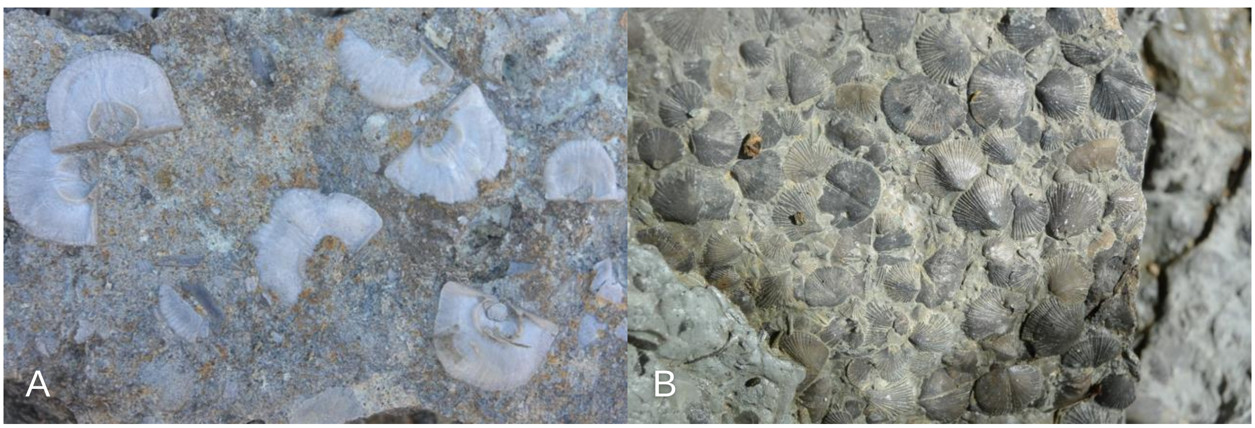

Figure 30. *Typical slabs of brachiopod-rich Cincinnatian limestone. A, disarticulated specimens of* Strophomena planumbona *(Liberty Formation at Garr Hill, Brookville, Indiana; valves are ~20 mm across); B,* Cincinnetina meeki *assemblage (Fort Ancient Member of the Waynesville Formation near Waynesville, Ohio; valves are ~10 mm across).*

Echinoderms

Echinoderms are among the most interesting Cincinnatian fossils. Most, such as edrioasteroids, crinoids, and cystoids, were likely passive suspension feeders, dependent upon the currents to bring suspended plankton into the vicinity of their food grooves. By analogy with living stalked crinoids, many Paleozoic crinoids with long pinnulate arms, such as *Glyptocrinus* and *Pycnocrinus*, are interpreted as having formed filtration fans. According to this model, such crinoids should be restricted to high-energy environments, but a few densely pinnulate camerate crinoids, including a recently described species of *Glyptocrinus* (Kallmeyer and Ausich, 2015), are found in mudstones indicative of a low energy depositional environment. Thus, these crinoids appear to have been successful in a range of rheological conditions.

In situ and ex situ study of modern crinoids has yielded considerable insight into crinoid feeding behavior (e.g. Macurda and Meyer, 1974). Many are "leeside" suspension feeders, recurving the backsides of their arms into the strongest water currents. Water flushes between pinnules to form a low-pressure zone

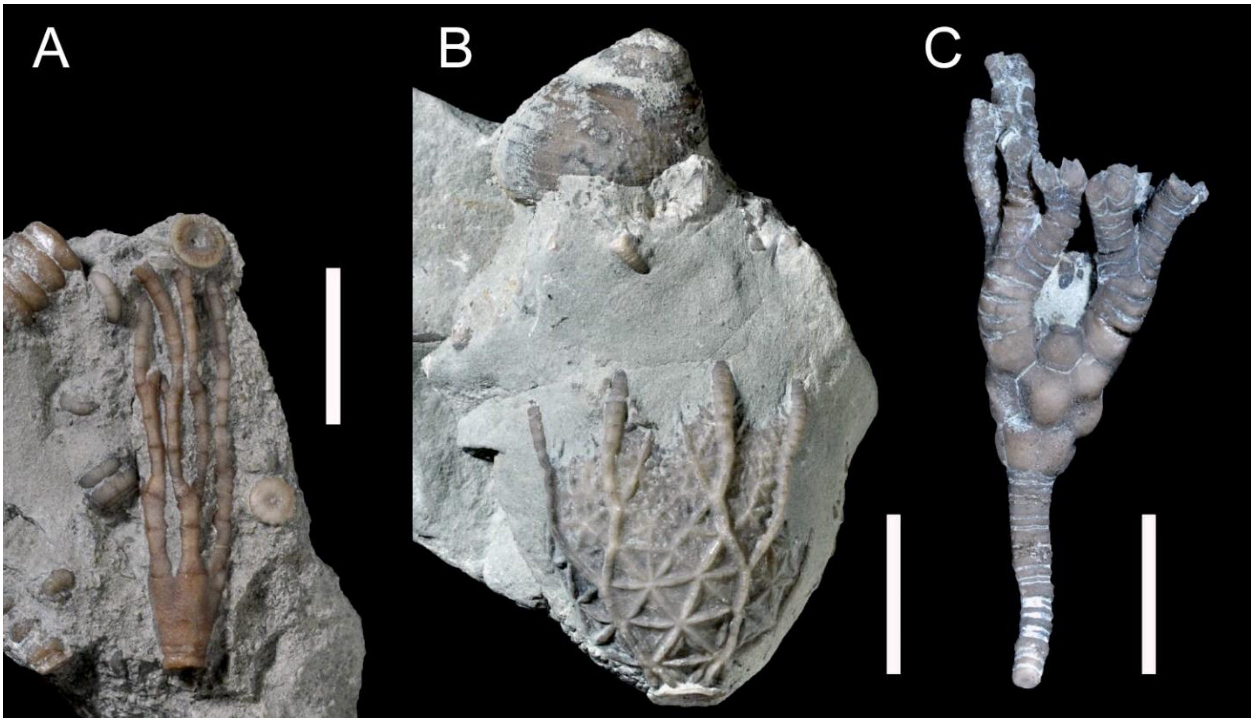

***Figure 31**. Typical Cincinnatian crinoids. A, simple disparid crinoid* Cincinnaticrinus varibrachialis *(Edenian-Maysvillian) with relatively simple arms; B, the camerate* Pycnocrinus dyeri *with attached parasitic(?) gastropod* Cyclonema *(Maysvillian-Richmondian); C, the cladid* Cupulocrinus polydactylus *(Richmondian) with thick arms and wide food grooves. All scale bars 10 mm. Photos by Jack Kallmeyer, courtesy of the Cincinnati Dry Dredgers.*

***Figure 32.** The edrioasteroid* Isorophus cincinnatiensis *attached to the large strophomenid brachiopod* Rafinesquina. *From the Corryville Member of the Grant Lake Formation once exposed near Florence, Kentucky. Edrioasteroids are locally abundant in certain beds, sometimes with multiple individuals (and multiple taxa) encrusting the same brachiopod. This relationship also has implications for* Rafinesquina *paleoecology; if the brachiopod was alive while encrusted, it must have lived concave-down. Scale is in mm. Photo by Jack Kallmeyer.*

on the other side, where any food particles are captured on the sticky tube feet and propelled into the cilia lined food groove. A combination of food and mucous then makes its way down to the centrally located mouth like a series of stream drainage systems. Thus, densely pinnulate arms would have been very efficient in food capture, but only if the current was sufficiently powerful to force water through the relatively dense meshwork of arms and pinnules.

However, Ordovician crinoids are quite diverse and certain species may have had feeding strategies that differed from the aforementioned modern highly pinnulate forms. Small disparid crinoids common in the deeper water environments of the Cincinnatian, such as *Cincinnaticrinus* (Figure 31A) and *Ectenocrinus*, lacked pinnules, instead possessing low flexibility, branch-like arms that may have used tube feet to capture particles from low energy water (Brett, 1984).

Typical Cincinnatian crinoids fed from a level around 20 to 50 cm above the seabed. Many, such as *Ectenocrinus*, were tethered by small, discoidal, multi-plated holdfasts, usually attached to shells (Brett et al., 2008c). Others were more elevated, with columns occasionally running 50 cm or more—Austin (1927) reported crownless stems of the Richmondian camerate *Canistrocrinus richardsoni* up to ~2 m (5-6 ft) in length along Cowan Creek in Clinton County, Ohio. However, in taxa such as *Pycnocrinus* (Figure 31B) it is uncertain whether the entirety of these columns was actually up in the water, as major segments of the distal stem formed loops that lay on the seafloor or intertwined with adjacent bryozoans or algae. By raising their crowns high above an inhospitable bottom, opportunistic crinoids could survive and even thrive in settings inimical to most other benthic life (Brett et al., 2008c). The large, unusual disparid *Anomalocrinus* was adapted to attaching to hard substrates, using volcano-shaped holdfasts (cf. *Podolithus*) cemented to hardgrounds, reworked concretions, and large bryozoans. These crinoids had extremely long columns that may have extended up to nearly a meter in length. Though articulated crinoids are rare in the Cincinnatian, so many long stems mean that individual ossicles are quite common, and crinoid columnals make up the dominant bioclast in many limestone beds.

Blastozoan echinoderms are extremely rare in the Cincinnatian, but the few that are present, such as the glyptocystitid rhombiferan cystoid *Cheirocystis*, lacked arms and instead had tiny coiled, thread-like brachioles. These were so slender that they had little or no space for tube feet and it has been suggested that these organisms lacked tube feet altogether (Sprinkle, 1973). If so, they must have fed in a very different way than crinoids, perhaps using mucoid secretions and cilia to trap microplankton. Like certain short-stalked crinoids, *Cheirocystis* must have fed from an intermediate position elevated a few centimeters above the seafloor. Another rhombiferan, the callocystitid *Lepadocystis moorei*, is known from the uppermost Cincinnatian (upper Whitewater and Elkhorn Formations).

Among the most iconic fossils of the Upper Ordovician in the Cincinnati area are edrioasteroids. These small coin sized echinoderms formed a small sub-circular disk of imbricated, scale-like plates, with five, typically curved upward facing ambulacra. These organisms attached to hard substrates by the aboral surface and utilized tube feet to capture food particles. They are commonly found attached to brachiopod shells (Figure 32) and, more rarely, bivalves and corals such as *Tetradium*.

Delicate ophiuroid echinoderms, or brittle stars, are very rarely preserved in Cincinnatian shales. Some were likely actively crawling scavengers and predators, using their entire slender sinuous rays to propel themselves along the seafloor in search of organic matter and microorganisms, which they process with the small "jaws" at the corners of their star shaped mouths. Many modern ophiuroids are suspension feeders, plucking particles out of the passing currents with tube feet or specialized spines on their arms, though it is unclear whether any Ordovician taxa shared this feeding strategy.

Close relatives of the ophiuroids, asteroids (starfish or sea stars) are known to be important predators in modern communities. These animals use tube feet to actively crawl across the seabed. Some forms are capable of wrapping their arms around bivalved prey such as clams and exerting a pull with their tube feet. Eventually, these animals weaken their prey sufficiently to allow a portion of the starfish stomach lining to be inserted and start digesting their victim's tissues. This same mode of life may have been present in the starfish of the Cincinnatian, as shown by a unique specimen of the *Promopalaeaster dyeri* preserved "red handed" with its arms wrapped around a bivalve shell (Meyer and Davis, 2009, figure 12.15D).

Annelids and Other "Vermes"

Infaunal deposit feeders are represented by trace fossils, particularly the feeding burrows *Planolites*, *Palaeophycus*, and *Chondrites* that are abundant and/or well preserved in silty beds. These are likely the traces of sediment mining worms, though in many cases, precise affinities of the burrowing organism are unknown. However, scolecodonts, the tiny chitinous jaws of polychaete worms, are abundant in some shales in the Cincinnatian, proving that this type of predaceous worm lurked within these muds (Eriksson and Bergman, 2003). The armored-plated machaeridians, now known to be annelid worms (Vinther et al., 2008), are also found in the Cincinnatian. Other worm-like organisms were suspension-feeding(?) encrusters, such as the tube-like *Cornulites* and spiraled "*Spirorbis*" (similar in shape to, but likely very distantly related from, the modern *Spirorbis*).

Arthropods

Arthropods are a vast group of jointed legged, skeleton shedding invertebrates. In the Ordovician they were represented by a number of dominantly marine organisms. It is as yet uncertain whether there were terrestrial forms, although burrows in the upper Cincinnatian redbeds of the Juniata and Queenston formations in the Appalachian Basin have been attributed to millipedes (Retallack and Feakes, 1987). Marine forms are diverse and represented by trilobites, eurypterids, and crustaceans. The latter includes ostracodes and (perhaps) the slightly larger bivalve forms known as leperditians, which may have scavenged detritus from the seafloor and were especially common in muddy shallow lagoonal settings.

Trilobites are the iconic fossils of the Upper Ordovician of the Cincinnati Arch. Two genera in particular were evidently highly abundant and rather eurytopic: *Flexicalymene* and *Isotelus*. Probably no Cincinnatian fossils are better known than *Flexicalymene*; these small forms were abundant in many muddy, offshore settings. As their name suggests, these trilobites had an ability to flex their bodies into a tightly coiled ball (Figure 33). Certain horizons within the soft "butter" shales of the Cincinnatian yield large numbers of articulated enrolled specimens and specific beds have been traced for tens of kilometers. These occurrences indicate mass mortalities and rapid burial (obrution) of seafloors. The trilobites evidently responded to pre-burial stresses by coiling into compact balls. Usually an effective defense, in certain circumstances this strategy may have been an "Achilles heel". When disturbance was followed by rapid sedimentation billions of trilobites were entombed in their own skeletal caskets (see Hunda et al., 2006 and Brett et al., 2012 for discussion of taphonomy of trilobite beds). The large asaphid *Isotelus* was apparently a generalist "weed" taxon: fragmentary remains of these trilobites are found in most all facies and may be locally super-abundant, forming the major bioclasts in some limestones of the Bromley Shale.

Trilobites lacked biting mouthparts and so were constrained to feeding on relatively soft food. Thus, they may have been partly detritivores or scavengers, feeding on decaying organisms. Certain trilobites, however, were probably predators on soft-bodied organisms. By analogy with modern horseshoe crabs, trilobites may have utilized the bristly inner joints of their legs (gnathobases) to grasp soft bodied organisms such as worms from within the sediment and pass them forward to the mouth, which was underlain by a wedge-shaped oral plate, the hypostome. In some cases, trilobites such as *Isotelus* may have worked food between anterior legs and the hypostome to break it down into small pieces to be ingested by a suctorial mouth. In rare cases from the Fairview Formation and elsewhere, the coffee bean shaped trace fossil *Rusophycus* have been observed to intercept a worm burrow in the sediment. Asaphid trilobites, such as

***Figure 33**. Large enrolled specimens of the trilobite* Flexicalymene *from the Cincinnati area. "*Flexies*", as they are known to collectors, are common and often well preserved. Disarticulated pieces, if not complete specimens, can be found in almost every Cincinnatian formation, though they somewhat rarer in the Mohawkian. Image courtesy of Brenda Hunda and the Cincinnati Museum Center.*

Isotelus had smooth, spade-like cephala that may have been adapted to furrowing in sediment after prey; they match in size and shape some large, closely associated *Rusophycus*. Other, smaller *Rusophycus* likely represent the traces of trilobites such as *Flexicalymene*.

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The Cincinnatian is also home to some of the oldest eurypterids, with multiple species of *Megalograptus* from the Richmondian Stage (Caster and Kjellesvig-Waering, 1964). Fragmentary specimens have also been found by collectors in older units, such as the Arnheim Formation and Corryville Member of the Grant Lake Formation, but remain unpublished. Another merostome, *Neostrabops martini*, has been described from a single specimen from the Corryville Member of the Grant Lake Formation along Stonelick Creek in southern Ohio (Caster and Macke, 1952).

Mollusks

Vagile benthic mollusks such as gastropods, bellerophontids, and monoplacophorans (tergomyans) are found in nearly every Cincinnatian formation. These snails and their close relatives had varied modes of life, but most were active crawlers, utilizing a muscular foot to navigate the seabed and a rasping radula to scrape up algae or detritus and prepare it for digestion. Similarly, polyplacophorans, or chitons, also slowly slid around on a muscular foot, but unlike the aforementioned groups, chitons were ensconced in a flexible series of plates, rather than a single conch. This group is all but unknown from Cincinnatian deposits; only a single incomplete specimen has been found (Puchalski, 2005), though several forms are known from the Mohawkian of Kentucky (Hoare and Pojeta, 2006).

Cyclonema, the prototypical platyceratid gastropod of Cincinnatian assemblages (Figure 31), may have lived as an active benthic scavenger or even predator. However, as with younger members of this clade, some *Cyclonema* were adapted to a more unusual sedentary mode of life, wherein the snails affixed themselves to the tegmens of camerate crinoids such as *Glyptocrinus* or *Pycnocrinus* (e.g., Morris and Felton, 1993; Figure 31). This relationship has often been interpreted as commensal, with the gastropods positioned over and likely feeding from the anal vents of the echinoderms (coprophagy) but doing their hosts no harm. However, other authors have argued that these snails could also be parasitic, injuring or otherwise negatively impacting the crinoids (Baumiller and Gahn, 2002).

Bivalves were also abundant in Cincinnatian waters, though as with most gastropods, their aragonite shells dissolved long ago, leaving only molds. Thus, they are a much less conspicuous element of the fauna than brachiopods, though they are extremely abundant and even dominant in some horizons. And, as with the gastropods, there are exceptions: similar to *Cyclonema*, the wing oyster-like pterineid *Caritodens* is often perfectly preserved in fine, brown calcite. Some bivalves were clearly epifaunal, such as the aforementioned *Caritodens* and the ribbed, mussel-like *Ambonychia*. The latter may even have had byssal threads, similar to modern mussels. Many others were infaunal or semi-infaunal, such as the common *Modiolopsis* and related modiomorphids. Bivalves are particularly common in silty or shaly units, though this could be a taphonomic bias against preservation in higher energy environments.

Predators in the Ordovician seafloor communities were relatively uncommon and surely not as significant as in modern communities. The master predators of the Ordovician waters were probably the nautiloid and endoceroid cephalopods. By analogy to modern cephalopods, notably the chambered *Nautilus*, these nektonic mollusks were likely active predators or scavengers. A typical nautiloid cephalopod probably swam using a form of jet propulsion by uptaking water into its mantle cavity and forcing it out through a narrow nozzle referred to as a hyponome. With the exception of *Nautilus*, *Allonautilus*, and *Spirula*, most modern cephalopods lack significant shells but the converse is true with Ordovician cephalopods, all of which were shelled. Most Ordovician cephalopod shells were straight (orthoconic) or slightly curved, though some coiled more tightly (e.g. *Charactoceras*, *Trocholites*), presaging the later ammonoids. Gas-filled chambers (septa) within these shells linked by a central tube (the siphuncle) aided in buoyancy control.

Ordovician cephalopods widely varied in size. The common *Treptoceras* typically grew to about 30 centimeters long, but the curious endoceroids were the real "monsters" of Ordovician seas, with conical shells up to several meters long and up to 30 centimeters in *diameter*!

Relatively sophisticated eyes enabled nautiloids to track prey, which they would then seize with a cluster of tentacles. These surrounded a mouth equipped with a sharp, parrot-like beak that could tear into soft tissue or weak exoskeletons. A number of brachiopods in the Cincinnatian show scallop-shaped divots in their exoskeletons that are interpreted as bite marks (Alexander, 1986). These may very well record predatory strikes by large nautiloids, though some of these brachiopods clearly survived the attacks and lived to partially heal their wounds.

Graptolites

The pelagic, open water fraction of Ordovician ecosystems was rather sparse compared with modern marine environments, or at least rarely preserved. However, among the most important groups of Ordovician fossils are several long-enigmatic organisms that floated or swam in the water column: the graptolites and conodonts. Widely distributed and common across many different environments, these cosmopolitan skeletal remains are essential to biostratigraphy, the practice of correlating rock units based on their fossil contents.

Graptolites are an extinct group of colonial hemichordates with an elongated, often sawblade-shaped colony or rhabdosome. The thecae were occupied in life by filter feeding zooids with ciliated crowns of tentacles. These aspects are inferred from living pterobranchs, little known deep sea organisms with colonial proteinaceous skeletons that show remarkable similarities to graptolites. Late Ordovician graptolites are generally preserved as carbonized specimens but concretions in the Cincinnatian have yielded three-dimensionally preserved rhabdosomes. These include essential index fossils such as *Diplacanthograptus spiniferus*, which occurs in the Lexington Limestone and lower Kope Formation, and the tiny *Geniculograptus pygmaeus,* nominal species of the *pygmeaus* Zone that includes the upper Kope and Fairview Formations (Mitchell and Bergstrom, 1991).

On the Cincinnati Arch graptolites are most common in the Kope Formation, and only rarely found in older or younger strata. However, certain planktonic forms are known from the Fairview and Arnheim Formations (the latter including the eponymous *Arnheimograptus*), and enigmatic dendroids such as the whip-like *Mastigograptus*, the bottle brush-like *Inocaulis* (often found in lagoonal deposits and possibly a dasyclad alga), and the encrusting, diminutive *Chaunograptus* are known throughout the Cincinnatian.

Chordates and Conodonts

Although of the first vertebrate faunas are known from the Upper Ordovician marginal marine strata of Laurentia, including famous occurrences in the Mohawkian-age Harding Sandstone of Colorado and more sporadic reports from Ontario and Michigan, no such fossils are known from the Cincinnati Arch region, despite intensive sampling for over a century. However, while the Late Ordovician marine environments of eastern North America may have been "seas without fish" (Meyer and Davis, 2009), they were teeming with possibly related protovertebrates: the diminutive conodont animals. Conodonts are minute tooth-like elements composed of apatite, similar in composition to vertebrate teeth. Their owners were long shrouded in mystery, but exceptionally preserved specimens discovered since 1980 (e.g. Briggs et al., 1983) have revealed that conodonts were actually parts of natural assemblages (the so-called “conodont apparatus") lodged in the pharynx of tiny lamprey-like animals with circular mouths and large eyes. These animals were apparently chordates and perhaps even very primitive vertebrates. Because conodont elements are widespread in marine facies and were derived from organisms that evolved rather rapidly, conodonts are the "gold standard" of biostratigraphy. As a bonus, conodonts can easily be recovered from limestones by dissolving the rock in dilute acids and concentrating their residues. The Upper Ordovician rocks of the Cincinnati Arch frequently lack graptolites, making conodont zonation is the primary guide to relative age. Several important conodont zonal boundaries intersect the Cincinnatian, notably the *Amorphognathus superbus* - *Amorphognathus ordovicicus* transition in the basal Richmondian, which marks the Ka2-Ka3 stage slice boundary.

Communities and Faunal Gradients

Carlton E. Brett

The Upper Ordovician strata of the Cincinnati Arch have been studied extensively from the standpoint of community paleoecology. Earlier works included studies of Fox (1962), Hatfield (1968) who used statistical techniques to recognize recurrent groupings of marine invertebrates in the Cincinnatian. More recently, the use of gradient analytical techniques enabled researchers to identify gradational patterns of distribution of species along paleoenvironmental gradients. In pioneering studies, Dattilo (1996), Holland et al. (2001) and Miller et al. (1997, 2001) were able to identify recurring gradients of fossil distribution primarily related to depth using the technique of detrended correspondence analysis (DCA) to identify gradational patterns of distribution of fossil taxa. Their datasets included relative abundance information of fossils among hundreds of samples of fossil assemblages sampled systematically through the Edenian Kope and Fairview formations. Furthermore, by quantifying successive samples using DCA scores the researchers were able to produce curves for stratigraphic sections that permitted a proxy of relative sea level fluctuation and provided a technique for correlation using pattern matching of cyclic reversals. By combining sedimentological indicators, such as desiccation cracks and evidence for photic position from microendoliths and other depth information Brett et al. (2015a) inferred actual depth gradients along particularly well correlated horizons such as the Mount Auburn Member of the upper Maysvillian Grant Lake Formation. Here they argued for a northward dipping ramp ranging from average sea level (intertidal) to a depth of about 30 to 40 m over ~200 km, suggesting gradients of just 10 to 20 cm per km (Figure 34.)

A typical gradient in the Late Ordovician commenced with low diversity assemblages in deeper, muddy and commonly low oxygen settings seen rarely in the deeper facies of the Kope Formation and its offshore equivalents in the dark, organic rich Utica facies in the subsurface north of the outcrop belt. These assemblages are typified by small lingulate brachiopods such as *Leptobolus* and the trilobite *Triarthrus*, which may have been a low oxygen specialist. These benthic fossils are typically associated with abundant graptolite rhabdosomes, representing pelagic organisms whose organic skeletons accumulated preferentially in low oxygen settings that inhibited scavenging. Indeed, some Utica facies are devoid of benthic fossils but yield abundant graptolites.

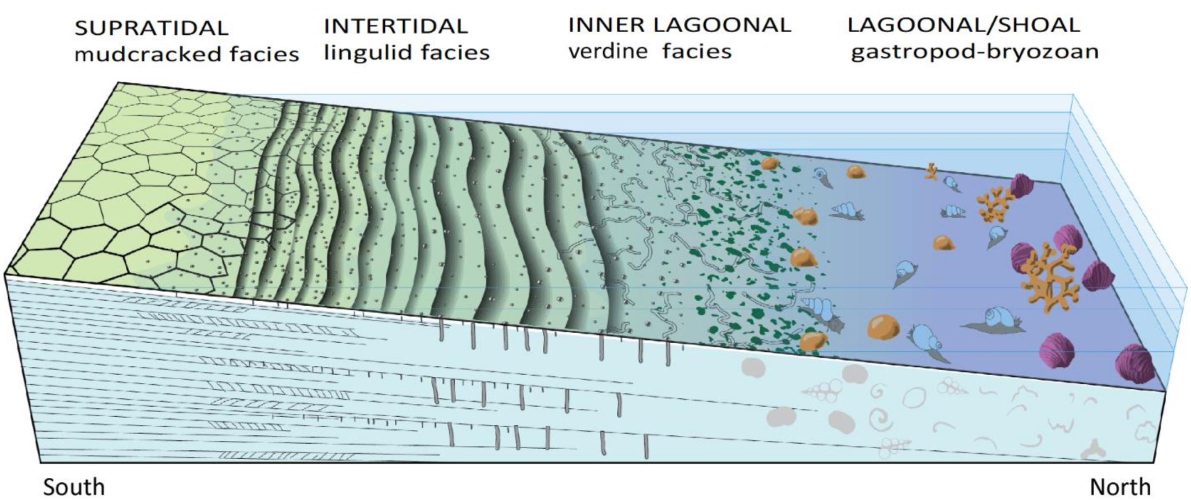

Figure 34. *Regional cross-section of an idealized, northward sloping paleoramp in the Late Ordovician of Kentucky, ranging from peritidal (to the south; left) to shallow subtidal (in the north; right). Drawing by B. Dattilo.*

Low energy offshore settings only affected by the deepest storm waves were inhabited by a somewhat higher diversity of benthic forms including small ramose bryozoans, and delicate but long-stemmed crinoids such as *Ectenocrinus* and *Cincinnaticrinu*s. A low diversity of small brachiopods, especially dalmanellids and in some levels the strophomenid *Sowerbyella* were abundant in these settings; many of these show “snowshoe” morphologies adapted to resting on soft soupy mud substrates. Thin siltstones or calcisiltites with guttered bases, tool marks and small scale hummocky lamination are common and represent distal storm silt flows.

A greater diversity of typically larger branching, frondose or mounded bryozoans occur in deeper subtidal facies. The larger strophomenids, *Rafinesquina* and in some Richmondian age beds *Strophomen*a and various small species of *Vinlandostrophia* were typically prolific in these storm-affected portions of the shelf often occurring in dense, edgewise stacked pavements reflecting disruption and aggregation of skeletal remains under the influence of deep storm waves and currents. In the Richmondian these settings supported higher diversities of brachiopods (e.g., *Hiscobeccus*, *Leptaena*, *Plaesiomys*, *Glyptorthis*) and abundant solitary rugose corals (*Grewingkia*).

Shelly accumulation and reworking by storms during periods of low sediment influx permitted the buildup of thin packstone or even grainstone beds, that show sharp bases and rippled tops characterized by mixed well preserved and disarticulated, fragmented skeletons (see Brett et al., 2008; Dattilo et al., 2008 for discussion of sediment starvation model for shell beds). Stabilized pavements of shells during times of relative sediment shutoff, provided substrates for coin-sized edrioasteroids such as *Isorophus* (Meyer, 1990). Larger and somewhat more robust camerate crinoids, such as *Glyptocrinus*, behaved opportunistically and in some cases formed dense clusters on muddy seafloors (Milam et al., 2017).

Mudstone rich facies, often represented by very soft “butter” shales tended to occur in highstands when mud deposition predominated over skeletal buildup; these facies have been studied in detail by Frey (1986) and more recently by Aucoin et al. (2015, 2016). In mud and silt rich settings mollusks such as *Ambonychia*, *Caritoden*s and modiolopsid bivalves and in some cases gastropods and nautiloids (e.g. Treptoceras) are common and well preserved often with black periostracal films preserved on shell exteriors. These facies are also famed for their spectacular often articulated trilobites, such as *Flexicalymene*, commonly occurring as enrolled specimens, and the large *Isotelus*. Annelid worms were often abundant in these mud bottom settings as indicated by abundant scolecodonts.

Still shallower water facies, approaching average storm wave base, are recorded in wavy bedded, often muddy packstones such as those represented in the Grant Lake Formation. Macroscopic algae as well as microendoliths in shells suggest that these sediments accumulated in well-lit, shallow euphotic zone waters (Vogel and Brett, 2009). During much of the Katian, these facies were typified by of robust branching or frondose bryozoans and a few species of overwhelmingly abundant brachiopods, especially *Hebertella* and, in the Maysvillian to early Richmondian, the robust orthid *Vinlandostrophia ponderosa.* These latter occur by the millions with preservation ranging from closed articulated and infilled with geodal spar, to highly fragmented, corroded and commonly blackened valves. This suggests strong reworking and time-averaging. Probably these sediments were intermittently stirred by numerous storm waves, but on the whole these sediments accumulated in low energy settings. Crinoids tend to be less common in these settings but in some cases, especially where hardgrounds were developed, edrioasteroids were present.

In some cases the normal wave base zone is marked by typically narrow belts of cross bedded skeletal grainstones composed of skeletal fragments, including bryozoans and crinoid debris or even gastropods, especially *Loxoplocus* in the well-known Devils Hollow and Marble Hill shell beds (Swadley, 1978). At some levels, large stromatoporoid sponges and colonial corals occur abundantly in these high energy settings.

Upramp from these high energy shoals are very distinctive facies interpreted as recording broad shelf lagoonal settings. These are typified by interbedded light gray to greenish gray micritic limestone, commonly slightly fossiliferous wackestones and thin, very dark gray shales. The latter are typically sparsely fossiliferous but may contain abundant carbonized remains of small non-calcified green algae. The wackestones contain a few species of brachiopods especially *Hebertella*, and ramose and domal bryozoans, as well as abundant *Caritodens* and modiolopsid bivalves, gastropods and nautiloids sometimes very well preserved. In some cases colonial corals like *Cyathophylloides*, *Tetradium* and or stromatoporoids and solenoporid as demosponges sponges may be very common.

These distinctive rhythmically banded facies must represent oscillating conditions from nearly pure lime mud accumulation to more clay rich, dysoxic muds. These alternations may record a longer term climatic oscillation perhaps related to Milankovitch precessional cyclicity. Varied evidence suggests that these facies represent low energy but rather shallow, probably just 5 to 10 m of water.

Finally, the most upramp facies found in southern and western portions of the Cincinnati Arch are represented by pale greenish gray, buff weathering argillaceous and commonly dolomitic micrites and mudstones. Many of these show very thin, slightly wavy laminae and small-scale ripples and some bedding planes exhibit well developed small scale desiccation cracks indicating periodic emersion. Fossils are rare in these facies. Some of the more distal green gray shales show horizontal burrows, a few bivalves and may yield domal bryozoans such as *Cyphotrypa*. Slightly more inshore facies may contain small in situ linguloid brachiopods and a variety of ostracodes and/or leperditians. These facies indicate muddy inner lagoons to tidal flat and supratidal environments. These facies may be thick in certain portions of the section. The aggradation of thicker successions of tidally laminated muds may indicate a balance between slow base level rise and sediment accumulation in early transgressions.

The Cincinnatian as a Case Study for the Evolutionary Paleobiology of Biotic Invasions

Carlton E. Brett, Alycia L. Stigall, Kyle R. Hartshorn

The Upper Ordovician strata of the Cincinnati Arch have served as a natural laboratory for testing of ideas in evolutionary paleoecology. In a series of papers Holland and Patzkowsky (2004, 2007) and Patzkowsky and Holland (1993, 1997, 1999, 2007) first established and then utilized a sequence stratigraphic framework of major 3rd order sequences to examine patterns of biotic change and stability within these rocks. This basic framework provided a backdrop for their studies and those of subsequent workers to temporally constrain biotic patterns with greater precision than many prior analyses and has also served as a platform across which additional sequence stratigraphic refinements could be built (see discussion in this volume).

In an early paper, Patzkowsky and Holland (1997) used data on the distribution of taxa within the Upper Ordovician of eastern Laurentia to test for the presence of blocks of stability earlier recognized by Brett and Baird (1995) in the Silurian-Devonian of the Appalachian Basin and referred to them as ecological evolutionary subunits (EESUs). Patzkowsky and Holland (1996, 1997) identified within brachiopod and coral faunas a somewhat similar pattern, with major faunal shifts associated with certain sequence boundaries in eastern Laurentia as a whole. These events included a faunal extinction and turnover at the M4-M5 sequence (High Bridge-Lexington contact, locally) associated with an apparent climatic change recorded in changing carbonate lithologies. Although not evident in the Cincinnati Arch region, where M4 is recorded in shallow to peritidal micritic limestones with low diversity faunas, overall this event resulted in a loss of biodiversity; rhynchonelliform brachiopods suffered about 77% species loss across the Laurentian craton. Certain taxa disappeared locally from the Cincinnati Arch region but persisted elsewhere, primarily in warmer water tropical environments of the Red River province.

Another critical faunal change occurred in the later Cincinnatian Richmondian Stage near the C4-C5 boundary previously recognized by Foerste (1912) that Holland (1997) termed the "Richmondian Invasion". During this time, more than 60 genera representing as many as five phyla appeared relatively abruptly in the Cincinnati region (see list in Lam, 2015). These included warmer water taxa derived from the present day northern US and Canada (close to the Ordovician equator), such as the corals *Grewingkia*, *Cyathophyolloides*, *Protaraea*, and others, as well as certain brachiopods, supporting the older "Arctic hypothesis" of Foerste (1912). More recent study indicates greater complexity and that there may have been multiple waves of invasion from different source areas, including both mid-continent regions and cooler water areas near the Laurentian margin (Jin, 2001; Wright and Stigall, 2013; Bauer and Stigall, 2014; Lam and Stigall, 2015). Thus, it is likely that relatively high sea levels and altered current pathways facilitated invasion from multiple formerly isolated regions (Lam and Stigall, 2015; Lam et al., 2018). A more detailed high-resolution stratigraphy should enable a more nuanced view of these invasions and their relative timing and may provide further insights into a time of probable rather rapid climatic/eustatic change.

Two principal faunal turnovers were recognized by Patzkowsky and Holland (1997). However, ongoing studies by Brett et al. (2015b) and Aucoin and Brett (2016) indicate that there were in fact other incursions, including a number of short-lived minor appearances or incursion epiboles (Brett and Baird, 1997; see Stigall and Fine, 2018). Additionally, other more significant invasion events, originally identified by Foerste (1914), have not yet received detailed modern study. One of these took place during the late Mohawkian, associated with Holland and Patzkowsky's (1996) sequence M6, the upper Lexington/Point Pleasant (or Cynthiana of older usage). This event includes the abrupt appearance and/or proliferation of a number of clonal animal taxa, including *Cyathophylloides*, stromatoporoids, and probable chaetetids (*Solenopora*), as well as a brachiopod fauna, including *Orthorhynchula* and *Rhynchotrema*, that characterize the later Cincinnatian faunas. This was first pointed out by Foerste (1914), who called it a precursor Fairmont fauna, in reference to the upper member of the Fairview Formation (lower Maysvillian). Stromatoporoid and coral-rich strata (Stamping Ground, Strodes Creek, Devils Hollow) were widely distributed at this time, not only in the Lexington platform region of central Kentucky but also on the Nashville Dome and in eastern Tennessee (Young et al., 2014). These occurrences deserve additional study.

A second important event might be characterized as the Kope or "Rogers Gap" incursion, a fauna described extensively Foerste (1914). This turnover took place in the transition from the upper Point Pleasant and Kope Formations (the Rogers Gap of Foerste). A number of brachiopods, including *Sowerbyella*, *Eridorthis*, *Leptaena gibbosa*, and *Clitambonites*, either appeared or abruptly proliferated at this time, as did the crinoids *Merocrinus*, *Ectenocrinus* and others (Foerste, 1914). Similarly, the glyptocystitid rhombiferan *Cheirocystis fultonensis* appears suddenly in the uppermost Point Pleasant and basal Kope (Fulton submember). Ross and Ross (2002) observed the influx of more than 20 new bryozoan species into the Cincinnati arch, as well as the loss of some long-standing species at this time. These faunal turnovers may be nearly as significant and abrupt as the Richmondian invasion but as yet they have received little detailed study and have not even been identified as such by most workers.

Studies by Holland and Patzkowsky (2007) quantified patterns of faunal gradients with a time-environment approach. They specifically recognized, based on independent sedimentological data, a series of shallow to deeper zones that included: 1) peritidal and nearshore, 2) shallow subtidal, close to fairweather wave base, 3) deeper subtidal and 4) offshore, below average storm wave base (mainly siliciclastic mudstones). Using data obtained from systematic sampling within 3rd order depositional sequences, these researchers were able to quantify gradients of onshore to offshore species composition through time using multivariate statistical techniques, especially non-metric multidimensional scaling (NMMDS) and detrended correspondence analysis (DCA) and to compare these gradients for time slices based upon their own 3rd order sequence stratigraphic framework (Holland and Patzkowsky, 2002, 2007). They were able to show the persistence of gradients, despite minor modifications, through considerable spans of time as represented by multiple 3rd order sequences, suggesting relative niche stability (Holland and Patzkowsky, 2007). However, the extent of species persistence within individual EESUs recognized in the pattern of coordinated stasis reported especially from the Middle Devonian of the Appalachian Basin (Brett and Baird, 1995; Brett et al., 1996, 2007) was not demonstrated to occur through the span of several sequences. Rather, a somewhat more volatile pattern of species-level turnovers among the various 3rd order sequences was documented.

Holland and Patzkowsky (2007) also quantified faunal gradients and patterns of community stability during the C1 (Edenian, Kope Formation) to C6 (Elkhorn sequence in previous terminology; revised as C8 herein) sequences to consider ecosystem impacts of the Richmondian Invasion. They found that gradients and faunal composition, at least at a generic level, were relatively consistent during the C1 through of C3 sequences, representing a time span of perhaps 5 million years. Further studies of Malizia and Stigall (2011), Brame and Stigall (2014), and Stigall (2014) demonstrated niche conservatism and habitat tracking within most taxa during this pre-invasion interval.

However, late in the C4 sequence (Arnheim Formation of local lithostratigraphy) gradients appeared to break down with the loss of previously dominant taxa (e.g., *Vinlandostrophia ponderosa*, which persisted through much of lower C4 only to become abruptly rare or absent higher in the sequence), offshore taxa invading previously shallower subtidal zones and a series of epiboles of taxa such as *Leptaena richmondensis*, *Rhynchotrema dentatum*, *Strophomena*, and very rare steptelasmid rugose corals, all of which would become common higher in the Richmondian. These lines of evidence suggested to Holland and Patzkowsky (2009) that there was instability during a time of transition into the full Richmondian Invasion. We point out, however, that epiboles such as those noted in the Arnheim also occur throughout the Lexington and Cincinnatian (see, for example, Stigall and Fine, 2018) and may not be a unique feature of C4. Following a return to relatively stable Cincinnatian conditions and an abundance of generalist taxa in the lower part of C5 (Stigall, 2010), Holland (1997) recognized the full-on Richmondian Invasion and Holland Patzkowsky (2007, 2009) documented substantial change in faunal gradients, including some departure in the position of a few taxa (such as sowerbyellid brachiopods) along the relative depth gradient.

The rather coarse time-binning of most of the mid-to-upper Richmondian (Waynesville, Liberty, and Whitewater Formations) as C5 hinders a detailed understanding of the patterns of invasion. The revised sequence stratigraphic interpretations presented herein may improve this resolution, as the former C5 has been broken down into three 3rd order sequences (C5 to C7) and 4th order sequences have been identified for some of the sequences (e.g., C5A through C5C for the lower to middle Waynesville). Aucoin and Brett (2016) further postulated that much of the successful Richmondian Invasion (as opposed to a few earlier, short-lived incursion epiboles; see Brett et al. 2015b) occurred at, or immediately before, the deposition of the Clarksville Member 4th order depositional sequence (the Clarksville phase of the Invasion; C5C of the present sequence classification) and perhaps in a fraction of the longer time interval of incursion, originally postulated to be about half a million years. There also appears to have been a later and separate phase of invasion that largely involved molluscan taxa, especially nautiloids and bivalves, which occurred at or near the base of the lower Whitewater depositional sequence (C7 of present classification).

Remarkably, the Richmondian invasion, in contrast to faunal turnovers recorded in the Devonian of the Appalachian Basin (Brett and Baird, 1995; Rode and Lieberman, 2004; Brett et al. 2009; Stigall, 2012), showed limited loss of brachiopod taxa (the extirpation of *V. ponderosa* is a notable exception, though other *Vinlandostrophia* remained abundant), although there is evidence in the data of Ross and Ross (2002) of the loss of more than 15 bryozoan species. In fact, the Cincinnatian fauna displays an *increase* in total species richness as incumbent taxa and invaders mingled in some settings.

Aspects of the Richmondian diversity patterns, however, closely mirror those observed during the Late Devonian Biodiversity Crisis and other intervals with of significant interbasinal invasion in Earth history (Stigall et al., 2017). In general, incumbents that survived through the full Richmondian interval were eurytopic generalists (Stigall, 2010). Stigall (2010) further showed that the successful invaders were eurytopic taxa with broad geographic ranges prior to their incursion. Furthermore, speciation declined to near zero during the primary invasion interval of the C4 and early C5 sequences. Speciation decline is a common feature of interbasinal invasions and is attributed to the loss of specialist taxa, which are characterized by higher speciation rates, as well as the lack of opportunities for population isolation during invasive regimes due to interbasinal connectivity (Stigall 2012; Stigall et al., 2017). This conceptual framework is supported by detailed ecological niche modelling studies by Malizia and Stigall (2011), Walls and Stigall (2011), Stigall and Brame (2014), and Stigall (2014) that demonstrated restriction in the geographic/ecological range (niche evolution) of both incumbents and invaders across the late C4 and early C5 sequences. In summary, this suite of analyses demonstrates that species adjusted to the increased competition on the seafloor via niche partitioning. Species contracted their niche occupation to the core preferred niche. Ecological generalists had the capacity to contract and continue to maintain viable populations, whereas ecological specialists did not and went extinct. Only after the final waves of the invasion ended and the community structure restabilized in the later Richmondian sequences did speciation and production of ecological specialists resume (Stigall, 2010; Stigall et al. 2017).

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MID-MEETING FIELD TRIP

Carlton E. Brett, Kyle R. Hartshorn, Christopher D. Aucoin, Thomas J. Schramm, T.J. Malgieri

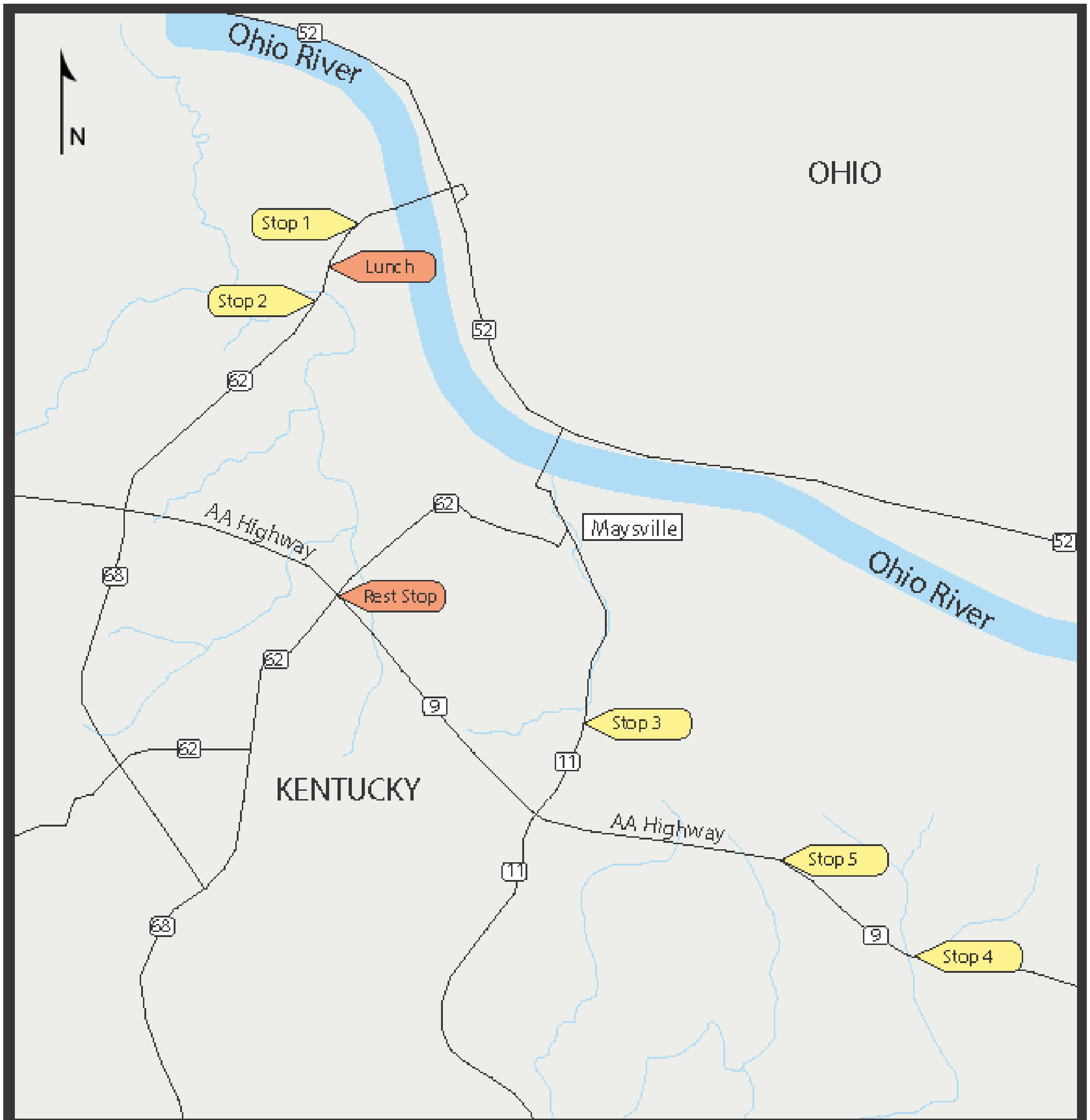
Excursion to Maysville, Kentucky, and Vicinity

This teaser of a field trip will provide a brief but worthwhile appetizer of the fossil riches that the Cincinnatian has to offer. A historic river town, Maysville and surrounding counties are a classic study area for the Upper Ordovician Cincinnatian Series, and the type region for the middle Cincinnatian Maysvillian Stage (middle upper Katian). Cincinnati itself is roughly 80 km (~50 miles) to the northwest, downstream along the Ohio River.

The hilly Kentucky countryside in between the Greater Cincinnati area and Maysville is traversed by the Alexandria-Ashland Highway (AA Highway or Kentucky Route 9, in part). Construction of the AA Highway resulted in dozens of roadcuts, many spaced in relatively close proximity, which have enabled high resolution, bed-by-bed stratigraphic correlation (Brett and Algeo, 2001). These findings rehabilitated traditional but previously less favored “layer cake” models of regional stratigraphy, showing that stratal packages and even individual beds, each with their own distinctive fauna, lithology, and sedimentary structures, are predictably traceable from outcrop to outcrop for many tens of kilometers. Most of these exposures cut through the Kope Formation, which comprises the lower Cincinnatian Edenian Stage. A few include lower (upper Point Pleasant; uppermost Chatfieldian to basal Edenian) or higher strata (Fairview Formation; lower Maysvillian).

Near Maysville itself, and just to the east, the AA Highway and other major routes (US Highway 62, US Highway 68, Kentucky Route 11, etc.) completely expose the Fairview and Grant Lake formations, effectively providing a composite reference section for the North American Maysvillian Stage. Heading east on the AA past Maysville, there are several outcrops of the lower Richmondian Bull Fork Formation (equivalent to the Arnheim and Waynesville Formations of Ohio), and, near Tollesboro, the Ordovician-Silurian boundary is exposed at outcrops that show the contact between the Preachersville Member of the Drakes Formation (upper Richmondian) and the Lower Silurian (Llandovery, Rhuddanian-Aeronian) Brassfield Formation. See Peck (1966) for more on the Ordovician geology of the Maysville area.

Eastward still, one encounters the late Llandovery to Wenlock-age Estill Shale and Bisher Formation around Charters, the black, platy Upper Devonian (Famennian) Ohio Shale starting near Vanceburg, towering roadcuts in the Devonian-Mississippian Berea Sandstone (with spectacular, large-scale soft sediment deformation features) near Garrison, and the Lower Mississippian Sunbury Shale and deltaic Borden Formation. Proceeding east again, now into the Appalachian Basin, there are Lower and Middle Pennsylvanian strata, including the coal beds typical of the period. Thus, these humble byroads of rural Kentucky expose a section of the Paleozoic spanning roughly 145 million years, all accessible within a single day of driving. For a more complete picture of the geological wonderland that is the AA Highway, see Potter et al. (1991).



Stop 1: US 62 / US 68 west of Maysville, Kentucky ("The Big Maysville Roadcut")
Stop 2: US 62 / US 68 south of Lawrence Creek, west of Maysville Kentucky
Stop 3: Roadcuts on KY 11 ~0.6 miles north of the AA Highway at Maysville, Kentucky
Stop 4: AA Highway west of KY 1449 (Orangeburg Road) near Orangeburg, Kentucky
Stop 5: AA Highway northwest of Clarkson-Sherman Road, south of Maysville, Kentucky

Figure 35. *Map of the Maysville, Kentucky area with stops to be visited during the mid-meeting field trip.*

Mid-Meeting Field Trip Road Log

This road log starts at the Ohio-Kentucky state line on the William H. Harsha Bridge, with the assumption that the reader is approaching Maysville from the north (as will be the case with this field trip coming from Athens, Ohio). In addition to key turns and stops (**bolded**), the log calls out other outcrops that will not be subjects of the current field trip but may be of interest to future visitors, plus useful local landmarks to aid wayfinding. Distances are in miles, for ease of use with American odometers.

Total	*Increment*	*Description*
0.0	0.0	Ohio River (the second largest river in the United States by discharge, over 1500 km long; downstream is to the right, northwest)
0.5	0.5	Drive southwest on US Highway 62 / US 68 over the William H. Harsha Bridge
0.6	0.1	Kentucky side of river; pass ramp for Kentucky Route 8
0.8	0.2	**Stop at the base of large roadcut on US 62 / US 68**

Stop 1A: Lower end of the great US 62 / US 68 roadcut

Beds exposed in the lower outcrop and adjacent ditches comprise the Edenian age Kope Formation, especially the Southgate Member, Alexandria submember. The shales and thin siltstones or limestones show the prominent cyclicity of the Kope and yield a moderately diverse fauna.

1.2	0.4	**Continue south (uphill) to the approximate middle of the roadcut**

Stop 1B: Middle of the great US 62 / US 68 roadcut

The middle part of the roadcut offers the opportunity to explore the closely stacked, bryozoan-rich packstones of the upper Kope Formation, particularly the Grand Avenue submember.

1.5	0.3	**Continue south to upper (southern) end of roadcut, just north of junction with Germantown Road (Kentucky Route 3056)**

Stop 1C: Upper end of the great US 62 / US 68 roadcut near the KY 3056 junction

The upper end of the roadcut exposes the silty Taylor Mill submember (uppermost Kope), rich in trace fossils. It is overlain by the basal Fairview Formation (Mount Hope Member) at the C1-C2 sequence boundary.

1.6	0.1	**Turn right (west) onto KY 3056**
1.65	0.05	Immediately west of US 62 / US 68, **turn right (north) onto Pickett Lane**
2.0	0.4	**Drive north on Picket Lane to entrance of Cummins Nature Preserve (on left)**

Lunch Stop: Cummins Nature Preserve

This small local nature preserve offers a picnic ground, restrooms, and Kentucky scenery.

2.3	0.3	**Reverse direction and head south on Pickett Lane, back toward US 62 / US 68**

3.2	0.9	**Turn left (east) onto KY 3056**
3.25	0.05	**Turn right (south) onto US 62 / US 68**
3.3	0.05	Cross the John P. Loyd Memorial Bridge over Lawrence Creek
3.4	0.1	**Pull off on the shoulder at a large outcrop along US 62 / US 68**

Stop 2A: North end of roadcut on US 62 / US 68 just south of Lawrence Creek (optional)
This roadcut provides an easier way to inspect the upper Fairview Formation (Fairmount Member), versus climbing up on the big roadcut at the previous stop.

3.8	0.4	**Continue south to the south end of the roadcut**

Stop 2B: South end of roadcut on US 62 / US 68 just south of Lawrence Creek (optional)
The southern end of this cut exposes the uppermost Fairview Hill Quarry beds, with large crinoid columnals, and the overlying brachiopod and bryozoan rich rubbly packstones of the Bellevue Member of the Grant Lake Formation. The contact between the two units is the C2-C3 sequence boundary.

4.0	0.2	Drive south, passing a small outcrop of Grant Lake Formation (Corryville Member)
4.2	0.2	Outcrop of Grant Lake Formation near milepost 16
4.8	0.6	Small outcrop of Grant Lake Formation
5.1	0.4	Small outcrop of Grant Lake Formation
6.0	0.9	**Take exit for AA Highway**
6.4	0.4	**Turn left (west) onto AA Highway (Kentucky Route 9)**
6.7	0.3	Roadcut of upper Grant Lake Formation at the entrance ramp to US 68
8.5	1.8	Roadcut on both sides of AA highway in hill slope (for access, park to right/south in parking lot at top of hill and walk back down to cut); not an official stop for this field trip, but has some features worth noting: middle-upper Grant Lake Formation, with a series of ledgy pack- to grainstones separated by rubbly/shaly packstones rich in large, robust, and fully articulated *Vinlandostrophia ponderosa* and *Hebertella* sp. brachiopods, as well as bryozoans, nautiloids, and rare cyclocrinitids; pinkish phosphate granules are interspersed with fossil debris
8.7	0.2	Pass junction with US 62 / US 68; the latter highway leads to a large number of lower to middle Cincinnatian and upper Mohawkian roadcuts between and around Mays Lick and Millersburg; those localities are currently under study by the present authors but sadly outside the scope of this field trip
9.2	0.5	Major shopping plaza with Kroger, etc. on the right (south side of the road)
9.5	0.3	Small outcrop of Mount Auburn Member of the Grant Lake Formation on left (north) side of the road
9.6	0.1	Shopping plaza with Walmart and outcrop of Arnheim Formation in back (on right)

10.0	0.4	Pass junction with Kentucky Route 1448 (Maple Leaf Road)
10.6	0.2	Low outcrop in the uppermost Grant Lake Formation (Mount Auburn Member) and Arnheim Formation
11.0	0.4	Outcrop of the upper Arnheim Formation (Oregonia Member)
11.3	0.3	Good section of Arnheim Formation (Oregonian Member) with *Leptaena*-rich beds near the middle
11.4	0.1	Outcrop of Arnheim Formation on left (north side of the road)
11.45	0.05	Junction with Kentucky Route 11; **turn left (north) for optional Stop 3 (presumed below) or continue straight on the AA Highway to proceed to Stop 4**
11.5	0.05	Head north; roadcut of upper Grant Lake Formation (Mount Auburn Member) on the right (east); this is part of the first stop of the post-meeting field trip
11.7	0.2	Roadcut of Grant Lake Formation; prominent ledges before side road may be the Flemingsburg bed (middle Corryville Member; see post-meeting field trip for discussion)
11.8	0.1	Start of outcrop of rubbly middle Grant Lake Formation (Corryville Member) on right (east), rich in *Vinlandostrophia*, *Hebertella*, and bryozoans (post-meeting Stop 6C)
11.9	0.1	End of roadcut, near milepost 9
12.0	0.1	Pass side road or driveway to the right (east)
12.1	0.1	**Pull over on shoulder starting at upper end of roadcut on the right (east)**

Stop 3: Roadcuts on KY 11 ~0.6 miles north of the AA Highway (optional)

This outcrop of the upper Fairview features the upper Fairview Fairmount Member. In particular, the Hooke-Gillespie submember shows thick siltstones with ball and pillow deformation structures. Up-section, the Lawrenceburg submember and Hill Quarry beds (uppermost Fairview) are overlain by Bellevue Member of the Grant Lake Formation (C2-C3 sequence boundary)

12.4	0.3	**Continue downhill** (north) to the base of a long roadcut on the right (east) side showing the lower Fairview Formation (Mount Hope Member) in contact with the uppermost Kope Formation (Taylor Mill submember) at the C1-C2 sequence boundary; the “Z bed” and “2-Foot shale” at the base of the Fairview are an excellent and extensive regional marker
12.6	0.2	**Turn vehicles around at Taylor Mill Road** (on the right/east side); note large cut on the left (west) side of the road, which exposes the Grand View (shaly) and Grand Avenue (stacked thin to medium bedded, bryozoan-rich packstones) submembers of the Kope Formation; this is Stop 6A of the post-meeting field trip
13.7	1.1	**Return south to the junction with the AA Highway and turn left (east)**

13.9	0.2	Drive east, passing large cut in the Arnheim Formation (locally mapped as Bull Fork Formation, which is herein regarded as a facies)
15.7	1.8	Low cuts in the middle Richmondian Waynesville Formation (mapped as the upper Bull Fork Formation) on the right (south) side of the highway
16.0	0.3	More low cuts in the Waynesville Formation (Bull Fork facies)
16.2	0.2	Cuts of Waynesville Formation (Bull Fork facies) on both sides of the AA Highway; this is Stop 5, but we will pass it and loop back around after Stop 4
16.4	0.2	Pass junction with Clarkson-Sherman Road
17.4	1.0	**Pull off on shoulder just before junction with Kentucky Route 1449 (Orangeburg Road);** rubbly roadcut on the south side of the road

Stop 4: AA Highway west of KY 1449 (Orangeburg Road) near Orangeburg, Kentucky
This somewhat degraded roadcut exposes the lower and middle Waynesville Formation (Bull Fork facies), equivalent to the Fort Ancient and Clarksville Members of Ohio.

17.5	0.1	**Find legal way to turn around at KY 1449 and return west on the AA Highway**
18.8	1.3	**Pull over at the locality bypassed previously, with rubbly exposures on both sides**

Stop 5: AA Highway northwest of Clarkson-Sherman Road, south of Maysville, Kentucky
A weathered but very interesting roadcut exposing the Clarksville and basal Blanchester Members of the Waynesville Formation (Bull Fork facies), rich with brachiopods and horn corals. Collect a Richmondian fauna until everyone is tired but satisfied.

<u>End of mid-meeting field trip; reverse route to return to Athens, Ohio</u>

Mid-Meeting Field Trip Stop Descriptions

Stop 1: US 62 / US 68 west of Maysville, Kentucky ("The Big Maysville Roadcut")

Contributors: Kyle R. Hartshorn, Carlton E. Brett

Location: Large roadcut on both sides of US Highway 62 / US Highway 68 (the Clyde T. Barbour Parkway) starting 0.4 miles (0.7 km) southwest of the Ohio River, 3.8 miles (6.1 km) northwest of Maysville, in Mason County, Kentucky

Coordinates: North (lower) end at 38° 40' 55.0" N, 83° 47' 30.2" W; south (upper) end at 38° 40' 24.7" N, 83° 47' 51.6" W

Elevation: Base (north end) at ~177 m (~580 ft), top at ~259 m (~850 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1-Ka2; Cincinnatian, Edenian-Maysvillian, C1-C3): Kope Formation, Fairview Formation, and Grant Lake Formation (Bellevue Member)

Figure 36*. Northeast-looking view of the huge roadcut on US Highway 62/68 west Maysville, Kentucky. This immense section exposes middle Kope Formation to Grant Lake Formation (Katian, Ka2; Cincinnatian, Edenian-Maysvillian) and is a favorite of local fossil collectors and university field trips.*

This massive roadcut, over a kilometer long and nearly a hundred meters high, is *the* iconic outcrop of the Maysville area (Figure 36). Well known to local collectors and well studied by stratigraphers and paleontologists, it is a critical reference section for the Kope and Fairview Formations (Algeo and Brett, 2001), as well as the lower (Bellevue) member of the Grant Lake Formation.

The base of the cut starts just south of the William H. Harsha bridge over the Ohio River, in the Kope Formation (Katian, Ka1; Cincinnatian, Edenian; Figure 38). A replacement for the Eden Shale or Latonia Shale of older nomenclature, the Kope is named for exposures along Kope Hollow west of Ripley, Ohio, about 12.4 km (7.7 miles) to the northwest. This type locality is difficult to visit and a far more accessible reference section is available on Kentucky Route 445 in Fort Thomas, Kentucky, just north of the I-275 bridge (Brett and Algeo, 2001).

The Kope has a diverse and locally abundant fauna that records a relatively deep, offshore depositional environment. The small plectambonitoid brachiopod *Sowerbyella rugosa* (Figure 37B) and the "lace collar" trinucleid trilobite *Cryptolithus* are typical of the lower Kope, particularly the Brent and Pioneer Valley submembers, though relatively rare at this roadcut. The large strophomenid *Rafinesquina* and smaller but more abundant dalmanellid *Cincinnetina multisecta* (Figure 37C) are also major components of many beds, often higher in the section. Some show blackening or reddening interpreted as being the result pyrite and/or phosphate deposition during times of sediment starvation. At least six trilobite genera are known from the Kope, including the aforementioned *Cryptolithus*, the small, spiny odontopleurids *Acidaspis cincinnatiensis* and *Primaspis crosotus*, the rare proetid *Decoroproetus parviusculus*, occasional *Triarthrus beckii*, the large, smooth asaphid *Isotelus*, and the ubiquitous *Flexicalymene granulosa* (Figure 37A). *Flexicalymene* are commonly found throughout the section as fragments (likely disarticulated molts), but complete enrolled or prone specimens are known from certain beds, particularly the lower-middle Kope siltstones exposed in the gutter near the north end of the outcrop. Trilobite fragments are preserved as brown or pink (sometimes blackened or pyrite-rust-stained) calcite that is readily distinguishable from the surrounding blue-gray sediment, particularly when wet.

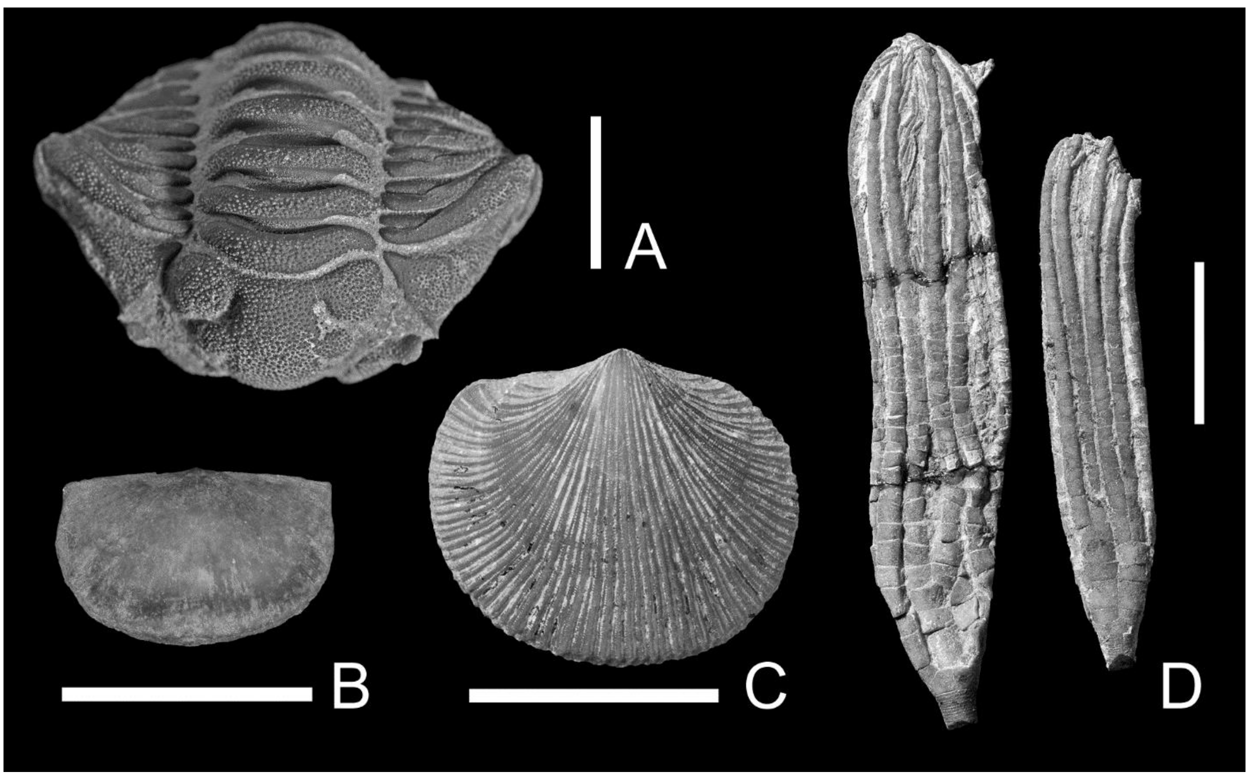


Figure 37. *Typical Kope Formation faunal components: A,* Flexicalymene granulosa *(scale bar: 5 mm); B, the common plectambonitoid* Sowerbyella rugosa *(scale bar: 10 mm); C, the dalmanellid brachiopod* Cincinnetina multisecta *(scale bar: 10 mm); D, pair of* Ectenocrinus simplex *crinoid calyces (scale bar: 10 mm). (Figure modified Hartshorn et al., 2016, figure 2.)*

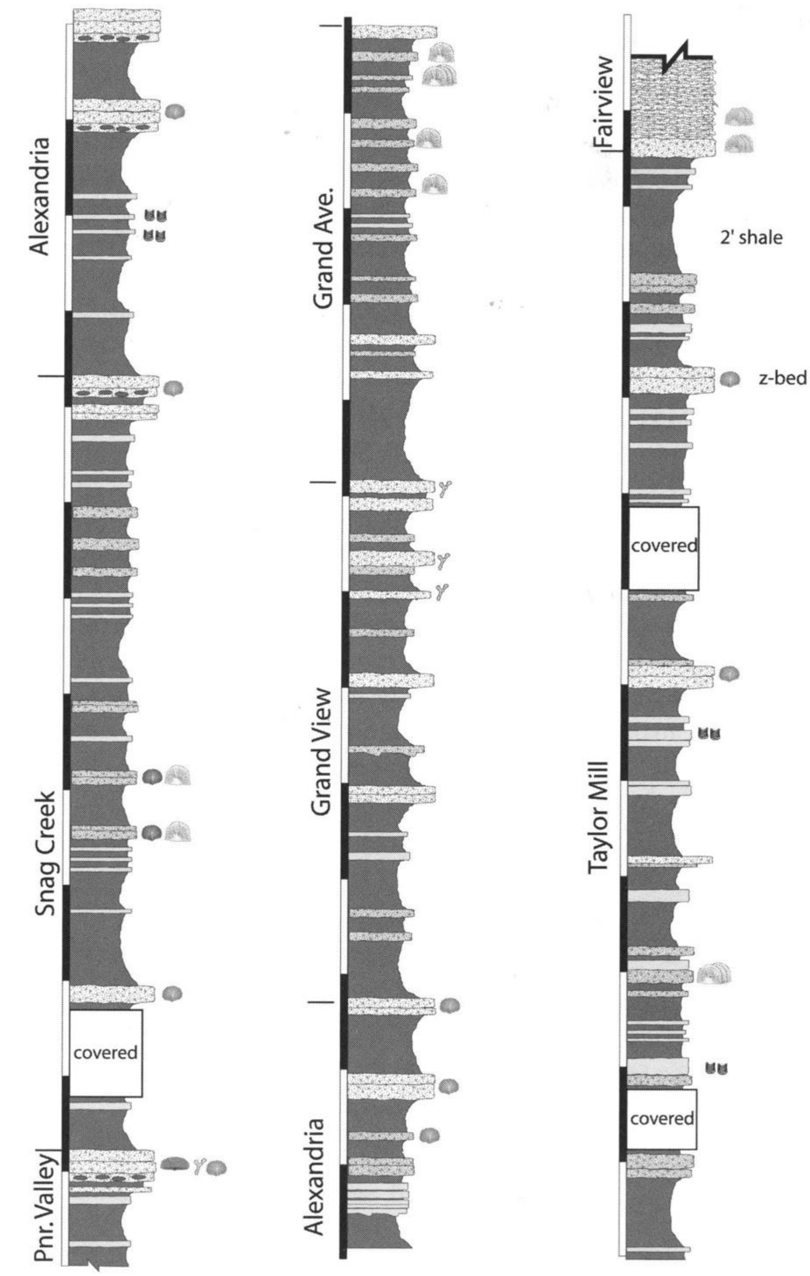


Figure 38. *Stratigraphic section for the Kope Formation and its submembers at US Highway 62/68 roadcut west of Maysville, Kentucky. From McLaughlin et al. (2008).*

Crinoids are abundant in the Kope, particularly *Ectenocrinus* (Figure 37D). In certain beds, dense accumulations of *Ectenocrinus* stems and calyces form "logjam" deposits that frequently produce well-preserved specimens. Other frequently found taxa include *Anomalocrinus*, *Cincinnaticrinus*, and *Iocrinus*. *Merocrinus* is also known from the Kope but restricted to the basal Fulton Submember (not exposed at this locality). Kallmeyer and Ausich (2015) recently described a new camerate crinoid with crenulate columnals, *Glyptocrinus nodosus*, from the middle Kope near Cincinnati. Crinoid holdfasts, especially

Lichenocrinus and *Podolithus*, the latter commonly regarded as belonging to *Anomalocrinus*, may be found attached to shells, reworked concretions, and hardground clasts throughout the formation.

Other characteristic Kope faunal elements include bryozoans, gastropods such as *Liospira* and *Cyclonema*, well preserved cephalopods (some encrusted by *Spatiopora* bryozoans), and scolecodonts. Certain shales and siltstones also contain abundant graptolites, including *Climacograptus*, rare *Dicellograptus*, *Geniculograptus* (especially *G. typicalis and G. pygmaeus*), *Mastigograptus*, and *Orthograptus*, among others. The Kope is in part equivalent to the black "Utica" shales of New York and the Appalachian Basin and contains many of the same forms.

The beds exposed in the lower end of the roadcut and in adjacent drainage ditches (Stop 1A) comprise the middle part of the Kope Formation, the Southgate Member. In particular, the soft shales and thin siltstones of the Alexandria submember are well exposed. Some beds show small-scale hummocky cross-stratification. Well-preserved *Flexicalymene* trilobites are relatively common in the shales, and graptolites, especially the zonally-significant (and tiny) *Geniculograptus pygmaeus*. The cluster of limestones above this shaly zone are numbered beds 27-30 in the typical Kope succession. The overlying ~4-5 m comprises the Grand View submember. Locally, some of these shales contain a recurrent appearance of *Triarthrus* trilobites, a taxon typically restricted to the lower Kope.

Approximately half to two-thirds of the up the roadcut (Stop 1B), the Grand Avenue submember forms the base of the upper Kope (McMicken Member). Note a package of closely-stacked, bryozoan-rich packstones. Continuing up the outcrop one reaches the uppermost subunit of the Kope, the Taylor Mill submember, which contains a profusion of gray siltstones. Many of these siltstones contain interesting sedimentary features (gutter casts, tool marks, etc.), as well as a rather diverse assemblage of trace fossils including the dumbbell-shaped *Diplocraterion*, arthropod (presumably trilobite) traces such as *Rusophycus* and *Cruziana*, and *Chondrites* burrows. This zone is well exposed just below the bench that intersects the road level near the south (upper) end of the outcrop (at Stop 1C).

The Taylor Mill is in sharp contact with an overlying ~0.4 m thick package of thick skeletal grainstones: the "Z bed". These limestones yield an immense number of dalmanellid brachiopods (*Cincinnetina multisecta*). Many of these brachiopods are fragmented and corroded, with highly variable coloration (black, red, etc.) We interpret this set of beds as a condensed interval and designate it as the base of the Fairview Formation, with the contact between the "Z bed" and the underlying Taylor Mill marking the C1-C2 sequence boundary and the base of the Maysvillian Stage.

The upper half of this outcrop also exposes the entire Fairview Formation, providing an excellent reference section for this unit (Algeo and Brett, 2001) in the type region of the Maysvillian Stage. The Fairview is significantly more limestone-rich than the Kope and brachiopods are locally more common. The lower Fairview is known as the Mount Hope Member, for classic exposures on the west side of Cincinnati. The basal, dalmanellid-rich "Z bed" is overlain by the self-descriptively named "2-Foot shale", a package of nearly pure shale; both of these beds are widespread and useful regional stratigraphic markers. Just above this bench, the North Bend submember comprises a brachiopod coquina packed with flakes of *Strophomena maysvillensis* (Foerste, 1912b; Schramm, 2011). This zone is easily accessible from atop the bench at the south end of the roadcut. However, the rest of the Fairview is more difficult to view and will be covered in more detail at subsequent stops.

Talus on top of the bench shows a characteristic Fairview assemblage, with abundant brachiopods and bryozoans. *Strophomena*, *Vinlandostrophia hopensis*, and *Plectorthis* spp. (Figure 39D) are typical examples of the Fairview fauna. Bryozoans are common, particularly ramose and foliated trepostomes (*Amplexopora septosa*, *Dekayia aspera*, *Homotrypa* spp., etc.) Fronds of the cystoporid *Constellaria florida*

(Figure 39A) are also relatively abundant; this genus is easily identifiable based on its stellate monticules. *Escharopora*, a blade-shaped cryptostome bryozoan, is represented by several species in the Fairview, including the smooth *E. falciformis* (Figure 39B) and the ridged *E. hilli* (Figure 39C). Another Fairview cryptostome is *Graptodictya*, a sheet-like form with numerous perforations (not to be confused with lacy fenestrate bryozoans—also common in the Fairview).

The expansive walls of the roadcut allow one to view, if not reach, the entire Fairview to great advantage. The upper member, the Fairmount, contains a variety of interesting sedimentary structures, including megaripples and deformed beds. The latter are found in the lower Fairmount Hooke-Gillespie submember (named for exposures on the AA Highway west of Maysville), which contains thick siltstones bulging with ball and pillow structures (Schramm, 2011). These are likely seismites, evidence for massive earthquakes that shook the Late Ordovician sea floor, inducing liquefaction and disrupting recently-deposited silty sediments; they may be a side effect of the Taconic orogeny taking place many hundred kilometers to the east. Today, the resulting deformed beds are useful stratigraphic markers throughout the Maysville region. This same horizon is well exposed in the roadcuts along Kentucky Route 11 north of the AA Highway (Stop 3) and can also be seen at various cuts on the AA Highway itself, on KY 11 north of Sherburne, and on the west side of US Highway 62 north of Ripley, Ohio.

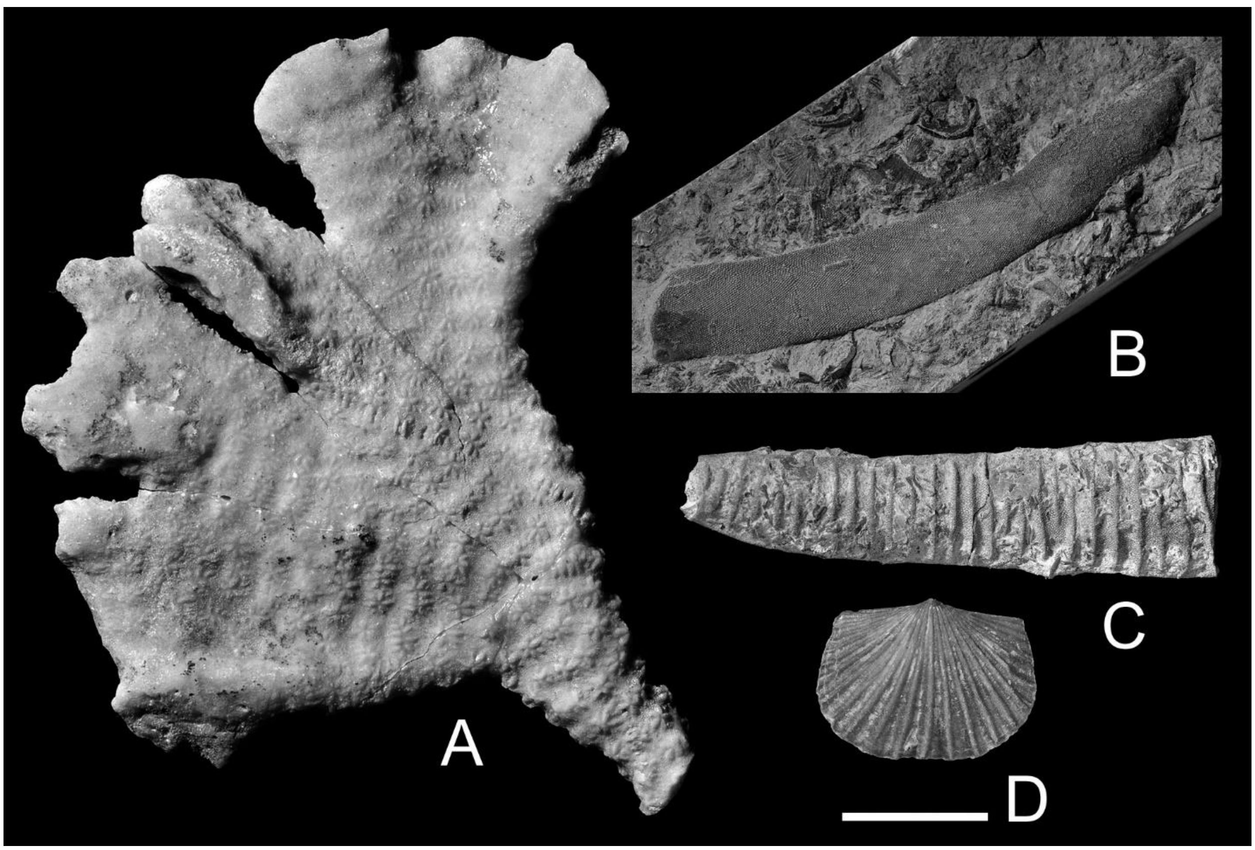


Figure 39. *Fairview Formation fauna: A, the distinctively stellate cystoporid bryozoan* Constellaria florida*; B, the blade-like frond of the cryptostome bryozoan* Escharopora falciformis*; C, another species,* Escharopora hilli, *with ridged ornamentation*; *D, the small orthid brachiopod* Plectorthis plicatella *(scale bar: 10 mm). (Figure modified from Hartshorn et al., 2016, figure 3.)*

The robust "Hill Quarry" beds form the top of the Fairview Formation in this area. Their resistant, tabular limestones are parted by minor shales that may preserve the complete calyces of camerate crinoids. In one spectacular example, a massive slab was found containing hundreds of complete specimens of *Glyptocrinus decadactylus* (Milam et al., 2017). This amazing assemblage likely represents an obrution deposit, where a grove of crinoids was buried alive by a single massive influx of sediment. Intrepid local collectors have also found isolated but still well-preserved crinoids in the shaly partings in or near this horizon. The Hill Quarry beds are also host to the locally rare but biostratigraphically important rhynchonellid brachiopods *Orthorhynchula linneyi*. *Orthorhynchula* appears to be only found in the uppermost Fairview (Fairmount Member) in this area, but it is very abundant throughout the Fairview-equivalent Calloway Creek Limestone to the south.

The Fairview is unconformably overlain by the Bellevue Member of the Grant Lake Formation. Near Cincinnati, another unit, up to 6 m thick, is present between the Hill Quarry beds and the base of the Bellevue: the Miamitown Shale. However, here the Miamitown is lacking, apparently cut out. Thus, the Fairview-Bellevue contact is regarded as a major 3rd order sequence boundary, separating the C2 and C3 sequences. The Bellevue consists of stacked grainstones and packstones, lacking much of the shale and tabular bedding of the Fairview. Near the base of the member (or perhaps in the uppermost Fairview below), a series of hardgrounds preserve edrioasteroids (Sumrall, 2010), and the rare mitrate stylophoran *Enoploura* (Deline, 2008). The Bellevue also contains large brachiopods, including *Rafinesquina*, *Hebertella* and, commonly, the first appearance of *Vinlandostrophia ponderosa*. As the upper benches are difficult and time consuming to reach, the Bellevue will not be a major focus of this stop (see Stop 2 and 3). The shaly, rubbly Corryville Member of the Grant Lake Formation may be poorly exposed at the very top of the cut.

Stop 2: US 62 / US 68 south of Lawrence Creek, west of Maysville Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn

Location: Roadcut on US Highway 62 / US Highway 68 starting ~0.2 km (~0.1 miles) south of the bridge over Lawrence Creek, itself south of Kentucky Route 3056; about 5.8 km (3.6 miles) northwest of Maysville in Mason County, Kentucky

Coordinates: North (lower) end at 38° 40' 11.3" N, 83° 48' 01.2" W;
south (upper) end at 38° 39' 58.3" N, 83° 48' 13.7" W

Elevation: Base at ~229 m (~752 ft), top at ~261 m (~855 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2; Cincinnatian, lower Maysvillian, C2-C3): Fairview Formation and Grant Lake Formation (Bellevue Member)

This roadcut is a smaller, younger sibling of the big cut just to the north, offering quick and easy access to some of the higher units that were difficult to observe in detail at the previous stop. The lower (northern) end of the outcrop exposes the upper Fairview Formation, with characteristic limestones and siltstones. One may walk up to the bench to view deformed siltstone masses (ball and pillow structures; Figure 40) and an intriguing channel-like feature filled with deformed and brecciated silty packstones. These are likely seismites, evidence of massive Ordovician earthquakes that shook and liquified the sea floor sediments (Schumacher, 2001). Similar deformed beds are abundant and geographically widespread in the Lexington Limestone, but somewhat less common in the Cincinnatian. Several are known from the Kope Formation and Fairview Formation, as well one in possibly Bellevue-equivalent strata near Shelbyville, Kentucky.

Figure 40. *Upper Fairview Formation (Fairmount Member, Hooke-Gillespie submember) siltstones showing slight deformation; US Highway 62/68 north of Lawrence Creek, west of Maysville, Kentucky.*

This particular package, the Hooke-Gillespie seismites, comprises several (often three) discrete deformed beds and is exposed at localities ranging from Ripley, Ohio to Sherburne, Kentucky, a north-south transect of roughly 55 km (~34 miles). These same deformed beds were visible in the high walls of Stop 1 and will be visible at Stop 3, about 7 km (4.5 miles) to the southeast.

The southern (upper) end of the roadcut exposes the uppermost Fairview Formation, a zone known as the Hill Quarry beds for historical exposures in various hill quarries around Cincinnati. These thick, robust limestone beds contain common and large crinoid columns, which may correlate with clusters of articulated camerate crinoids (*Glyptocrinus decadactylus*; Milam et al., 2017) found at other localities in this region (e.g., in the upper part of Stop 1), always in the same zone of the upper Fairview. This crinoid-rich horizon can be traced at least as far as Lawrenceburg, Indiana.

The overlying rubbly, thin-bedded packstones belong to the Bellevue Member of the Grant Lake Formation. The Bellevue represents the initial transgression of the C3 sequence and is filled with brachiopods (especially *Vinlandostrophia ponderosa*, *Hebertella*, and *Rafinesquina*) and common ramose bryozoans (*Parvohallopora* and others). The large, frond-like trepostome *Monticulipora molesta* is also characteristic of the unit, and once provided its (now obsolete) biostratigraphic definition (Nickles, 1902).

Stop 3: Roadcuts on KY 11 ~0.6 miles north of the AA Highway at Maysville, Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn

Location: Subset of a series of about eight roadcuts along a ~2.7 km (~1.7 mile) stretch of Kentucky Route 11 between the AA Highway (Kentucky Route 9) and the junction with Kentucky Route 2519, south of Maysville in Mason County, Kentucky

Coordinates: Southernmost (highest) cut at 38° 36' 15.1" N, 83° 45' 37.7" W; northernmost (lowest) cut at 38° 37' 30.4" N, 83° 45' 04.8" W

Elevation: Base of lowest cut at ~177 m (~580 ft), top of highest cut at ~262 m (~860 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1-Ka2; Cincinnatian, Edenian-Maysvillian, C1-C4): Kope Formation, Fairview Formation, and Grant Lake Formation (Bellevue, Corryville, and Mount Auburn Members)

Figure 41. *As at the previous stop, the upper Fairview Fairmount Member (Hooke-Gillespie submember) shows thick deformed siltstone horizons associated with channelized siltstones, with large pendulous ball and pillow structures. Approximately three in number, these deformed beds are likely seismites. The siltstones themselves are likely falling stage deposits. Kentucky Route 11 north of the AA Highway, south of Maysville, Kentucky.*

This string of roadcuts displays an exceptional section of the type Maysvillian, with extensive exposures of the Fairview Formation and Grant Lake Formation. Prior to the construction of the big US 62 / US 62 roadcut, it was among the best regional reference sections. This locality will be examined in detail on the first stop of the post-meeting trip. Therefore, the present stop will simply provide a brief overview and a photo-opportunity of one of the most spectacular features of the cut, the aforementioned ball and pillow horizons of the Hooke-Gillespie (Fairmount Member of the Fairview Formation; Figure 41). More discussion of the overall section can be found in the guide for the first post-meeting stop.

Stop 4: AA Highway west of KY 1449 (Orangeburg Road) near Orangeburg, Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn, Christopher D. Aucoin, Cameron E. Schwalbach

Location: Beveled roadcut on the south side of the AA Highway (Kentucky Route 9) 0.2 km (0.1 miles) west of the intersection with Kentucky Route 1449 (Orangeburg Road), 7.3 km (4.6 miles) southeast of Maysville and 2.1 km (1.3 miles) northwest of Orangeburg in Mason County, Kentucky

Coordinates: 38° 35' 05.4" N, 83° 42' 05.9" W

Elevation: Base at ~244 m (~799 ft), top at ~256 m (~841 ft)

Stratigraphy: Upper Ordovician (Katian, Ka3; Cincinnatian, lower Richmondian, C5): Bull Fork Formation (here regarded as equivalent to the Fort Ancient and lower Clarksville Members of the Waynesville Formation)

At first glance (Figure 43), this is an old and somewhat degraded outcrop. However, upon closer inspection, it provides one of the few outcrops in this region to show this particular stratigraphic horizon and offers some decent collecting as well. This outcrop is mapped as the upper Bull Fork Formation (Schilling and Peck, 1967); our field work indicates that it is correlative to the lower and middle Waynesville Formation of Ohio, and we use those names accordingly. The term Bull Fork is widely used in Kentucky for Richmondian-age argillaceous, rubbly-weathering pack- and wackestones. Depending on the outcrop, the Bull Fork may be laterally equivalent to the Arnheim Formation, the Waynesville Formation, or some combination. We have found that the Arnheim and Waynesville are still readily differentiable from one another in Kentucky. Thus, we tend to prefer the Ohio names for use with high-resolution stratigraphy work and treat Bull Fork as a name for the facies.

A small gully cut below the main platform shows stacked packstones rich in the large strophomenid brachiopod *Rafinesquina*; these beds are regarded as equivalent to the Bon Well Hill beds of the Fort Ancient Member of the Waynesville Formation (sequence C5B). Weathered claystones near the level of the platform are interpreted as a thin remnant of the Harpers Run (or *Treptoceras duseri*) “butter shale” (Aucoin and Brett, 2016; Aucoin et al, 2016). Mollusks are locally abundant in certain beds and relatively well preserved (Figure 44). Weathered out fossil debris includes moderately common enrolled *Flexicalymene* trilobites, further supporting the butter shale correlation. (Note, though, that the site has been picked over by students and local collectors for a number of years.)

Higher beds, largely covered on the wooded embankment above the platform, are recognized as the Clarksville Member of the Waynesville Formation. They show early occurrences of typical Richmondian faunas, including *Strophomena planumbona*, *Eochonetes clarksvillensis*, rare Hiscobeccus, and the rugose coral *Grewingkia canadensis* (Figure 45A).

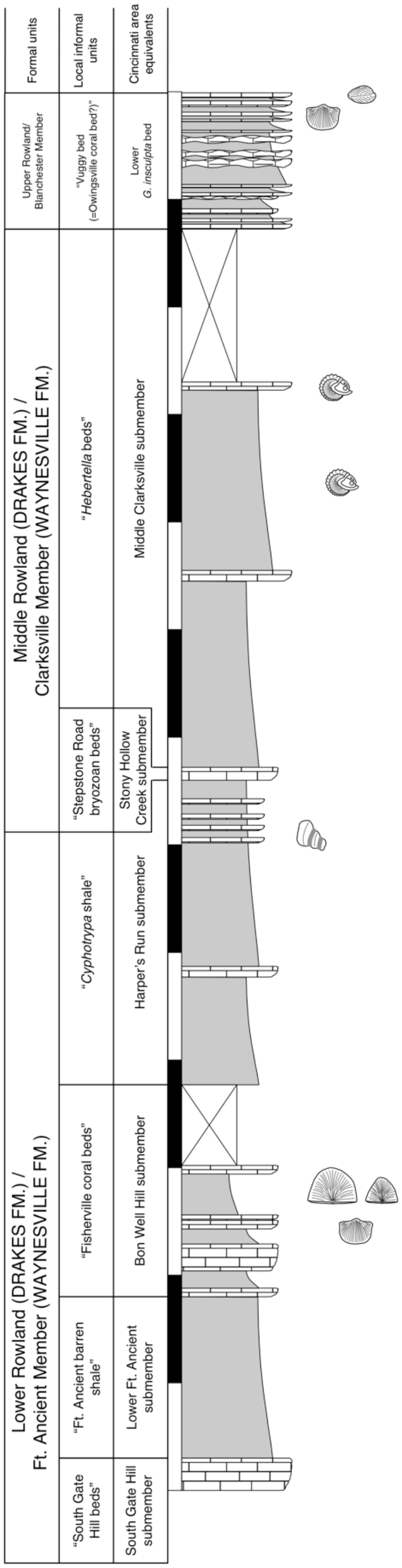


Figure 42. *Stratigraphic column of lower Waynesville section on the AA Highway at Kentucky Route 1449.*

Figure 43. *This roadcut on the AA Highway just west of the junction with Kentucky Route 1449 may not look like much, but it's got it where it counts. The richly fossiliferous Bull Fork facies of the lower Waynesville Formation yields mollusks, trilobites, brachiopods, and other Richmondian fauna.*

Figure 44. *Example slab from the roadcut on the AA Highway west of Kentucky Route 1449. This bed contains abundant and relatively well-preserved molds of gastropods and bivalves, extremely common pieces of* Flexicalymene *trilobites (likely molts), small twiggy bryozoans, brachiopods, and crinoid debris (cf.* Xenocrinus*). This is a fairly typical fauna for the southern exposures of the Waynesville Formation. Small cephalopods are also known from this locality. Due to prolonged weathering, almost all fossils are found in the talus.*

Nearby (but higher) outcrops contain *Glyptorthis insculpta* (Figure 45B) and the rare atrypid *Catazyga headyi*, both diagnostic of the basal beds of the Blanchester Member of the Waynesville Formation. Their occurrence may signal a condensed transgressive interval following a major sea level drop (the cause of the mid-Richmondian unconformity of Aucoin and Brett, 2016).

Stop 5: AA Highway northwest of Clarkson-Sherman Road, south of Maysville, Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn, Christopher D. Aucoin

Location: Beveled roadcut on both sides of the AA Highway 5.6 km (3.5 miles) south-southeast of Maysville in Mason County, Kentucky; 1.2 km (0.8 miles) east of Knoweshaw Road and 0.6 km (0.4 miles) northwest of Clarkson-Sherman Road

Coordinates: 38° 35' 46.5" N, 83° 43' 07.6" W

Elevation: Base at ~265 m (870 ft), top at ~271 m (~890 ft)

Stratigraphy: Upper Ordovician (Katian, Ka3; Cincinnatian, lower Richmondian, C5-C6): Bull Fork Formation (here equivalent to the Clarksville and basal Blanchester Members of the Waynesville Formation)

Small roadcuts on both sides of the AA Highway (Kentucky Route 9) expose about 5 meters of rubbly shale and nodular limestone beds normally mapped as the Bull Fork Formation (Schilling and Peck, 1967), but correlative to the middle Waynesville Formation of Ohio. This unassuming exposure (Figure 46) illustrates the abundance and diversity of the Richmondian fauna, even at relatively minor localities. Especially on the north side of the road, the heavily weathered slope contains a rich and diverse assemblage of brachiopods, typically as lose specimens, and is particularly notable for an abundance of the solitary rugose coral *Grewingkia* (Figure 45A) many of which are corroded, fragmentary, and bored with *Trypanites*. This interval was mapped as the "horn coral bed" of the Bull Fork Formation by Schilling and Peck (1967). Recent tracing of these beds in adjacent southern Ohio indicates that this horn coral-rich zone occurs near the top of the Clarksville Member of the Waynesville Formation.

As elsewhere, here the Clarksville Member of the Waynesville shows the first diverse Richmondian faunal assemblage. In addition to the rugose corals, brachiopods are quite diverse and abundant: *Strophomena planumbona, Rafinesquina* sp., *Eochonetes clarksvillensis* (Figure 45F), rare *Hiscobeccus capax* (Figure 45D), one or more species of *Hebertella* (cf. *H. occidentalis*), *Leptaena richmondensis* (Figure 45C), and several varieties of small *Vinlandostrophia*. Specimens range from fully articulated to extremely fragmented and corroded, indicating strong time averaging during an interval of relatively low sedimentation. Various bryozoans and the encrusting coral *Protaraea richmondensis* are frequently found on the larger brachiopods. Mollusks are relatively common, often preserved as chalky-weathering molds (similar to Figure 43). Some beds contain the large pterineid *Caritodens* preserved in brown calcite or are packed with disarticulated valves of a small bivalve, likely *Ctenodonta* or *Deceptrix.* Others contain gastropods, an abundance of *Tentaculites* (studied in detail by Wittmer, 2009), or rare trilobites.

The contact between Clarksville and Blanchester Members is marked by a sharp overhang and prominent ledge of grainstones above. These beds yield rare specimens of the brachiopod *Glyptorthis insculpta* (Figure 45B), confirming their identity as the "Lower *Glyptorthis* Bed" that marks the Clarksville-Blanchester boundary elsewhere. These beds may also contain occasion specimens of the tabulate coral *Tetradium*. At a nearby locality, correlative beds yield abundant specimens of the rare and highly restricted brachiopod *Catazyga headyi*, another species commonly found near the *Glyptorthis* zone. The overlying shales yield rare, well preserved trilobites (e.g. *Flexicalymene*) and are correlated to the Oldenburg beds of Indiana (Aucoin and Brett, 2016).

This "Richmondian Invasion" fauna reflects a substantial increase in diversity compared to the older Maysvillian strata. Holland and Patzkowsky (1996) attribute this bioevent to an influx of tropical taxa during a period of warming near the base of the Richmondian (lowest Ashgill of older terminology). This incursion apparently did not coincide with substantial loss of older, more established Cincinnatian taxa. Rather the invading taxa often joined existing faunas (Stigall, 2010), or were quickly transient and thus unobtrusive (e.g., *Catazyga*, often present in only a single bed near the lower *Glyptorthis* zone).

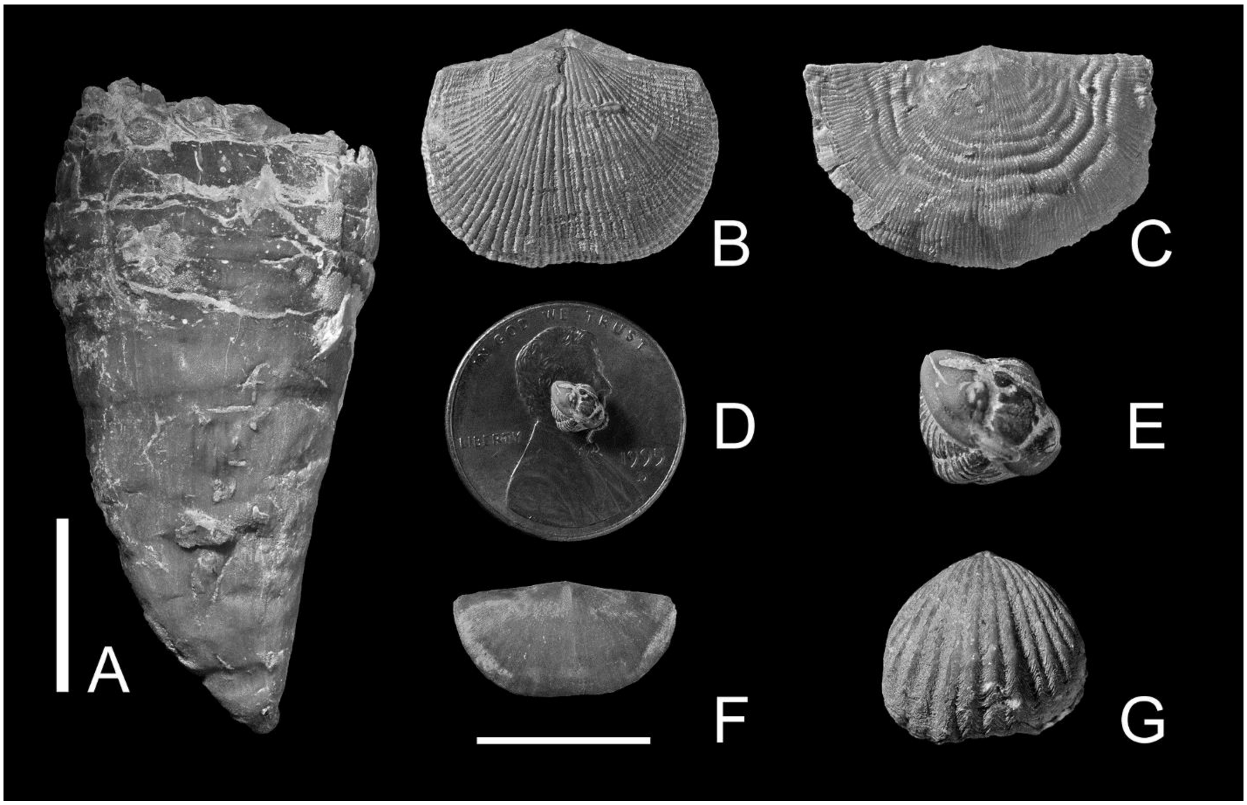


Figure 45. *Waynesville-Liberty fauna: A, the rugose coral* Grewingkia canadensis *(scale bar: 25mm); B,* Glyptorthis insculpta*; C.* Leptaena richmondensis*; D,* Flexicalymene retrorsa minuens *on an American penny, showing typical size; E,* Flexicalymene retrorsa minuens *(same individual as D enlarged ~2.5x); F, the plectambonitoid brachiopod* Eochonetes clarksvillensis *(scale bar: 10mm); G,* Hiscobeccus capax. *(Figure modified from Hartshorn et al., 2016, figure 6.)*

Figure 46. *The rubbly hill-slope of the "horn coral locality" on the AA Highway south of Maysville, Kentucky. The ledgy beds near the top of the outcrop are lower* Glyptorthis *zone, which marks the boundary between the Clarksville and Blanchester Members of the Waynesville Formation. The talus on the hill is very fossiliferous, with brachiopods, bivalves, rare trilobites, and common horn corals (*Grewingkia*). Jerry Rush, Tim Paton, and Carl Brett for scale.*

POST-MEETING FIELD TRIP

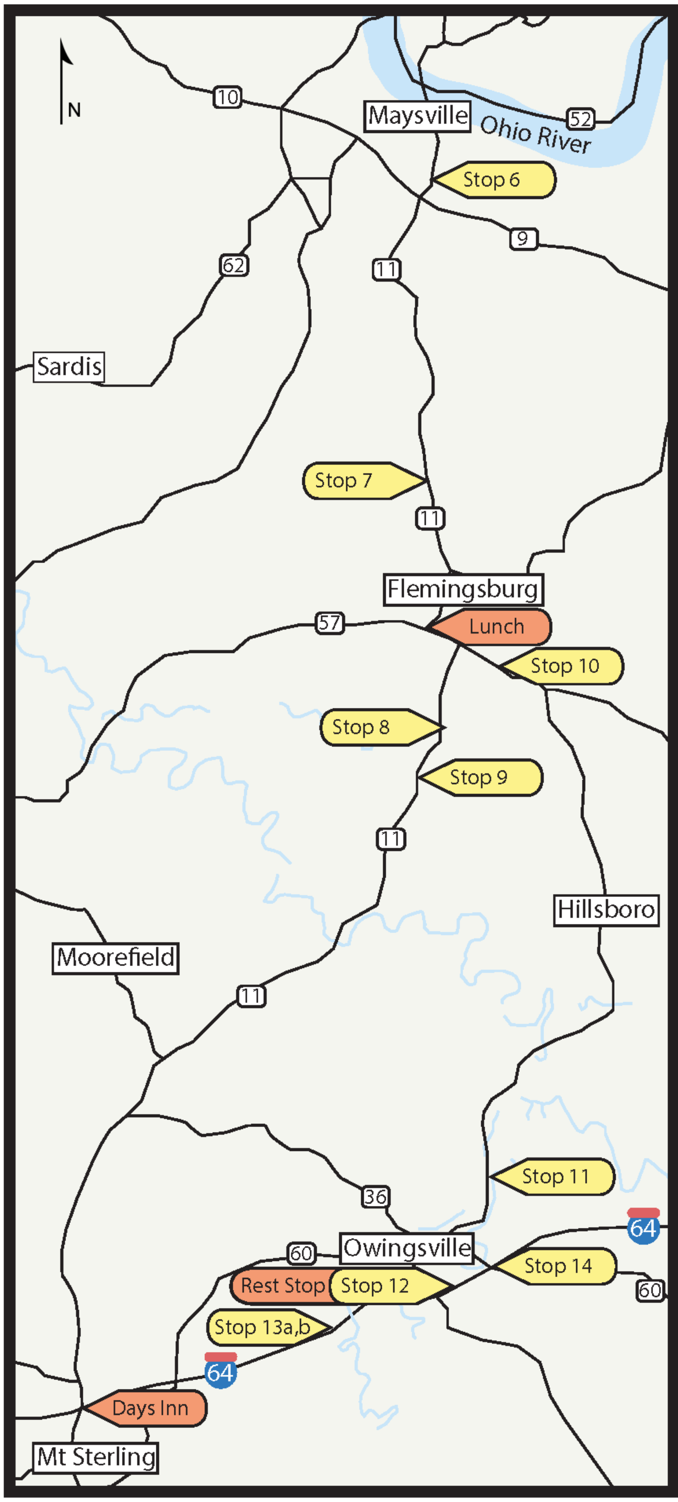
The two-day post-meeting field trip is intended to give participants a more in-depth look at the fossils and depositional environments of the eastern Cincinnati Arch in north-central Kentucky. Very deliberately, it is a complementary sequel to the mid-meeting trip and stop numbering is continued therefrom (i.e. starting at 6). On the first day, we will return to Maysville, then head south, down the eastern flank of the Cincinnati Arch. Along the way, we will stop at a variety of outcrops that expose the middle (Maysvillian) and upper (Richmondian) stages of the Cincinnatian (Katian, Ka2-Ka4), and briefly encounter the Ordovician-Silurian boundary. The second day will cover older rocks, with a look at the Mohawkian (Sandbian to lower Katian) strata that forms the core of the Ordovician outcrop area in central Kentucky, before heading north towards Cincinnati itself. Although, lamentably, the true type Cincinnatian will not be visited, this excursion coupled with the mid-meeting field trip provides an excellent primer on the Ordovician facies and faunas of the eastern and central Cincinnati Arch.

Day 1: Cincinnatian (Katian) Strata Between Maysville and Mount Sterling

Carlton E. Brett, Kyle R. Hartshorn, Cameron E. Schwalbach, Thomas J. Schramm, Christopher D. Aucoin, T.J. Malgieri

The first leg of the field trip will pick up where the mid-meeting trip left off: at Maysville, Kentucky. From there, the trip will head south on Kentucky Route 11 (KY 11 or Route 11), a respectable local highway with many excellent roadcuts of Maysvillian age (i.e. middle Katian, roughly Ka2). Key stops will include Flemingsburg and Tilton, where we will view the upper Maysvillian Grant Lake Formation and its contact with the basal Richmondian Arnheim Formation (approximately the Ka2-Ka3 stage slice boundary). Then the caravan will head south, taking Kentucky Route 111 (KY 111) towards Owingsville. Along the way we will pass through the small towns of Hillsboro, Grange City (and its roadcut showing the Ordovician-Silurian boundary), and Wyoming. Just outside of Owingsville we will stop at a rather large but relatively unknown roadcut that contains strata representing the entire Richmondian Stage (or nearly so). Finally, we will spend the remaining daylight hours on I-64 between Owingsville and Mount Sterling, as we visit a series of roadcuts that demonstrate the northwest-to-southeast facies change that takes place across the Cincinnati Arch. We will review sections of Maysvillian-to-Richmondian strata that contain units that are time equivalent to yet lithologically distinctive from the ones visited earlier in the day. Then we will retire to a hotel in Mount Sterling for the evening.

This north to south transect provides a look at facies deposited along a distal (north) to proximal ramp. A major purpose of this trip is to trace key levels, particularly near the Maysvillian-Richmondian boundary across a major transition from deeper subtidal to shallow shoal and even peritidal facies and to examine the transitions within the context of sequence stratigraphy.



Stop 6: Roadcuts on KY 11 north of the AA Highway at Maysville, Kentucky
Stop 7: KY 11 ~0.5 miles south of Mill Creek Road, north of Flemingsburg, Kentucky
Stop 8: KY 11 near Quarry Road, south of Flemingsburg, Kentucky
Stop 9: KY 11 near Tilton, Kentucky
Stop 10: KY 32 south of Flemingsburg, Kentucky
Stop 11: KY 111 at meander bend in Slate Run fork of the Licking River, near Wyoming, Kentucky
Stop 12: Vacant lot adjacent to McDonald's, just off KY 36 in Owingsville, Kentucky
Stop 13A: South side of I-64 west of Salt Well Creek in Bath County, Kentucky
Stop 13B: Faulted outcrop on I-64 near milepost 117, west of Salt Well Creek
Stop 14: Section along exit 123 ramp from I-64 east of Owingsville, Kentucky

Figure 47. *Map of the area between Maysville and Mount Sterling, Kentucky, with list of stops to be visited during the first day of the post-meeting field trip.*

Road Log for Post-Meeting Field Trip Day 1

As with the mid-meeting field trip, this road log starts at the Ohio-Kentucky state line. However, in the interests of time, this trip starts at the other major bridge in the Maysville area, the Simon Kenton Memorial Bridge that leads from Aberdeen, Ohio to downtown Maysville. Somewhat confusingly, this bridge is also used for US Highway 62 and US Highway 68, but the business routes thereof. The first day ends in Mount Sterling, Kentucky. As before, key turns and directions are **bolded** to differentiate them from wayfinding or geological notes. Distances are in miles.

Total	*Increment*	*Description*
0.0	0.0	Ohio River (downstream is to the right, northwest)
0.4	0.4	**Cross Simon Kenton Memorial Bridge to the Kentucky side of the river**
0.5	0.1	**Continue to junction with Business Route 8 (3rd Street), then turn left (east)**
0.8	0.3	**Proceed east to the junction with Coughlin Boulevard (Kentucky Route 2518), then bear right (southeast) to continue following Business 68**
1.1	0.3	**Turn right (southeast) to follow Kentucky Route 11 (Fleming Road)**; note outcrops of Kope Formation on the right, behind a car wash
2.2	1.1	Slumped, overgrown outcrops of Kope Formation (first major KY 11 roadcut)
2.6	0.4	Start of a ~0.1 mile long outcrop exposing the upper Kope Formation; **pull over on shoulder before junction with Taylor Mill Road (on the left/east)**

Stop 6A: KY 11 across from Taylor Mill Road south of Maysville, Kentucky (optional)
An exposure of the upper Kope Formation (upper Edenian) on the west side of the road, featuring the shaly Grand View Submember and Grand Avenue submember, a succession of stacked thin to medium bedded, bryozoan-rich packstones.

2.7	0.1	Continue south (uphill) and pass junction with Taylor Mill Road
2.8	0.1	**Pull over on shoulder just after intersection with Lawrence Road (on the right/west)**; this was Stop 3 of the mid-meeting field trip; participants should carefully **cross the road** to the outcrop; the vehicles should proceed south (uphill) while participants walk the outcrop, then pick them up at the top of the cut

Stop 6B: KY 11 just south of Lawrence Road south of Maysville, Kentucky (optional)
Review the lower Fairview Formation (lower Maysvillian), noting the Mount Hope Member and its contact with the underlying Kope Formation (Taylor Mill submember) at the "Z bed", along with the "2-Foot shale" and *Strophomena*-rich North Bend submember.

3.0	0.2	Outcrop of upper Fairview (Hooke-Gillespie submember of the Fairmount Member), featuring siltstones with ball and pillow deformation, as discussed during the mid-meeting field trip; this is the middle of Stop 6B

3.1	0.1	Outcrop of upper Fairmount (Lawrenceburg and Hill Quarry submembers), sharply overlain by the Bellevue Member of the Grant Lake Formation; this is the upper end of Stop 6B; participants should carefully cross road and **reboard vehicles**
3.2	0.1	Pass a side road on the east side that forms a gap in the outcrop
3.3	0.1	**Pull over at an outcrop of Grant Lake Formation on both sides of the road**

Stop 6C: KY 11 ~0.4 miles north of the AA Highway, south of Maysville, Kentucky (optional)
This roadcut exposes the Corryville Member of the Grant Lake Formation, with rubbly limestone that yields abundant *Vinlandostrophia ponderosa*, *Hebertella*, and bryozoans. We will see much better exposures of this unit later (e.g., Stops 8 and 9), so no need to spend much time here.

3.6	0.3	Continue south to another roadcut on the east side of the road, just before junction with the AA Highway; **pull over on shoulder**

Stop 6D: KY 11 ~0.1 miles north of the AA Highway, south of Maysville, Kentucky (optional)
A quick look at the Mount Auburn Member of the Grant Lake Formation (uppermost Grant Lake), with phosphatic grainstones and packstones.

3.7	0.1	**Continue straight (south) on KY 11, past the junction with the AA Highway**
3.8	0.1	Pass junction with Kentucky Route 1448 (East Maple Leaf Road)
5.5	1.7	Roadcut in Mount Auburn Member of the Grant Lake Formation
5.8	0.3	Pass junction with Kentucky Route 419 (on the right/west)
6.2	0.4	Outcrop of Grant Lake Formation
6.6	0.4	Outcrop of upper Grant Lake Formation
7.2	0.6	Strodes Creek Road; cross Strodes Creek
7.4	0.2	Outcrop of upper Grant Lake Formation (probably Mount Auburn Member)
7.8	0.4	Cross the North Fork of Licking River, followed by a large outcrop of Grant Lake (Corryville Member) on both sides of KY 11
8.1	0.3	Large outcrop of uppermost Fairview Formation and Grant Lake Formation (at least Bellevue and Corryville Members) at corner of KY 11 and Kentucky Route 3170, the turn-off to Lewisburg, Kentucky
8.2	0.1	Outcrop on left (east) side ascending hill
8.5	0.3	Outcrop in upper Grant Lake Formation (Mount Auburn Member?)
8.7	0.2	A good shaly outcrop, probably still Grant Lake Formation
9.4	0.7	Fleming-Mason County airport on left (east)
10.0	0.6	Outcrop of middle Grant Lake Formation (the shaly Corryville Member)
10.1	0.1	Junction with Kentucky Route 597 (Mt Gilead Road) on left (east)

10.6	0.5	Shamrock Food Mart (BP gas station) on right (west)
10.8	0.2	Pass junction with Mill Creek Road on the right (west)
11.1	0.3	Outcrop of ledgy limestone (Mount Auburn Member) on left (east)
11.3	0.2	Outcrop of Arnheim Formation on both sides near hill crest; **pull off on shoulder**

Stop 7: KY 11 ~0.5 miles south of Mill Creek Road, north of Flemingsburg, Kentucky (optional)
This outcrop affords an opportunity to briefly examine a minor but very fossil-rich exposure of the Arnheim formation (here mapped as part of the Bull Fork Formation).

11.7	0.4	Pass junction with Kentucky Route 324 (Helena Road) on the right (west)
12.2	0.5	Mason-Fleming County line
14.1	1.9	Small, weathered outcrop of Arnheim Formation, rich in *Leptaena* brachiopods
15.9	1.8	Junction with the Kentucky Route 57 bypass; turn right (west) to follow the KY 11 / KY 57 bypass around Flemingsburg, Kentucky
16.4	0.5	Pass junction with Kentucky Route 559 (both sides)
17.5	0.1	Junction with Kentucky Route 32; **turn left (east) onto Elizaville Avenue to head into the city of Flemingsburg, Kentucky**
18.4	0.9	Elizaville Avenue bends to left and merges with Main Cross Street; **bear left onto Main Cross Street**
18.6	0.2	**Rock down to Electric Avenue and then take it higher (left);** pass Flemingsburg recyclers; note small exposures of Mount Auburn Member of the Grant Lake Formation (Straight Creek grainstone facies) along road
18.8	0.2	**Park in the lot for Flemingsburg City Park**

Lunch Stop: Flemingsburg City Park
Enjoy a quick lunch at this park and picnic ground, situated along the Town Branch creek that runs through the middle of Flemingsburg. Flemingsburg-Fleming County Recreation Park is a backup option.

19.0	0.2	**Head southeast on Electric Avenue back to Main Cross Street and turn right**
19.3	0.3	**Bear left onto Clark Street as Main Cross Street merges into it, towards KY 11**
19.4	0.1	**Turn right (south) onto Mt Sterling Avenue (Business Route 11)**
19.8	0.4	**Continue straight (south) on KY 11 through the junction with KY 32**
20.7	0.9	Outcrop on both sides of KY 11, a wonderful exposure of upper Grant Lake Formation, especially the Mount Auburn Member (Straight Creek grainstone facies, with oncolites and a stromatoporoid bed at top of outcrop); the Corryville Member is present, perhaps including the Flemingsburg bed, in the lower part of exposure

21.3	0.6	Begin large outcrop of Grant Lake Formation (Corryville Member) on both sides with a *Solenopora* zone about 1.5 m above base, followed by the heavy grainstones of the Flemingsburg bed; **pull off before Quarry Road to examine section**

Stop 8: KY 11 at Quarry Road south of Flemingsburg, Kentucky

An extremely fossiliferous locality exposing the Corryville Member of the Grant Lake Formation, with abundant brachiopods (*Vinlandostrophia ponderosa* and *Hebertella*), gastropods, and large, brain-like *Solenopora* nodules.

21.6	0.7	Outcrops of very fossiliferous Grant Lake Formation in main cuts and corners of Quarry Road (the nominal quarry is in grainstones of the Mount Auburn Member)
21.7	0.1	Outcrop at milepost 8, a long section in the Corryville Member of the Grant Lake Formation
22.2	0.5	Cross bridge over the North Fork of Licking River
22.5	0.3	Large, high roadcut in Corryville and Mount Auburn (top) on left; stromatoporoids in Flemingsburg bed above upper bench
23.2	0.3	High outcrop on east side and lower cut to the west with light weathering, nodular upper Bellevue Member of the Grant Lake Formation at the base, near the junction with Creek Road; cross a small stream and start up hill
23.4	0.2	Begin the lower end of the long Tilton hill cut on west side of KY 11, opposite junction of Kentucky Route 2081 (Old Route 11) in the lower Corryville Member of the Grant Lake Formation; **pull over and prepare for discussion;** vehicles may drive up hill to await the participants as they walk up the cut

Stop 9A: North end of major roadcut along KY 11 north of Tilton, Kentucky

Another exposure of the Corryville Member of the Grant Lake Formation, with nodular limestones and shales full of *Vinlandostrophia ponderosa* and *Solenopora*.

23.5	0.1	Continue south past roadcuts on both sides in middle Corryville Member

Stop 9B: Middle of major roadcut along KY 11 north of Tilton, Kentucky

The middle of the outcrop exposes the middle-upper Corryville Member, including the Flemingsburg bed. The latter unit is largely light gray weathering grainstones overlain by a biostrome of small, irregular stromatoporoids and less common *Tetradium*.

23.7	0.2	Proceed past gap in outcrop
23.8	0.1	Beginning of lower end of the major upper roadcut

Stop 9C: South end of major roadcut along KY 11 north of Tilton, Kentucky (at KY 156)

The upper end of this outcrop exposes the uppermost Corryville Member of the Grant Lake Formation, including "pinstriped" calcarenites, overlain by ~3m of Mount Auburn Member (Straight Creek facies), comprising coarse skeletal grainstones with abundant stromatoporoids. The Grant Lake is overlain by the characteristic micritic wackestones and rubbly shales of the Sunset and Oregonia Members of the Arnheim Formation (respectively). This is the type section for the Tilton bed of the lower Arnheim.

23.9	0.1	Continue on foot to south (upper) end of outcrop then reboard vehicles
24.0	0.1	**Reverse direction at Kentucky Route 156 (Poplar Plains Road) and return north**
28.6	4.6	**Return north on KY 11 to the junction with KY 32, then turn right (east)**
29.1	0.5	Scruffy outcrop in Waynesville Formation (Stop 10C, but passing it for now)
29.2	0.1	Upper end of a large roadcut on both sides of the road (mapped as Bull Fork Formation; really Arnheim Formation with contact of Waynesville Formation near the top)
29.4	0.1	Lower end of the large roadcut, near the base Oregonia Member (upper Arnheim Formation); cross Fleming Creek
29.5	0.1	Begin a low cut in upper Sunset and lower Oregonia Members of Arnheim Formation; **pull over to shoulder and disembark; drivers will proceed east and turn around at the next available driveway / intersection (e.g., past mile marker 12 or at about 0.5 miles) and return to pick up participants on the other side**

Stop 10A: KY 32 east of Fleming Creek

These low roadcuts display an excellent section of the lower Arnheim Formation (basal Richmondian, C4), particularly a prominent ledge-forming limestone that sharply overhangs the upper Sunset shales, correlated to the Tilton bed of the previous stop.

30.5	1.0	Mileage includes distance for driver turnaround and return; **reboard vehicles and proceed west** across the valley to the large roadcut passed on the inbound journey
30.7	0.2	**Pull off on shoulder next to large outcrop**

Stop 10B: KY 32 west of Fleming Creek

This long outcrop exposes the entire Oregonia Member of the Arnheim Formation (C4B), with a rich Cincinnatian fauna including brachiopods, large bivalves, and trilobites. The basal Waynesville Formation (Fort Ancient Member, C5A) is exposed at the very top.

30.9	0.2	**Continue west a little further, then pull off on shoulder** next to low weathered (and sadly overgrown) benches of shale and packstone

Stop 10C: Old cuts on KY 32 near top of hill west of Fleming Creek

Though poorly exposed, these beds yield a diverse Richmondian fauna representative of the Clarksville Member of the Waynesville Formation (C5C), similar to that seen at Stop 4 of the mid-meeting trip.

31.1	0.2	**Make a U-turn (when safe) and proceed east on KY 32**, back through the outcrops just examined
32.6	1.7	Continue east, passing the junction with Kentucky Route 697
33.5	0.9	**Turn right (south) onto Kentucky Route 111 (Hillsboro Road)**
36.0	2.5	Pass the small village of Poplar Plains and KY 156
36.7	0.7	Cross small stream
37.1	0.4	The slabby outcrops along Locust Creek (n.b. not the one that gives its name to the Locust Creek deformed beds in the Point Pleasant Formation) east of the road are in the upper Waynesville Formation or Liberty Formation; this is one of the southernmost outcrops to show a "typical" (i.e. Ohio and Indiana, normal marine) Richmondian fauna
38.1	1.0	Small outcrop
39.5	1.4	Large outcrop on east side of KY 111 opposite the T-junction with Kentucky Route 1515 (Orchard Road); this is our first look at the upper Richmondian Drakes Formation; these yellowish-weathering, dolomitic limestones and shales belong to the Preachersville Member (upper Drakes); note a prominent ~40cm band of blueish shale in the upper half of the outcrop
39.9	0.4	Cross Hillsboro Branch Creek, followed by small outcrop of Preachersville Member
41.0	1.1	Enter village of Hillsboro, Kentucky
41.3	0.3	Pass junction with Kentucky Route 158 (Sunset Road; if taken west, this road leads to type section of Sunset Member of the Arnheim Formation)
44.2	2.9	Pass by Grange City covered bridge over Fox Creek (on the right/west)
44.3	0.1	Very overgrown outcrop on the east side of the road, showing slabby limestones
44.5	0.2	Outcrop on the right (west) side of the road exposes the dolomitic shales of the uppermost Preachersville Member of the Drakes Formation unconformably overlain by the Lower Silurian Brassfield Formation; our first look at the Ordovician-Silurian boundary
45.3	0.8	Pass through Grange City (more of a village, really), passing junction with Kentucky Route 211 (Colfax Road)
46.5	1.2	Degraded outcrop on the east side of the road; *Leptaena*-bearing limestones
46.7	0.2	Another poor outcrop on the south side of the road
47.0	0.3	Cross bridge over the Licking River; Fleming-Bath County line
48.0	1.0	Cross Indian Creek; good outcrops of lower Grant Lake Formation; pass junction with Kentucky Route 1602 (Oakley-Pebble Road)
48.3	0.3	Steep-sided roadcut on both sides of KY 111; Grant Lake Formation with stromatoporoids high above road level

49.0 0.7 Pass junction with Kentucky Route 1944 (White Oak Road)

49.1 0.1 Cross White Oak Creek, showing bank outcrops of Grant Lake Formation

50.9 1.9 Pass Happy Hollow Road; small cut in upper Grant Lake with stromatoporoids at top (likely the Flemingsburg bed)

51.5 0.6 North end of a large, multi-bench roadcut, one of most continuous Cincinnatian sections in central Kentucky; put on hazard lights and prepare to stop soon

51.8 0.3 **Pull off on shoulder near the south end of the roadcut**

Stop 11: Large roadcut on KY 11 at curve in the Licking River northeast of Owingsville, Kentucky

This large, high roadcut exposes more than 55 m (170 ft) of section ranging from the upper Maysvillian Grant Lake Formation to the upper Richmondian Drakes Formation, perhaps even to the Ordovician-Silurian boundary with the Brassfield Formation above. Five benches, each separated by 10-15 m cliffs, are accessible from a steep farm road leading up the southwest end of the outcrop.

51.8 0.0 Reboard vehicles and proceed south on KY 111 towards Owingsville, Kentucky

55.4 3.6 KY 111 ends at junction US Highway 60 (East High Street); **bear right onto US 60**

55.8 0.4 Junction with Kentucky Route 36; routes combine; **continue straight**

55.9 0.1 **Turn left following US 60 / KY 36**

56.0 0.1 **Turn right, continuing US 60 / KY 36**

56.1 0.2 Downtown Owingsville; **turn left onto KY 36 (Slate Avenue) south**

56.4 0.1 Weathered slope on east side of the road, plus some outcrops in a vacant lot

56.5 0.4 **Turn left (east) onto Miller Scenic View Drive towards McDonald's restaurant; pull in to the parking lot for brief rest stop and optional geologizing**

Stop 12: Owingsville McDonald's, just off KY 36 in Owingsville, Kentucky

Rest stop, snacks, and a brief examination of *Tetradium* and stromatoporoid beds of the Owingsville coral bed (middle Waynesville Formation; Bull Fork facies) in the lot immediately behind the restaurant.

56.6 0.1 **Return west on Miller Scenic View Drive and turn left (south) onto KY 36**

56.8 0.2 **Turn right (west) onto entrance ramp for I-64 westbound**; note large outcrops of Drakes Formation in the opposite exit lane; these cuts extend up to the Ordovician-Silurian boundary (Cherokee unconformity) with the overlying Lower Silurian Brassfield Formation

57.1 0.3 More outcrops of Brassfield Formation on both sides of the road, especially the cherty "Lower Massive Member" and perhaps also the basal Belfast Member (this is near the southern pinch-out of the Belfast, which is currently under study and may actually be somewhat older than originally thought); Preachersville Member of the Drakes Formation exposed at the base

57.5	0.4	Outcrop of lower Rowland Member of the Drakes Formation (Waynesville equivalent) on right (north)
57.8	0.3	Cross bridge over the Licking River
58.3	0.5	Large but overgrown outcrop of Drakes Formation overlain by Brassfield Formation on the left (south)
58.8	0.5	Major roadcuts on both sides of the highway with Drakes and Brassfield Formations, near milepost 119
59.4	0.6	Outcrop exposing Rowland Member of the Drakes Formation (rhythmic limestone/shale of the Fisherville beds) on both sides of I-64
59.5	0.1	Cross bridge over the Licking River (yes, again; the river is very meandering)
60.1	0.6	Cross bridge over Salt Well Creek
60.2	0.1	Long outcrop in upper Grant Lake/Ashlock and Arnheim Formations on the south side of I-64; especially note the light weathering beds of the Terrill Member, equivalent to the Mount Auburn Member (this is stop 13A, but we will return to it via the eastbound lane)
60.4	0.2	Outcrop of Arnheim Formation (Bull Fork facies) on the south side of I-64
60.7	0.4	Outcrop of upper lower Rowland/Waynesville (Bull Fork facies) on the south side of I-64 with prominent fault on the east side (this is stop 13B); ends at milepost 117
61.0	0.3	Another roadcut of lower Rowland/Waynesville on the south side of I-64
61.1	0.1	Outcrop of Drakes Formation (Rowland and Bardstown Members; Waynesville and Liberty equivalent) high on the hill on the south side of I-64
61.3	0.2	Small outcrop on south side of I-64
61.4	0.1	Overpass of Kentucky Route 1219 (N. Stepstone Road), with outcrops adjacent and underneath showing the upper Rowland and basal Bardstown Members of the Drakes
61.5	0.1	Major roadcut of Drakes Formation on the south side of I-64
61.6	0.1	Small outcrop of Preachersville Member of the Drakes Formation on the south side
61.7	0.1	Major ~0.2 mile long outcrop of upper Drakes Formation and Brassfield Formation
62.2	0.6	Bath-Montgomery County line; **get in the left lane**
62.2	0.1	Slow and stay left for **cross-over lane to eastbound lane; make U-turn to reverse directions on I-64;** alternately, continue west for 3 miles to exit 113 and reverse directions there (adding 6 miles to the total)
62.3	0.1	Cross Montgomery-Bath County line, now heading east
62.8	0.5	At hillcrest, note roadcuts of shaly greenish Preachersville Member of Drakes Formation overlain by orange weathering, dolomitic Silurian Brassfield Formation
63.0	0.2	Outcrop of Preachersville Member of Drakes Formation on the south side

63.2	0.2	Overpass with KY 1219 (N. Stepstone Road); outcrops show contact between the upper Rowland Member and basal Bardstown Member of the Drakes Formation, the latter equivalent to the Liberty Formation of Ohio and Indiana; the exposure beneath the bridge itself is upper Rowland dolomitic mudstone with poorly preserved *Tetradium* and small stromatoporoids
63.5	0.3	High roadcut on right (south) in Rowland and Bardstown Members of the Drakes Formation
63.5	0.1	Low cut showing the Fisherville rhythmite beds of the Rowland
63.7	0.2	Outcrop of Drakes Formation high on the hill
63.8	0.1	Another low cut exposing the Rowland Member of the Drakes Formation
64.0	0.2	Begin series of outcrops descending into the valley of Salt Well Creek; the upper cuts contain a large exposure of the lower Rowland (Fisherville beds) cut by a conspicuous normal fault; this is Stop 13B, but we will pass by it for now (note: depending on timing and safety, we may do these sections in reverse [descending] stratigraphic order, instead of their proper, chronological sequence)
64.3	0.3	Outcrop in the upper Arnheim (Oregonia Member); **pull over onto the shoulder and allow passengers to disembark**; passengers will walk down to the next outcrop (Stop 13A, 0.1 miles downhill); vans will wait here or slowly creep back up the hill

Stop 13A: South side of I-64 west of Salt Well Creek in Bath County, Kentucky

This roadcut provides an opportunity to observe the facies changes that take place as one traverses the Cincinnati Arch. The units are locally mapped as the Ashlock Formation, equivalent to the Grant Lake and Arnheim Formations of previous stops. They include Stingy Creek, Terrill, and Sunset Members of the Ashlock Formation (correlated to the upper Corryville and Mount Auburn Members of the Grant Lake Formation and Sunset Member of the Arnheim Formation; C3-C4).

64.7	0.4	Continue on foot west/uphill (0.4 miles) past an exposure of upper Arnheim (Oregonia Member) to large roadcut with fault on its east end

Stop 13B: Faulted outcrop on I-64 near milepost 117, west of Salt Well Creek

This outcrop exposes the lower Rowland Member of the Drakes Formation (correlated to the lower Waynesville Formation and sometimes mapped as the Bull Fork Formation; C5). The lower portion of this cut exposes a fossiliferous package of rhythmic limestones and dark shales (the Fisherville beds). We will also walk up the steep slope at the west end of the outcrop to view an extraordinary ledge covered by small domal bryozoans (*Cyphotrypa clarksvillensis*), an important regional marker bed.

65.3	0.6	Resume journey eastward on I-64, passing the just-visited outcrops and crossing Salt Well Creek
65.9	0.6	Cross the Licking River; outcrop of nodular rhythmic limestone of Fisherville beds and, lower, the upper Arnheim Formation
66.2	0.3	Very overgrown outcrop of shaly Drakes Formation

66.5	0.3	Rather nice outcrops on both sides of I-64 at a bend, with Drakes Formation (Preachersville Member) overlain by the Brassfield Formation
66.9	0.4	Spotty outcrop of Drakes Formation (Preachersville Member) overlain by Brassfield Formation
66.0	0.2	Outcrop of Drakes Formation (Preachersville Member) overlain by Brassfield Formation, high on the hill overlooking the interstate; excellent exposure of upper Brassfield "Bead Bed" above road level; overlain by "Noland Formation" (undifferentiated Plum Creek Shale and Oldham Limestone)
66.5	0.5	Cross Licking River
66.8	0.3	Roadcut of Rowland Member of the Drakes Formation on north side
67.4	0.4	Ordovician-Silurian boundary outcrop with Preachersville Member of the Drakes Formation overlain by the Brassfield Formation; this outcrop includes a large bedding plane exposure of the Brassfield south of the highway, from which a very diverse echinoderm fauna has been obtained (Ausich et al., 2015)
67.7	0.3	Pass exit 121 for KY 36 and Owingsville, Kentucky; note Drakes Formation outcrops on exit ramp
68.5	0.8	Cross Licking River (a third time on this eastbound drive alone, as the river meanders strongly)
68.8	0.3	Outcrop in upper Rowland (equivalent to Blanchester Member of the Waynesville Formation) exposing the coral-rich Owingsville bed, overlain by a shaly succession with *Tetradium*
69.0	0.2	Outcrop in upper Drakes Formation (Preachersville Member), possibly with Brassfield Formation on top of the bench
69.0	0.3	**Bear right to take I-64 exit 123 for US Highway 60**; note extensive outcrops of Drakes Formation along exit lane
69.3	0.3	**Pull off on shoulder of exit lane near intersection with US 60**

Stop 14: I-64 exit 123 offramp to US 60 east of Owingsville, Kentucky

This outcrop provides an excellent exposure of the uppermost Arnheim and Waynesville strata (C4B-C5), with abundant fauna including well-preserved mollusks, sponges, putative algae, corals, and more.

69.5	0.2	**Turn left (north) at the intersection with US 60, passing underneath I-64**
69.7	0.2	**Turn left (west) onto entrance ramp for I-64 west; proceed westward to exit 110** (note: while the ensuing route passes by exposures seen earlier; not all outcrops noted earlier are repeated here in the interests of clarity)
71.3	1.6	Pass I-64 exit 121 (Owingsville); again, note the large Drakes-Brassfield outcrop
74.9	3.6	Cross over Salt Well Creek and previously visited outcrops (Stops 13A and 13B)
77.1	2.2	Bath-Montgomery County line (resume outcrop logging)

77.6	0.5	Cross Salt Well Branch; outcrop on north side of highway ascending hill from Salt Well Branch; excellent exposures of Arnheim and lower Rowland; showing prominent rhythmic limestones of Fisherville beds; hillcrest at milepost 115
77.8	0.2	Another outcrop of the same interval
78.3	0.5	Outcrops of Ashlock Formation (Grant Lake-equivalent, in part) on both sides
78.6	0.3	Roadcut on both sides of I-64; shows contact of the Gilbert Member of the Ashlock Formation (Corryville-equivalent?) with the stromatoporoid-bearing upper Ashlock (Stingy Creek Member?)
79.0	0.4	Outcrop of Ashlock Formation on the north side
79.2	0.2	Low outcrop of Ashlock Formation on the north side
79.8	0.6	Pass I-64 exit 113 to US 60 (Mount Sterling east);
80.0	0.2	Outcrop of Ashlock Formation just west of the US 60 overpass
80.7	0.7	Long outcrop of Ashlock Formation
81.0	0.3	Low, overgrown outcrop of Ashlock Formation grainstones
81.3	0.3	Outcrop of Ashlock Formation at Kentucky Route 1991 (Hinkston Pike) overpass
82.5	1.2	**Take I-64 exit 110 for KY 11 and Mount Sterling**; outcrop of Tate (pale greenish) and Gilbert (Grant Lake) Members of Ashlock Formation on I-64 just east of and beneath the overpass for KY 11
82.7	0.2	**Turn left (south) onto KY 11 (Maysville Road)**; it is pure serendipity that we start and end the day on the magnificent Kentucky Route 11
82.9	0.2	**Turn left (east) onto Falcon Drive and left again onto Raglan Avenue to Days Inn Mount Sterling**

<u>End road log for post-meeting field trip day 1</u>

Post-Meeting Field Trip Day 1 Stop Descriptions

Stop 6: Roadcuts on KY 11 north of the AA Highway at Maysville, Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn

Location: Subset of a series of about eight roadcuts along a ~2.7 km (~1.7 mile) stretch of Kentucky Route 11 between the AA Highway (Kentucky Route 9) and the junction with Kentucky Route 2519, south of Maysville in Mason County, Kentucky

Coordinates: Southernmost (highest) cut at 38° 36' 15.1" N, 83° 45' 37.7" W; northernmost (lowest) cut at 38° 37' 30.4" N, 83° 45' 04.8" W

Elevation: Base of lowest cut at ~177 m (~580 ft), top of highest cut at ~262 m (~860 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1-Ka2; Cincinnatian, Edenian-Maysvillian, C1-C4): Kope Formation, Fairview Formation, and Grant Lake Formation (Bellevue, Corryville, and Mount Auburn Members)

This stop overlaps with Stop 3 of the pre-meeting field trip and is intended to recapitulate the observations of that previous visit in preparation for the review of younger strata later in the day.

Just south of Lawrence Road, on the east side of KY 11, the wackestones and packstones of the Mount Hope Member of the Fairview Formation sharply overlie the Taylor Mill siltstones of the uppermost Kope Formation. *Diplocraterion*-burrowed siltstones are occasionally visible in the ditch. As at Stop 1, the base of the Fairview is placed at the co-called "Z bed" at the base, overlain by the "2-Foot shale" (here about a meter thick). The cut also exposes a typical lower Fairview (Mount Hope) succession, with the *Strophomena*-rich North Bend submember on fine display.

The next outcrop to the south (uphill) exposes the Fairmount (upper Fairview), comprising a series of graded silty packstones and thick siltstones. The most siltstone-rich interval, assigned by Schramm (2011) to the Hooke-Gillespie submember, is interpreted as a regressive or falling stage, when forced regression caused rapid offshore deposition of silt in storm-surge channels associated with a prograding shoreface. This general progradation was interrupted by intervals of slower sedimentation when skeletal limestones accumulated.

Three distinct siltstone levels are conspicuously deformed and easily observable from the roadside. These large boulder-like ball and pillow structures measure up to a meter across and 50 cm thick. They display internal convolute lamination and are surrounded by irregular tongues or diapirs of deformed mudstone. Laterally, the deformed beds grade into non-deformed thinner tabular beds of siltstone. This may suggest a relationship between thickness of originally lenticular and possibly channeled siltstones and their tendency toward soft-sediment deformation. Particularly notable at this locality are well preserved soles of beds in pillows, which display stretched and deformed molds of silt-filled, sharply incised trace fossils and tool marks as well as local reticulate patterns interpreted as "load cracks". This evidence strongly suggests that the semi-cemented silts originally rested on firm, overcompacted muds, which were subsequently liquefied and injected upward as the pillows foundered. In some cases the laminae of the silts were curled upward and overturned while still displaying deformed sole features, suggesting forceful injection of mud from below.

These three pillow horizons have been widely-traced in the siltstone-rich upper Fairmount and they have been interpreted as seismites (Schumacher, 2001; Brett et al., 2008). These beds were partially to completely cemented and in one case broken into blocks, possibly also by seismic shocks. These blocks then lay exposed as irregular hardgrounds during periods of sediment starvation and were encrusted on tops as well as lateral surfaces by bryozoans including ptilodictyid holdfasts (easily confused with crinoid holdfasts, which are also found on Cincinnatian hardgrounds). Their surfaces were eventually buried in clay and preserved. This occurrence was described in more detail in Brett et al. (2008; see p. 136).

The highest part of the Fairmount Member shows thicker skeletal pack- and grainstones with thin silty shales, assigned by Schramm (2011) to the Lawrenceburg and Hill Quarry beds. These likely represent a 4th order transgression and perhaps early highstand within the upper Fairmount. An uppermost Fairview unit, the Miamitown Shale, is found above the Hill Quarry beds on the western flank of the Cincinnati Arch and represents the highstand and falling stage deposits of this subcycle. However, near Maysville the Miamitown appears to have been removed, truncated under the sharp contact with the overlying Bellevue Member of the Grant Lake Formation (the C2-C3 sequence boundary).

As at previous stops, a particularly notable interval occurs above a thick ledge of packstone and siltstone, slightly below the sharp and disconformable upper contact of the Fairview. This zone contains camerate crinoid remains at this outcrop and is almost certainly correlative to the beds that yielded an extraordinary aggregation of several hundred complete *Glyptocrinus decadactylus* (Milam et al., 2017). Articulated *Glyptocrinus* crowns are known at this level as far west as Lawrenceburg, Indiana, more than 110 kilometers (~70 miles) to the northwest. This could represent an extraordinarily widespread event or series of closely spaced events during deposition of the upper Fairmount.

The remaining outcrops to the south expose all three members of the upper Maysvillian Grant Lake Formation: the Bellevue, Corryville, and Mount Auburn Members, in ascending order. These units will be covered in more detail (and at better localities) at later stops. However, a brief walk or drive up the section will provide a satisfactory overview. The succession starts with the bryozoan and brachiopod rich pack- to grainstones of the Bellevue. Although intensely fossiliferous, the high-energy depositional environment of the Bellevue is not particularly known for well-preserved specimens. Nevertheless, hardgrounds and local shale pockets have yielded exceptional finds, including a new species of cyclocystoid, *Zygocycloides blairi*, described from this very cut (Smith and Wilson, 1995).

Whereas the Bellevue represents the transgressive systems tract of the C3 sequence, the Corryville is the C3 highstand. Notably more argillaceous than the underlying Bellevue, the Corryville here consists of rubbly-weathering shales and limestones. Like the Bellevue, the Corryville is very fossiliferous, and is often the best unit to find complete specimens of large brachiopods such as *Vinlandostrophia ponderosa* and *Hebertella*. The Corryville is bisected by a ~2 m package of more robust limestones, termed the Flemingsburg bed or Flemingsburg submember for excellent exposures south of Flemingsburg, Kentucky (e.g., Stop 8). We interpret the Flemingsburg as a 4th order transgressive systems tract within the greater Corryville highstand (i.e. the C3B TST, with the Bellevue being the C3A TST). A bundle of prominent limestone ledges near a side road in the KY 11 roadcut may represent the Flemingsburg bed.

Finally, the uppermost Grant Lake (Mount Auburn Member) is found in the roadcuts closest to the AA Highway. The Mount Auburn represents a return to phosphate-rich packstones/grainstones, in many respects similar to the older Bellevue. We interpret it to be the transgressive systems tract of the C4 sequence, with the overlying shaly Arnheim Formation (exposed on nearby cuts along the AA Highway) representing the C4 highstand. These units will be seen in much more detail at subsequent stops.

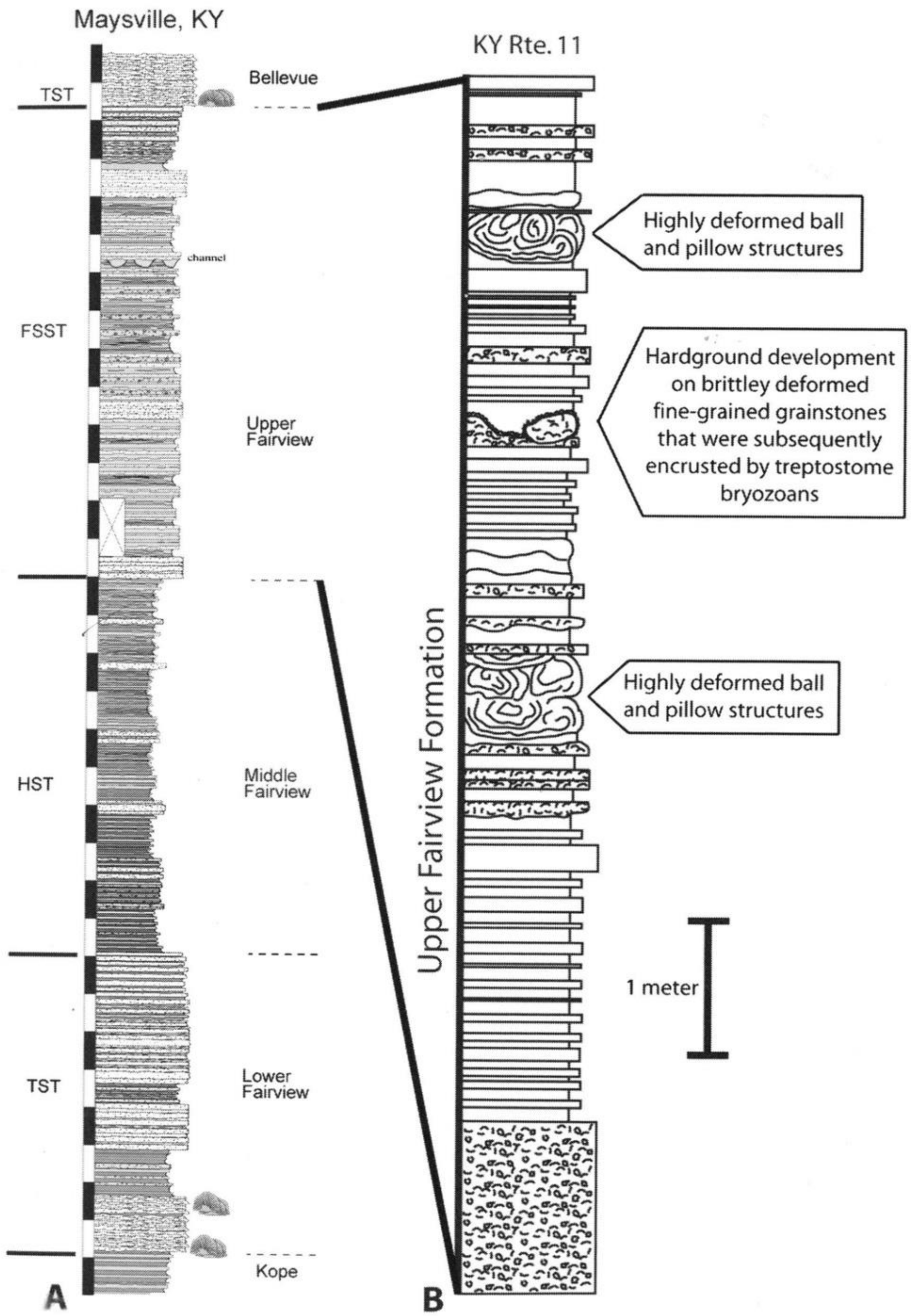


Figure 48. *Stratigraphic column for Fairview Formation at the Kentucky Route 11 roadcut south of Taylor Mill Road at Maysville, Kentucky. From Brett et al. (2008). A, overall column of the entire Fairview Formation; B, detail view of the upper Fairview Formation, focused on the Hooke-Gillespie deformed beds.*

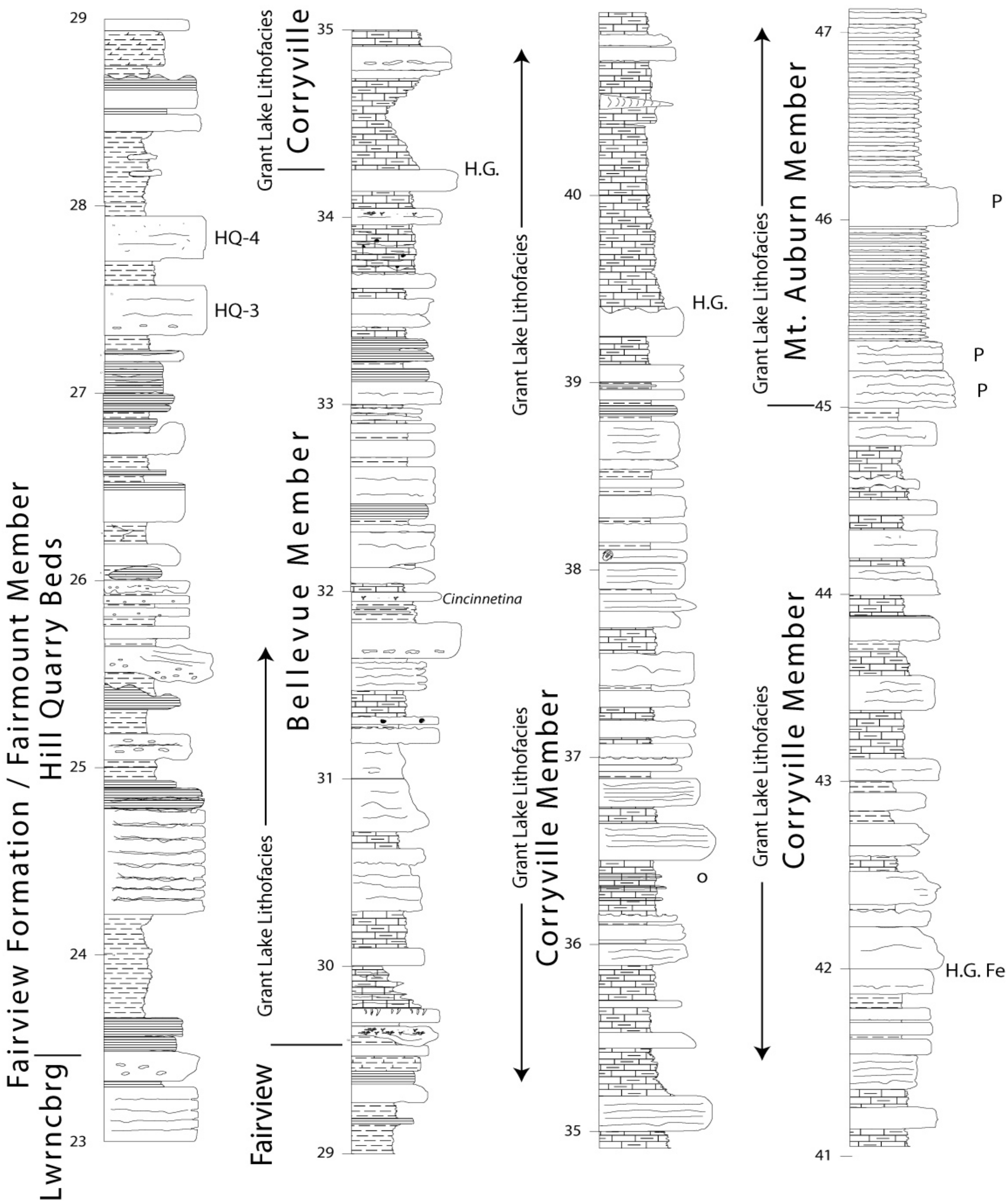


Figure 49. *Stratigraphic columns for the upper portion of the section along Kentucky Route 11 north of the AA Highway, south of Maysville, Kentucky. From Schramm (2011). Fe = rust-stained horizon, H.G. = hardground; P = phosphate.*

Stop 7: KY 11 ~0.5 miles south of Mill Creek Road, north of Flemingsburg, Kentucky

Contributors: Kyle R. Hartshorn, Carlton E. Brett

Location: Small, low outcrop on both sides of the Kentucky State Route 11 ~0.8 (~0.5 miles) south of its junction with Mill Creek Road, ~2.1 km (~1.3 miles) northeast of Helena in Mason County, Kentucky

Coordinates: 38° 30' 17.0" N, 83° 45' 32.2" W;

Elevation: Base at ~262 m (~861 ft), top at ~265 m (~872 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2-Ka3?; Cincinnatian, lower Richmondian, C4): Bull Fork Formation (equivalent to Sunset and Oregonia Members of the Arnheim Formation)

This quick, optional stop offers participants the first opportunity to inspect the lower Richmondian Arnheim Formation (here mapped as a part of the Bull Fork Formation, which we regard as a facies). Ledges of silty wackestones and shales near the base are assigned to the Sunset Member (lower Arnheim). The overlying fossiliferous rubbly shale and ledgy packstones are assigned to the Oregonia Member (upper Arnheim) and yield a fauna dominated by the strophomenid brachiopod *Rafinesquina*. Some bedding planes show an abundance of the distinctive and stratigraphically significant brachiopod *Leptaena richmondensis*. This *Leptaena* epibole in the basal Oregonia is traceable around the majority of the Cincinnati Arch. *Leptaena* often co-occurs with *Rhynchotrema dentatum*, and it is possible that this small rhynchonellid may also be found here. Other faunal elements include well-preserved and locally abundant ctenodontid bivalves, some with rare calcite preservation of shells and hinge teeth (Figure 50).

Figure 50. *An extraordinary bed of well-preserved bivalves from the middle Arnheim Formation along Kentucky Route 11 south of the Shamrock Food Mart / Mill Creek Road, north of Flemingsburg, Kentucky.*

Stop 8: KY 11 near Quarry Road, south of Flemingsburg, Kentucky

Contributors: Kyle R. Hartshorn, Carlton E. Brett; Thomas J. Schramm

Location: Roadcuts along Kentucky Route 11 (Mt. Sterling Road), near the intersection with Quarry Road, 4.7 km (2.9 miles) south of Flemingsburg, Fleming County, Kentucky

Coordinates: 38° 22' 53.6” N, 83° 44' 54.4” W

Elevation: Base at ~241 m (~790 ft), top at ~250 m (~820 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2; Cincinnatian, Maysvillian, C3): Corryville Member of the Grant Lake Formation, including the Flemingsburg bed

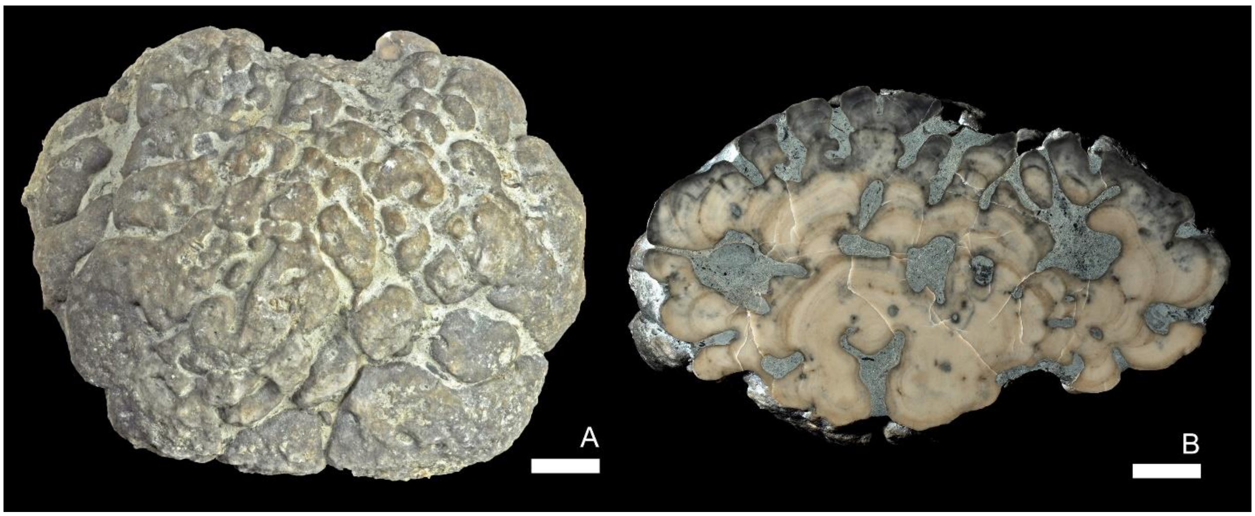


Figure 51. *A, complete* Solenopora *nodule (scale bar: 10 mm); B, sagittal section of a* Solenopora *nodule showing internal morphology (scale bar: 10 mm). (Figure modified from Kallmeyer et al., 2018.)*

The section of Kentucky Route 11 south of Flemingsburg, Kentucky exposes numerous roadcuts through the middle to upper Grant Lake Formation (Weir et al., 1984), slightly younger than the Bellevue Member of the Grant Lake Formation at the top of Stop 1. Many of these roadcuts are just over decade old, having been blasted circa 2005-2006, and provide a critical stratigraphic context for the Grant Lake Formation in this region (Schramm, 2011; Hartshorn et al., 2016; Malgieri and Brett, in preparation).

The rubbly-weathering Corryville Member of the Grant Lake Formation is highly fossiliferous, with an abundance of bryozoans, spar-filled gastropod molds, and the large orthid brachiopods *Hebertella* and *Vinlandostrophia ponderosa*, the latter being particularly numerous in some horizons. This unit is also host to a variety of algal oncolites and coated grains, as well as wrinkled, brain-like lumps of *Solenopora* (Figure 51). Large (up to about 30 cm, though typically 5 to 15 cm) and abundant within certain horizons, these *Solenopora* nodules provided a sheltered microhabitat for a variety of small organisms, including polychaete worms (their jaws preserved as small, black scolecodonts), brachiopods such as the tiny atrypid *Zygospira* and the scab-like craniid *Petrocrania*, and encrusting cyclostome bryozoans (cf. *Cuffeyella*). When cut and polished, *Solenopora* reveal a fibrous microstructure and distinct growth laminations. Their calcitic preservation has an attractive pinkish-brown hue, which becomes especially apparent when raw specimens are wetted, making *Solenopora* especially easy to find after a rain. Weathered specimens are often drabber.

Solenopora was regarded as a coralline-like calcareous red algae throughout the 20th century (see Poignant, 1991 for a review). More recently, Riding (2004) argued that *Solenopora* is instead a chaetetid sponge (although the affinity of chaetetids themselves has itself been debated, as has their relationship to the similarly enigmatic tetradiids). This reevaluation was based on the type species, *S. spongioides*, from the Saku Member of the Vasalemma Formation (Upper Ordovician: Katian, Ka1; Keila-Oandu) of Estonia. However, the status of some other taxa assigned to *Solenopora* was unaddressed. Study of thin sections made of Kentucky specimens indicates that their microstructure is close enough to *S. spongioides* that they can be considered congeneric and may indeed be chaetetids (Kallmeyer et al., 2018**)**. Conversely, another local species, *"Solenopora" richmondensis* from the upper Whitewater Formation (Katian, Ka4; Cincinnatian, upper Richmondian, C7-C8) of Indiana and adjacent Ohio, appears to be a separate, most likely algal taxon (Blackman et al., 1982; Brooke and Riding, 1998; Kallmeyer et al, 2018).

Stop 9: KY 11 near Tilton, Kentucky

Contributors: Kyle R. Hartshorn, Carlton E. Brett, Thomas J. Schramm

Location: Major roadcut on Kentucky Route 11 starting at intersection with Old Kentucky 11 and ending about 0.2 km (0.1 miles) north of Kentucky Route 156, 1.2 km (0.7 miles) north of Tilton in Fleming County, Kentucky

Coordinates: North end at 38° 21' 31.3" N, 83° 45' 34.3" W;
south end at 38° 21' 10.2" N, 83° 45' 35.9" W

Elevation: Base at ~238 m (~780 ft), top at ~270 m (~885 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2-Ka3?; Cincinnatian, upper Maysvillian, C3-C4): upper Grant Lake Formation (Corryville and Mount Auburn Members) and Arnheim Formation (Sunset and Oregonia Members)

Roughly ~3 km (2 miles) south of the previous stop, just after a junction with Old State Route 11, another series of roadcuts expose a nearly complete section of the upper Grant Lake Formation (Corryville and Mount Auburn Members) and much of the overlying Arnheim Formation. This section affords a look at almost the entire Corryville (Figure 53), including the Flemingsburg bed. The uppermost Corryville is a "pinstriped" calcarenite overlain by ~3m of Mount Auburn Member (similar to the Straight Creek facies of Schumacher et al., 1991), a coarse skeletal grainstone with major stromatoporoid biostrome packed with a jumble of brown or pinkish *Labechia* (Figures 17, 52). Most of the stromatoporoids at this locality are heavily recrystallized, but a few rare specimens have exquisitely preserved microstructure. Layers near the base commonly show coated grains and oncoids.

A second biostrome is present in the dark gray shales and micritic limestones of the overlying Sunset Member of the Arnheim Formation. This cut provides a crucial reference section for the Sunset Member of the Arnheim Formation in its type area (Sunset, Kentucky is just a few kilometers to the southeast). The 2 m thick Sunset is transitionally overlain by a 20-30 cm thick micritic wackestone bed that contains small brown stromatoporoids and oncoids, here termed the Tilton bed for this locality. This bed is interpreted as the TST of the upper Arnheim sequence (C4B), which commences with the Oregonia Member. It is overlain by highly fossiliferous gray mudstone and thin packstones rich in brachiopods (the Oregonia), including *V. ponderosa* but also other species of *Vinlandostrophia*, *Rafinesquina*, *Hebertella* and ramose bryozoans. This bed is most notable for its moderately common small, flat *Leptaena richmondensis* and *Rhynchotrema* *dentatum*, the vanguards of the Richmondian Invasion. About 3 m of upper Arnheim is exposed in the inaccessible upper portion of this cut, but is accessible on outcrops at Kentucky Route 156 where upper beds yield abundant *Strophomena* cf. *concordensis* and a very small *Vinlandostrophia* sp.

The Grant Lake and Sunset at this and other nearby outcrops are remarkably similar to the upper Lexington Limestone exposed near Winchester to the southwest (Stop 15). There, the Strodes Creek Member exhibits a nearly identical lithology, with interbedded fine micrites, organic-rich shales, and a stromatoporoid biostrome, though it is separated from the Grant Lake Formation by several million years (Ka1 vs Ka2; Chatfieldian vs Maysvillian). This repeated facies motif likely indicates close similarities in climate and depositional setting.

Figure 52. *Upper part of the succession along Kentucky Route 11 north of Tilton, Kentucky, exposing the Corryville Member of the Grant Lake Formation (far right), Mount Auburn Member of the Grant Lake Formation (C4 and C4A TST), with spectacular stromatoporoid biostrome), shaly, micritic Sunset Member of the Arnheim Formation, Tilton bed (C4B TST), and Oregonia Member of the Arnheim Formation (C4 and C4B HST).*

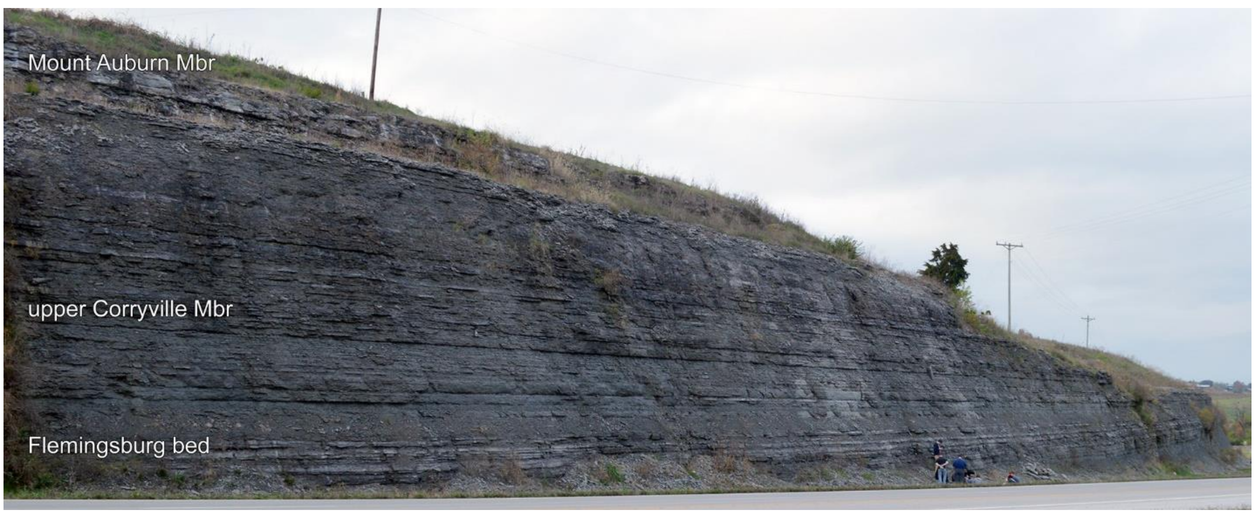


Figure 53. *Middle section of the succession along Kentucky Route 11 north of Tilton, Kentucky, exposing the Corryville Member of the Grant Lake Formation. The Flemingsburg bed is at the level of the students at center-right. The Mount Auburn Member is faintly visible above the bench at the top of the image.*

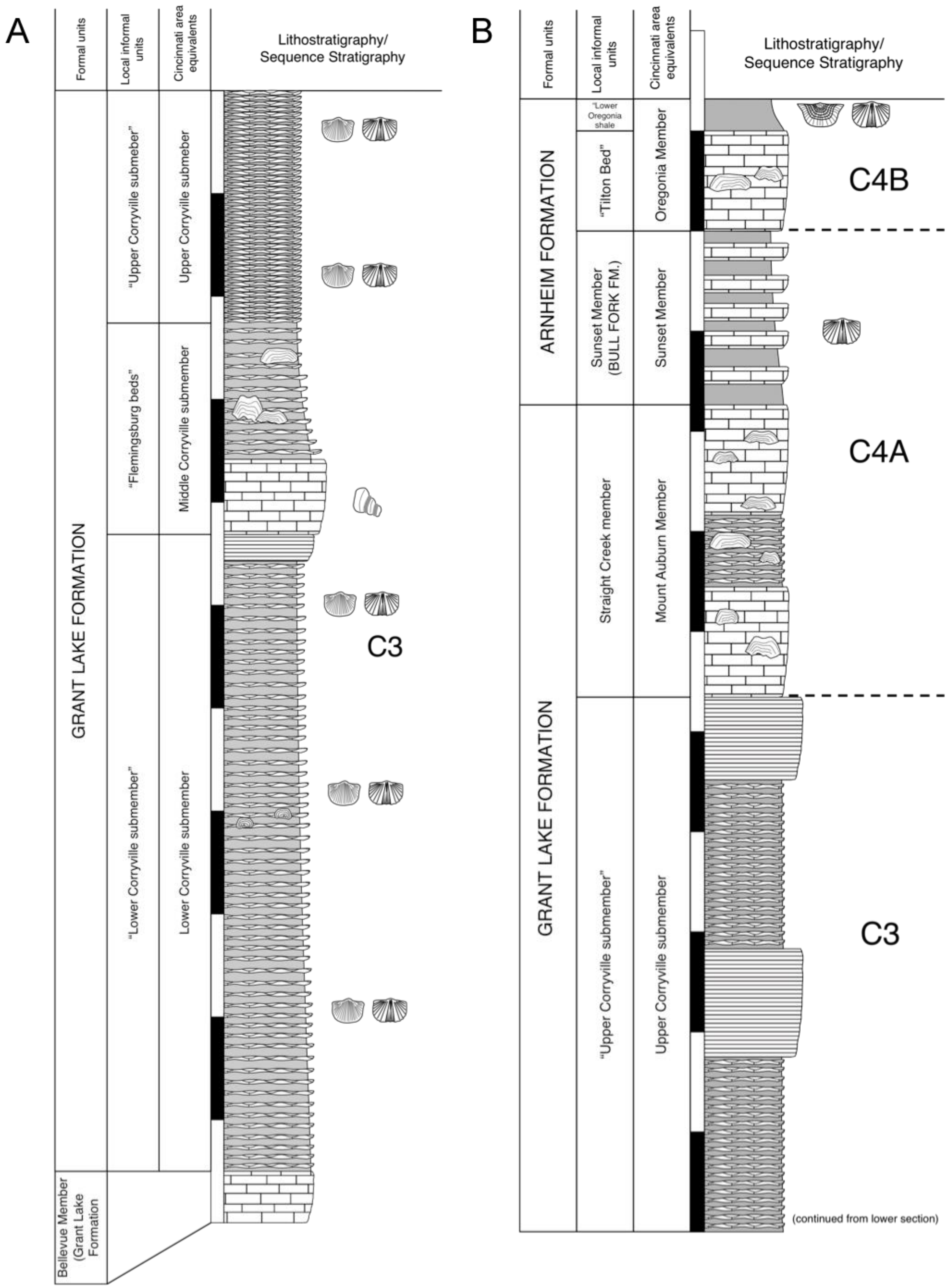


Figure 54. *Stratigraphic column of the lower (A) and upper (B) sections of the roadcut along KY 11 north of Tilton, Kentucky exposing the Corryville Member and Mount Auburn Members of the Grant Lake Formation, overlain by the Sunset and Oregonia Members of the Arnheim Formation, including the Tilton bed.*

Stop 10: KY 32 south of Flemingsburg, Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn

Location: Series of three roadcuts along Kentucky Route 32, a) low cuts on both sides of road 0.3 km (0.2 miles) east of bridge over Fleming Creek; b) large cuts in hillside on both sides of the highway starting immediately west of Fleming Creek; c) poorly exposed, partially overgrown section on north side of the highway at top of hill ~0.3 (~0.2 miles) west of Fleming Creek, 0.8 km (0.5 miles) south of Flemingsburg, Fleming County, Kentucky

Coordinates: Middle cut (b) at 38° 24' 11.7" N, 83° 43' 31.4" W

Elevation: Lowest ~242 m (~795 ft), highest ~267 m (~875 ft)

Stratigraphy: Upper Ordovician (Katian, Ka3; Cincinnatian, lower Richmondian, C4-C5): Bull Fork Formation (here equivalent to the Sunset and Oregonia Members of the Arnheim Formation plus the Fort Ancient and Clarksville Members of the Waynesville Formation)

This interval, assigned to the Bull Fork Formation by USGS mappers, provides an exceptional exposure of the entire upper (Oregonia) member of the Arnheim Formation and spotty but very fossiliferous weathered outcrop of the Waynesville Formation.

The lowest exposures (Stop 10A; Figures 55C,E) are available in the low cuts on both sides of KY 32 east of Fleming Creek where a stack of three or four compact packstone and crinoidal grainstone beds with minor cross-bedding form a distinct ledge, the Tilton bed, that overhangs soft shales of the Sunset Member and forms the base of the Oregonia Member as presently defined. These ledges show patchy in situ heads of pinkish weathering *Solenopora* (Figure 55F), but no stromatoporoids in contrast to the section at Tilton (Stop 9). The compact 30-cm thick upper grainstone is sharply overlain by darker gray shale and thin rubbly weathering, highly fossiliferous muddy packstones capped by thicker limestone ledges. These beds yield a rich fauna, including small ramose bryozoans, small *Vinlandostrophia*, *Hebertell*a sp., and most notably a small, flattened form of *Leptaena* (Figure 55D) and the rhynchonellid *Rhynchotrema dentatum*; the latter taxa, diagnostic of the lower Oregonia Member and illustrating some of the earliest hints of the Richmondian Invasion.

The large hillside outcrop (Stop 10B; Figure 55A) overlaps with the *Leptaena-Rhynchotrema* beds of Stop 10A and continues upward through a series of about five sub-meter alternations of ledgy pack-grainstones and rubbly fossiliferous gray shales. These beds yield few diagnostic fossils but instead are very rich in "typical" Cincinnatian forms such as *Isotelus* trilobites (Figure 55B), various ramose bryozoans, *Rafinesquina alternata*, *Hebertella occidentalis*, *Vinlandostrophia* spp. (rare *V. ponderosa*), as well as large bivalves (*Ambonychia*, *Modiolopsis*, *Caritodens*) and gastropods including *Cyclonema*.
The contact with the overlying lower Waynesville Formation—Holland and Patzkowsky's (1996) C4-C5 boundary—is obscure and cryptic at this locality but apparently lies at the base of a cluster of grainstone that sharply overlies a distinctly recessive shale. These beds are overlain by shale and rhythmic chalky to slightly orange-weathering weathering nodular wackestones and dark shales that form a thin equivalent of the lower Fort Ancient shales of the Waynesville formation (C5A).

Following a covered stretch with minor loose rubble of slabs there is a poor outcrop (Stop10C) near the hill crest that shows abundant tan weathering slabs with abundant molds of gastropods (*Loxoploxus*) that may represent a thin tongue of Marble Hill beds seen on the northwest side of the Cincinnati Arch. Higher beds yield a rich fauna of typical Richmondian brachiopods, including *Cincinnetina*, *Hebertella*, *Strophomena planumbona*, *Eochonetes*, *Leptaena*, and *Hiscobeccus*, especially in the upper terraces. Near the top some beds yield abundant the rugose coral *Grewingkia* and *Tentaculites*. Wittmer (2008) correlated this section bed for bed with that on the "horn coral beds" of the Clarksville Member on the AA Highway east of Maysville (Stop 5) and found comparable *Tentaculites* rich layers.

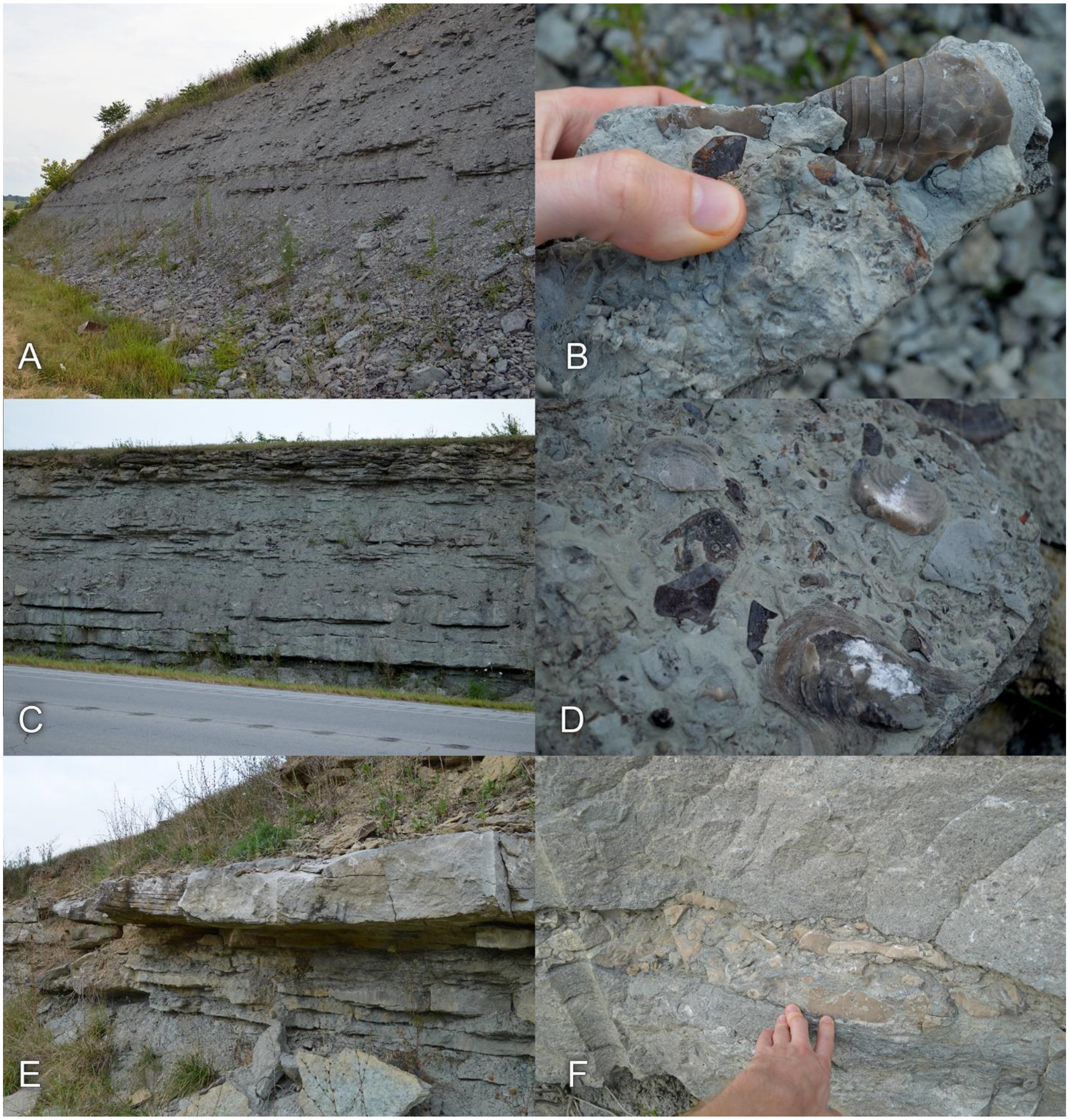


Figure 55. *Outcrops on Kentucky Route 32 near Fleming Creek, southeast of Flemingsburg, Kentucky. A, the large middle outcrop on the west side of the creek showing the shaly upper Oregonia Member; B, an articulated but sadly incomplete Isotelus trilobite from Oregonia; C, section from the outcrop on the east side of the creek, showing upper Sunset, Tilton, and lower Oregonia; D, typical slab from the strata above the Tilton bed, with* Leptaena, Isotelus *fragments, and a* Caritodens *bivalve (*Rhynchotrema dentatum *and* Vinlandostrophia *are also known from this zone); E, a view of the upper cross-bedded grainstone ledge of the Tilton bed, sharply overlying the shales of the Sunset; F, a large solenoporid between two grainstone ledges within the Tilton bed, essentially living on the foresets of a coarse carbonate sand environment.*

Stop 11: KY 111 south of Wyoming, Kentucky

Contributors: Carlton E. Brett, Kyle R. Hartshorn, T.J. Malgieri

Location: Large, high roadcut mainly along west side of Kentucky Route 111, extending for about 0.5 km (0.3 miles) north of intersection with Waterdell Road, ~5.8 km (~3.6 miles) south of Wyoming, Bath County, Kentucky.

Coordinates: 38° 10' 58.5" N, 83° 43' 25.9" W

Elevation: Base (gutter at north end) at ~203 m (~665 ft), top at ~255 m (~836 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2-Ka4; Cincinnatian, Maysvillian-Richmondian, C3-C8), Grant Lake Formation (Corryville and Mount Auburn-Terrill Members), "Bull Fork Formation" (equivalent to Sunset and Oregonia members of the Arnheim Formation and Fort Ancient and Clarksville members of the Waynesville Formation), Rowland Member of the Drakes Formation (Blanchester Member equivalent, including Owingsville coral beds), and Bardstown and Preachersville Members of Drakes Formation

Figure 56. *overview of the large multi-tiered roadcut along Kentucky Route 111 near Wyoming, Kentucky exposing the Grant Lake Formation through the Drakes Formation; note multiple benches which afford access to various levels within the succession.*

The huge Kentucky Route 111 cut extending upward for about 50 m has a total of four terraces or benches (Figure 56), which are accessible by a narrow and steep farm road that leads to the hill top on the southwest end of the outcrop. This cut thus provides one of the most complete sections of the upper Cincinnatian Series in central Kentucky. The outcrop displays much of the Grant Lake Formation, Corryville Member equivalent at the base, including typical rubbly weathering shell-rich beds rich in *Vinlandostrophia* and *Hebertella*. A thin stromatoporoid biostrome may represent the Flemingsburg bed seen in the Tilton outcrop. Here it lies below a suite of rhythmic wackestones and dark shales at the top of the Corryville resemble the Stingy Creek Member of the Ashlock Formation further south.

Of considerable interest in this section is the probable Mount Auburn equivalent which has here undergone substantial thinning and facies change. In comparison with the coarse rudstones and grainstones seen at Tilton (Stop 9), the interval here is represented by a thin, pale gray colored micritic wackestone bed with patchy occurrence of stromatoporoids near its base, showing a transition the facies of the equivalent Terrill Member which in its type area to the southwest shows pale greenish dolomicrites and shales with desiccation cracks. This interval can be examined in greater detail at a roadcut on I-64 just west of Salt Well Creek (Stop 13).

The Arnheim-equivalent lower Bull Fork formation shows division into a thin rhythmically bedded gray wackestones and thin dark shales; the Oregonia Member, is thin at this locality and is visible on the first bench. An extraordinary feature of this section is the occurrence at the south end of a sharply incised channel filled with up to 3 meters of skeletal rudstone and grainstone. This is a striking example of an erosional contact at the C4-C5A boundary, also seen at the eastern Owingsville exit from I-64 (Stop 14).

The base of the overlying succession is visible on the second bench the basal Waynesville equivalent has here undergone full transition into shallow lagoonal facies generally identified as the lower submember of the Rowland Member on the western side of the Cincinnati Arch. These include dark shales with abundant carbonized algae and a series of rhythmically interbedded chalky weathering micritic wackestones with abundant modiolopsid bivalves, gastropods (Figure 61), the small domal bryozoan *Cyphotrypa*, and the brachiopod *Hebertella*: the Fisherville beds. These are overlain by a very distinctive pale chalky weathering interval of shaly micrites provides another marker that can be traced into the lower Rowland. These beds are overlain by ledgy, richly fossiliferous wacke- and packstones teaming with *Hebertella* and with local patches of the colonial corals *Tetradium* and *Cyathophylloides*, which occur abundantly as float on the bench. Unfortunately, these beds are exposed in the steep face and cannot be readily accessed and measured but they will be seen at subsequent stops.

The higher portions of the outcrop are poorly studied due to their lack of accessibility but consist of a series of dolomitic ledgy limestones and dark greenish gray shale presently assigned to the undifferentiated Drakes Formation. The top of the exposure shows a thick succession of barren, dolomitic shale, the Preachersville Member, and sporadic pieces of orange, dolomitic talus suggest that the Lower Silurian Brassfield Formation may be exposed in the upper fringes, at least locally.

Figure 57. *A smaller cut on the northern side of the road, to the southeast of the big roadcut. Exposes the uppermost Corryville Member (shaly) and Mount Auburn Member (lumpy limestone with stromatoporoid biostrome) of the Grant Lake Formation, capped by the Sunset Member of the Arnheim Formation (micritic limestone, above shale notch).*

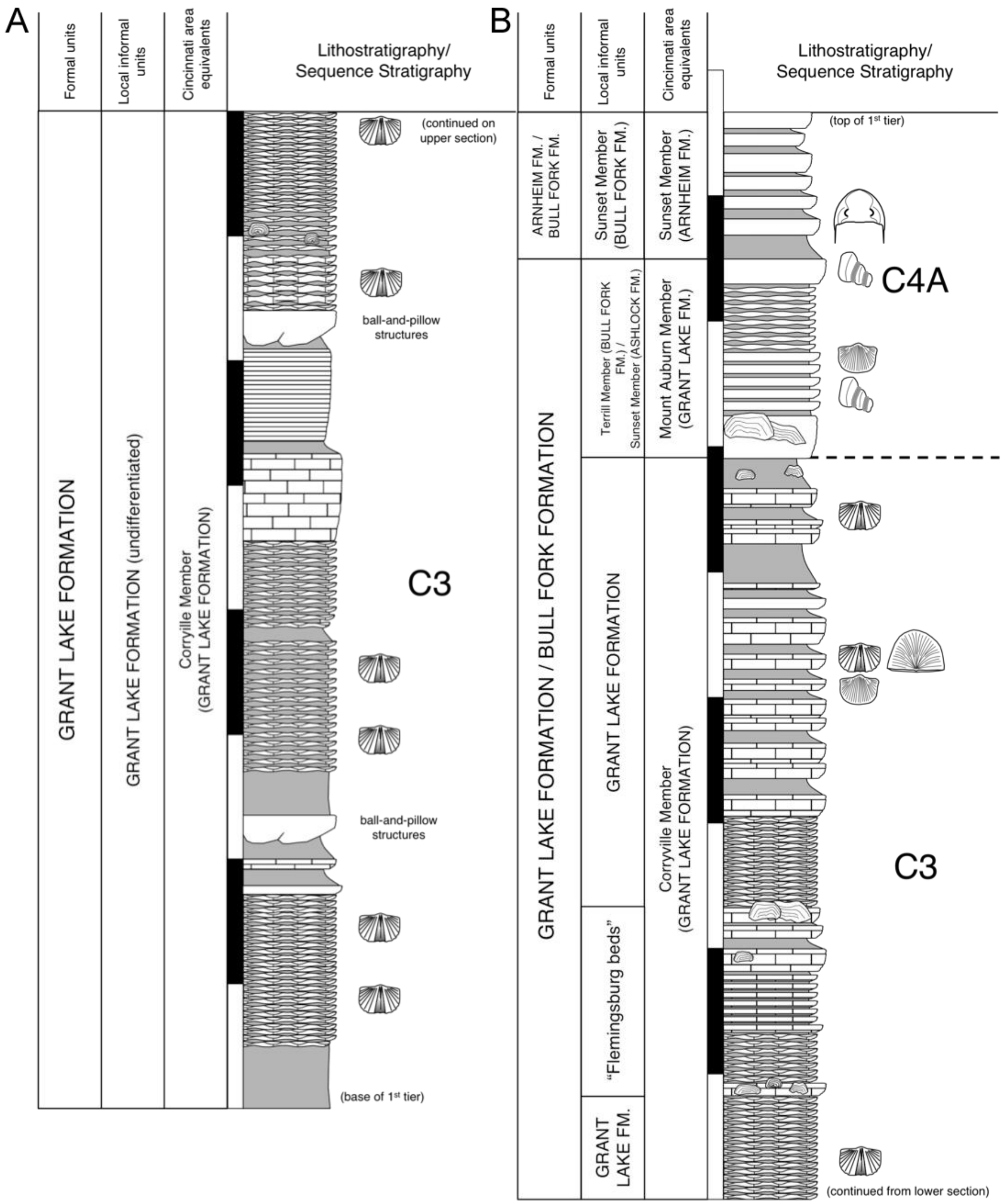


Figure 58. *Stratigraphic column of lower (A) and upper (B) parts of the first tier of the large four-tiered roadcut along Kentucky Route 111 near Wyoming, Kentucky exposing the Grant Lake Formation through the Bull Fork Formation (Arnheim Formation equivalent).*

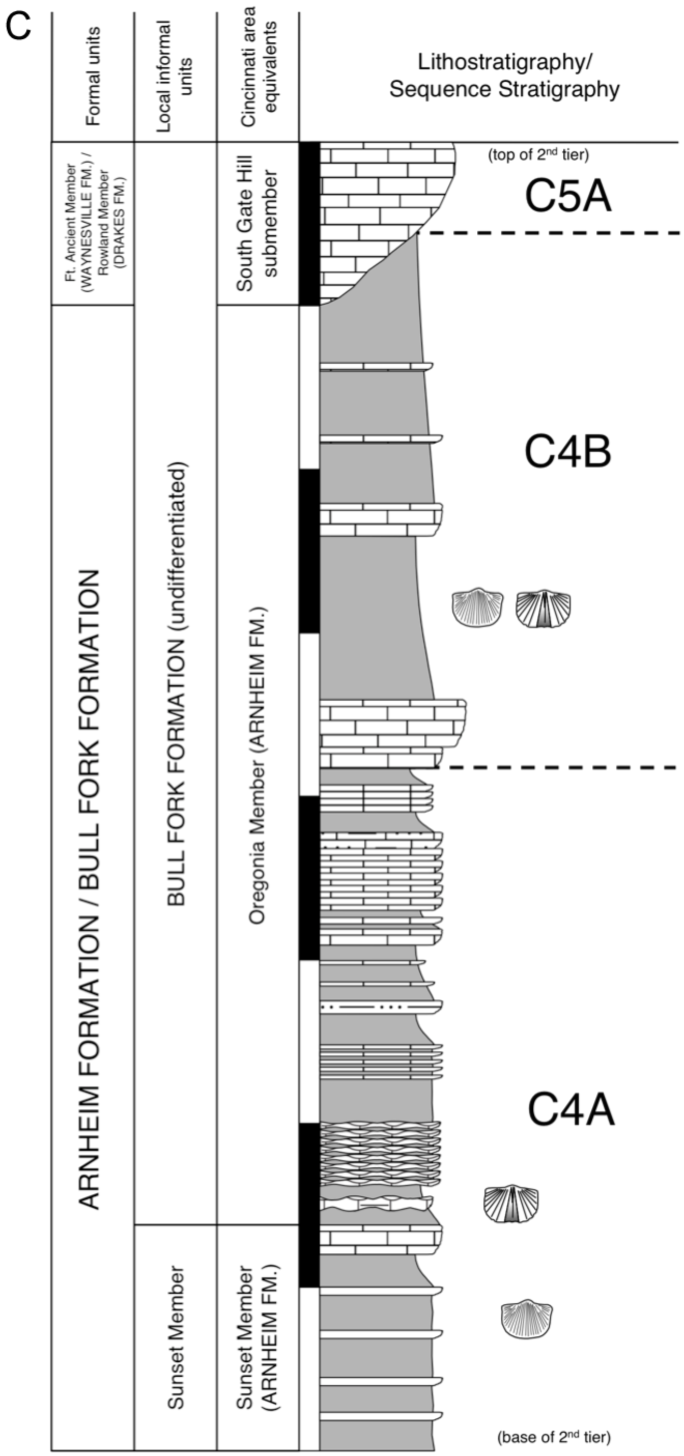


Figure 59. *Stratigraphic column of the second tier (C) of the large four-tiered roadcut along Kentucky Route 111 near Wyoming, Kentucky exposing the Bull Fork Formation (correlative to the Arnheim and basal Waynesville Formations).*

Figure 60. *Colonial coral (cf.* Protaraea*?) from talus at the base of the Kentucky Route 111 roadcut, perhaps from some of the higher coral beds in the Drakes Formation.*

Figure 61. *The micritic limestones found at many levels of the Kentucky Route 111 roadcut afford exceptional preservation for aragonitic-shelled organisms such as bivalves and gastropods.*

Figure 62. Vinlandostrophia ponderosa *brachiopods are common in the lower part of the Kentucky Route 111 roadcut.*

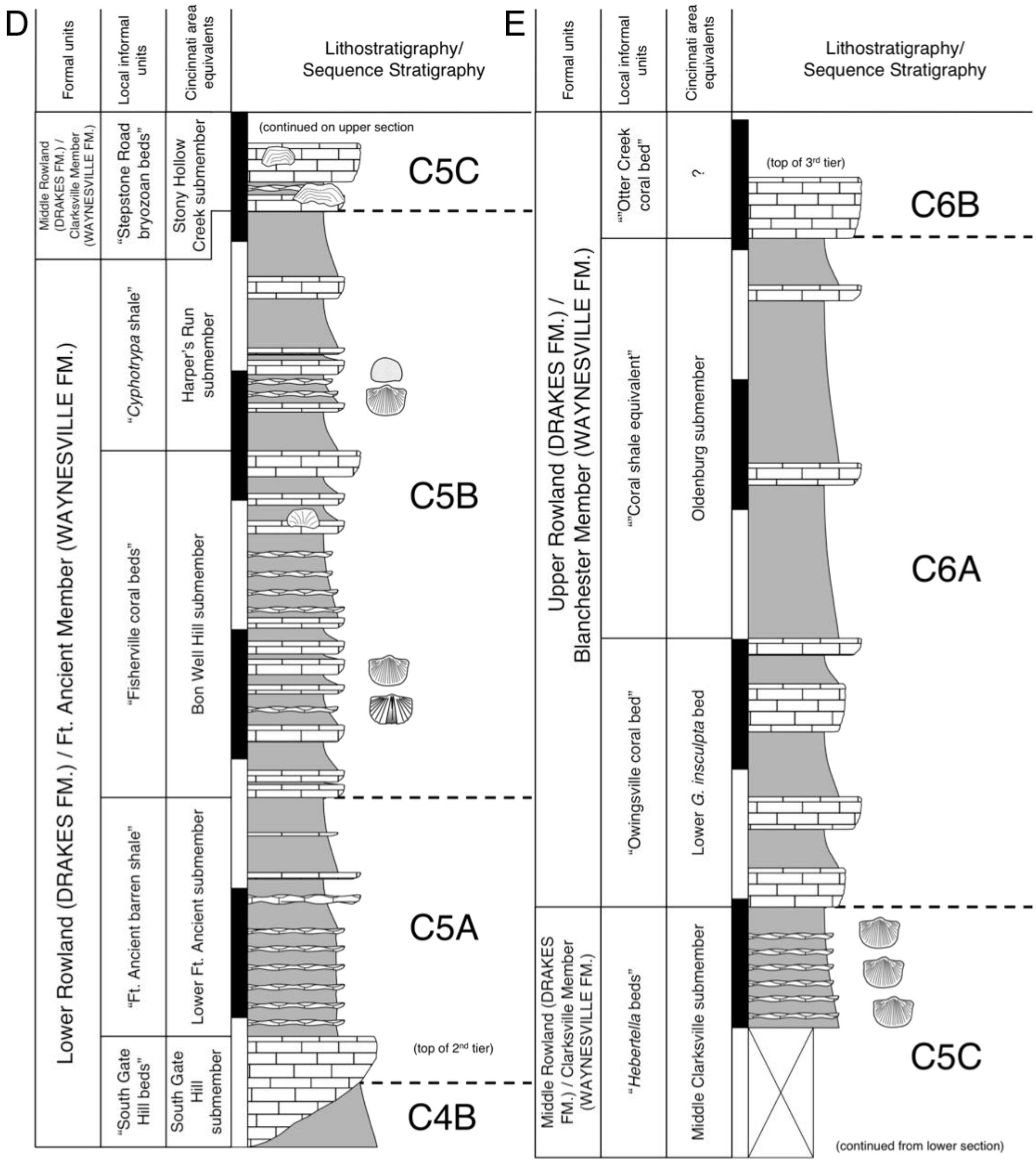


Figure 63. *Stratigraphic column of the lower (D) and upper (E) third tier of the large four-tiered roadcut along KY 111 near Wyoming, Kentucky exposing the Rowland Member of the Drakes Formation.*

Stop 12: Vacant lot adjacent to McDonald's, just off KY 36 in Owingsville, Kentucky

Contributors: Kyle R. Hartshorn

Location: Lot to the west of McDonald's restaurant just off Kentucky Route 36 south of Owingsville, Kentucky, near I-64 exit 121

Coordinates: 38° 07' 46.0" N, 83° 45' 14.8" W

Elevation: ~233 m to ~242 m (~764 ft to ~795 ft)

Stratigraphy: Upper Ordovician (Katian, Ka3; Cincinnatian, middle Richmondian, C5-C6): Rowland Member of the Drakes Formation (Waynesville Formation equivalent)

Well suited for a quick pitstop, this fine dining establishment features a complementary outcrop, likely an attempt to attract itinerant geologists. The hill cut exposes the middle to upper Rowland Member of the Drakes Formation, including the stromatoporoids and corals of the Owingsville coral bed. Other fauna is present as well, and at least one edrioasteroid has been found on a brachiopod shell from this locality.

***Figure 64**. The northern (A) and western (B) parts of the outcrop at the Owingsville McDonald's, all exposing the Bull Fork Formation / Rowland Member of the Drakes Formation (Waynesville equivalent).*

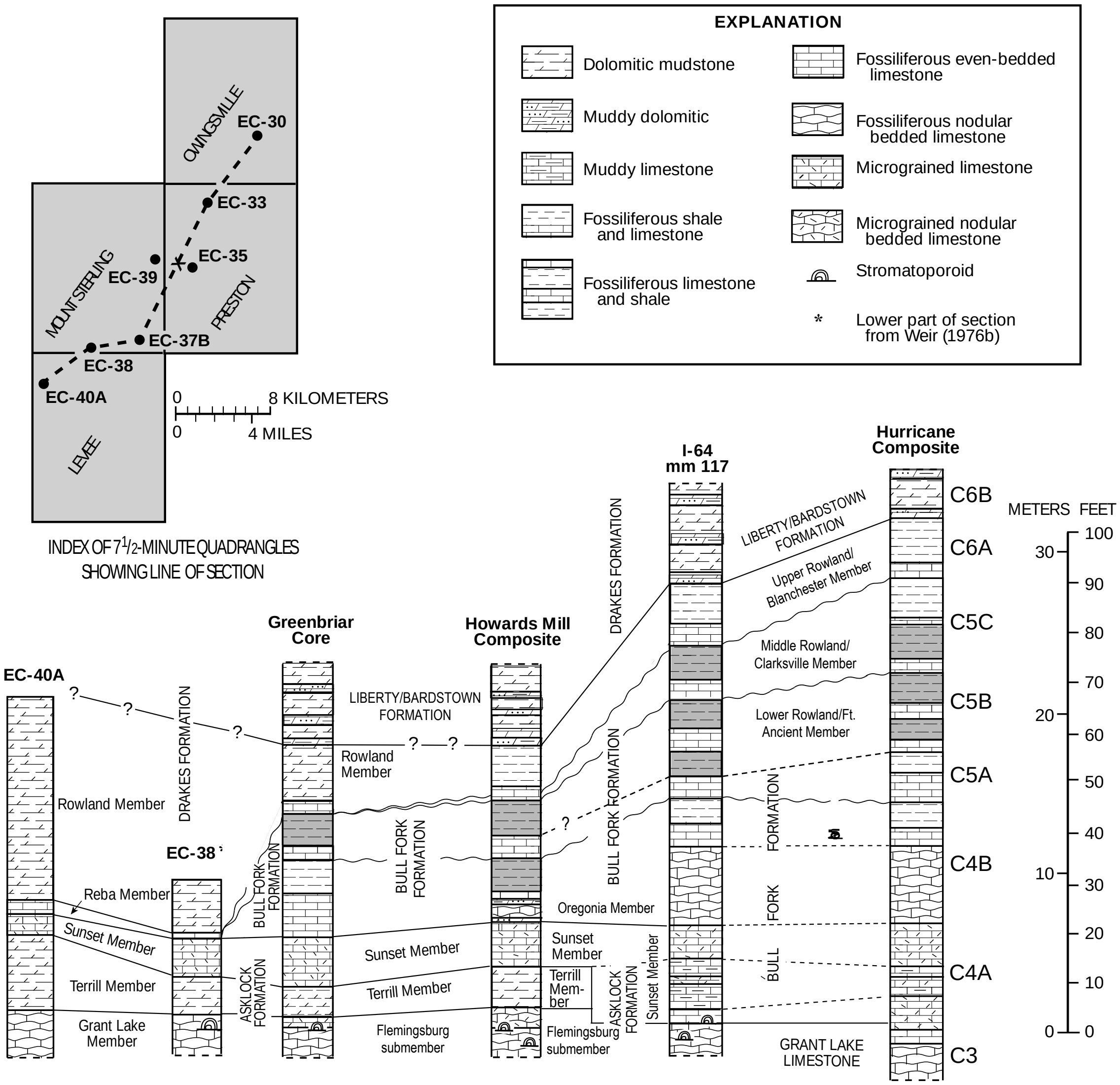


Figure 65. *Northeast-southwest stratigraphic cross section of the upper Cincinnatian Bull Fork and Drakes Formations in the vicinity of Owingsville and Mt. Sterling, Kentucky, showing complex truncational patterns. Notably, the upper Rowland Member of the Drakes Formation apparently overlies a major truncation surface. Adapted from Weir et al. (1986).*

Stop 13A: South side of I-64 west of Salt Well Creek in Bath County, Kentucky

Contributors: Carlton E. Brett, Cameron E. Schwalbach, Christopher D. Aucoin, T.J. Malgieri

Location: Roadcut along south side of I-64 eastbound, between mileposts 117 and 118, just west of the crossing of Salt Well Creek near Preston, Bath County, Kentucky

Coordinates: 38° 06' 40.1" N, 83° 48' 30.8" W

Elevation: ~238 m to ~248 m (~782 ft to ~815 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2-Ka3; Cincinnatian, uppermost Maysvillian to lower Richmondian, C3-C4): uppermost Grant Lake/Ashlock Formation (Flemingsburg bed[?], Stingy Creek Member, and Mount Auburn/Terrill Member) and Arnheim Formation (Sunset Member and Oregonia Member / Reba Member of the Ashlock Formation)

This outcrop provides an interesting perspective on the upramp facies changes within the upper Grant Lake Formation. The lowest outcrop in the lower end of this outcrop show *Tetradium*-rich micritic beds, which are believed to be a remnant of the Flemingsburg bed seen north of Tilton (Stops 8 and 9). About 2 m above these, the lateral equivalent of the Mount Auburn consists of a series of pale greenish to dove gray wackestones with green verdine filled burrows and abundant mollusks including gastropods and small nautiloids (Figure 66). Few corals or stromatoporoids occur at this locality. This section shows the transition of the Mount Auburn into the peritidal or perhaps lagoonal facies of the Terrill Member of the Ashlock Formation. These pass upward into rhythmic Sunset beds and these in turn into fossiliferous packstones with the small flattened *Leptaena* and *Rhynchotrema*, diagnostic of the upper or Oregonian Member of the Arnheim Formation (and its southern equivalent, the Reba Member of the Ashlock Formation).

Figure 66. *Outcrop on I-64 just west of Salt Well Creek near Preston, Kentucky. The pale gray, blocky, micritic wackestones of transitional Terrill Member of the Ashlock Formation are overlain by rhythmic wackestones and dark shales of the Sunset Member of the Ashlock/Arnheim Formation. James Thomka for scale, at the Terrill.*

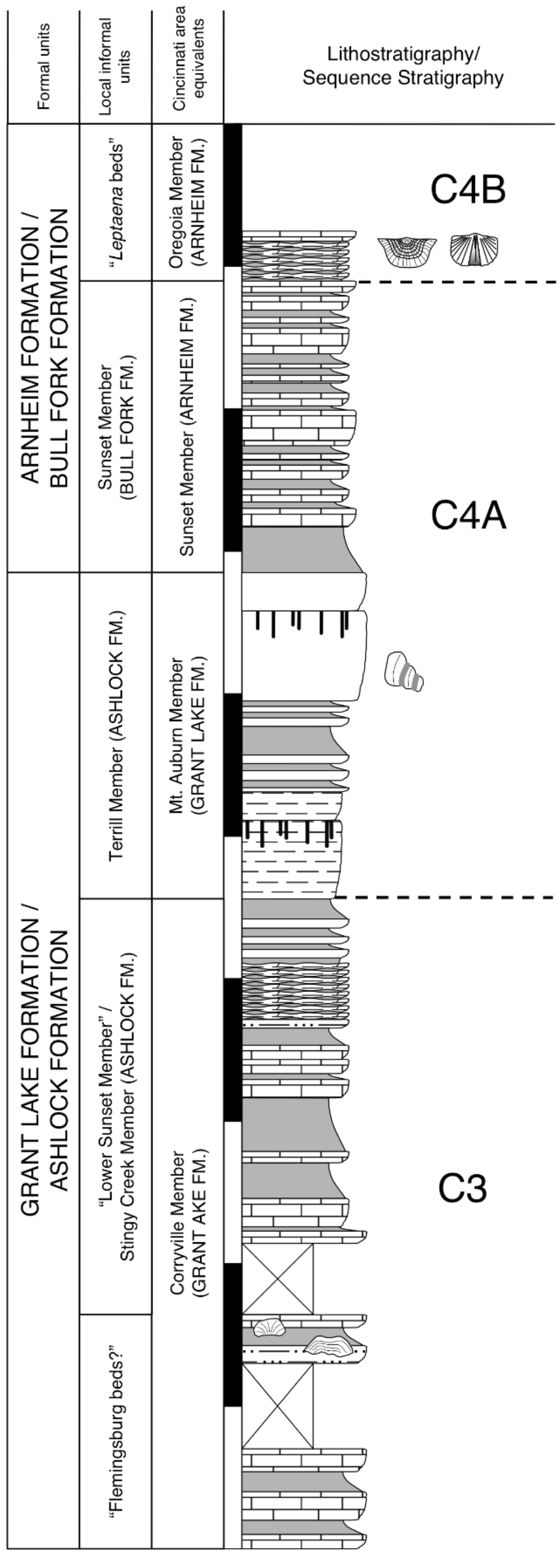


Figure 67. *Stratigraphic column of the roadcut along I-64 near mile 117.5, west of Salt Well Creek in Bath County, Kentucky exposing the Grant Lake/Ashlock Formation through the Arnheim/Bull Fork Formation.*

Stop 13B: Faulted outcrop on I-64 near milepost 117, west of Salt Well Creek

Contributors: Carlton E. Brett, Christopher D. Aucoin, Cameron Schwalbach; T.J. Malgieri

Location: Roadcut on the south side of I-64 (along the eastbound lane) near mile marker 117, approximately 1.1 km (0.7 miles) east of the North Stepstone Road bridge and about 1.0 km (0.6 miles) west of the bridge over Salt Well Creek; 6.1 km (3.8 miles) southwest of Owingsville in Bath County, Kentucky

Coordinates: 38° 06' 39.3" N, 83° 48' 53.2" W

Elevation: Base at ~259 m (~850 ft), top at ~287m (~940 ft)

Stratigraphy: Upper Ordovician (Katian, Ka3; Cincinnatian, Richmondian, C5-C6): Rowland Member of the Drakes Formation (Waynesville Formation equivalent)

This distinctive section, which displays a small displacement normal fault at the eastern end, the highly rhythmic succession of wackestones and shales in the lower Rowland Member of the Drakes Formation (equivalent to the lower Waynesville Formation; Figures 68, 69). Again, dark carbonized algae are abundant in dark shales intercalated with mollusk-rich packstones. A whole rock carbonate carbon isotope analysis of this section indicates that this rhythmic succession shows a strong excursion coincident with the main peak of the Waynesville Excursion of Bergström et al. (2010). These are overlain by chalky weathering greenish-gray shales and thin nodular wackestones rich in the hemispheroidal bryozoan *Cyphotrypa*. These beds may represent the same muddy highstand deposits as the *Treptoceras duseri* or trilobite butter shale interval of the Fort Ancient Member in Ohio (the Harpers Run submember of Aucoin and Brett, 2016).

The first bench exposes a remarkably dense bed of ball-shaped bryozoans, the “ball bryozoan bed” or “Stepstone Road bed” (Figure 70; Schwalbach, 2017). Note that most of these are attached to modiolopsid bivalves, which are preserved as bioimmuration “scars” on the undersides of the colonies. This ledge is the equivalent of the basal coral-*Cyphotrypa* biostrome at Owingsville. The succession is overlain by fossiliferous packstones and shales up to a major blocky ledge of vuggy dolostone which is thought to be equivalent to the Owingsville coral bed. Here there are only remnants of poorly preserved corals or stromatoporoids. As at Owingsville, this basal bed is overlain by dolomitic mudstone with abundant poorly preserved *Tetradium* and some *Cyphotrypa*. These appear to show a transition into the more typically barren, dolomitic mudstones of the upper Rowland. The sharp basal contact of the basal blocky (Owingsville) bed has proven to be a major regionally angular unconformity, the mid-Richmondian unconformity (Brett et al., 2015b; Aucoin and Brett, 2016; Schwalbach, 2017).

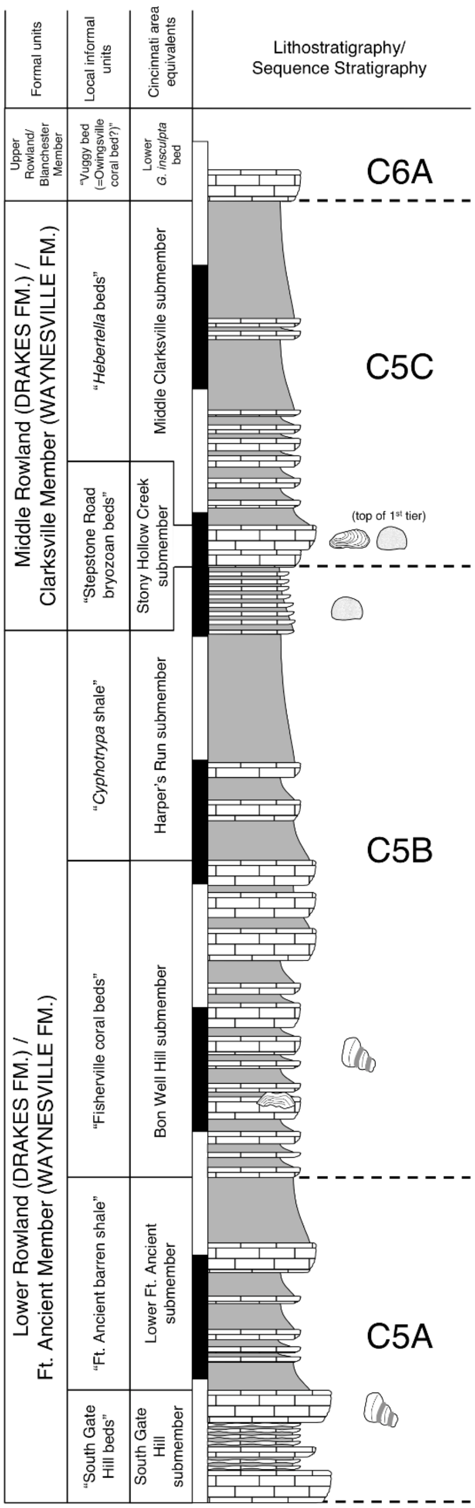


Figure 68. *Stratigraphic column of the roadcut along I-64 near mile 117.2, west of Salt Well Creek in Bath County, Kentucky exposing the Bull Fork Formation/Rowland Member of the Drakes Formation.*

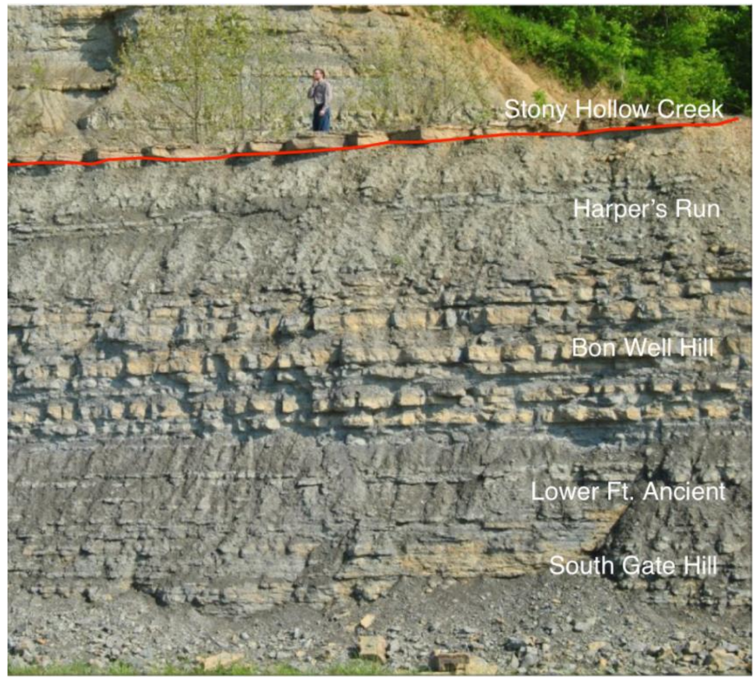


Figure 69. *Photograph of the roadcut along I-64 near mile 117.2, west of Salt Well Creek in Bath County, Kentucky showing lithostratigraphic interpretation and correlation to Ohio-Indiana subunits of Aucoin and Brett (2016). Sequence boundary in red. James Thomka for scale.*

Figure 70. *Assemblage of globular* Cyphotrypa *bryozoans erodes out of the top of the bench on the I-64 roadcut. This bed is widely traceable in this region, a useful marker in the Rowland Member of the Drakes Formation. Note that many of the specimens (e.g. lower center) have scoop-shaped indentations, all that remains of the bivalves underneath. The bryozoan larvae must have settled on the bivalves and overgrown them.*

Stop 14: Section along exit 123 ramp from I-64 east of Owingsville, Kentucky

Contributors: Carlton E. Brett, Christopher D. Aucoin, Cameron E. Schwalbach

Location: Extensive outcrops on the exit 123 ramp from I-64 eastbound to US Highway 60 southeast of Owingsville in Bath County, Kentucky

Coordinates: Lower end: 38° 08' 20.0" N, W 83° 43' 17.4";
upper end: N 38° 08' 08.14.0", W 83° 45' 38.5" W

Elevation: Lower end ~229m (~750 ft), upper end ~245m (~804 ft)

Stratigraphy: Upper Ordovician (Katian, Ka3; Cincinnatian, Richmondian, C4-C6): upper Arnheim Formation (Bull Fork facies) and lower Rowland Member of the Drakes Formation

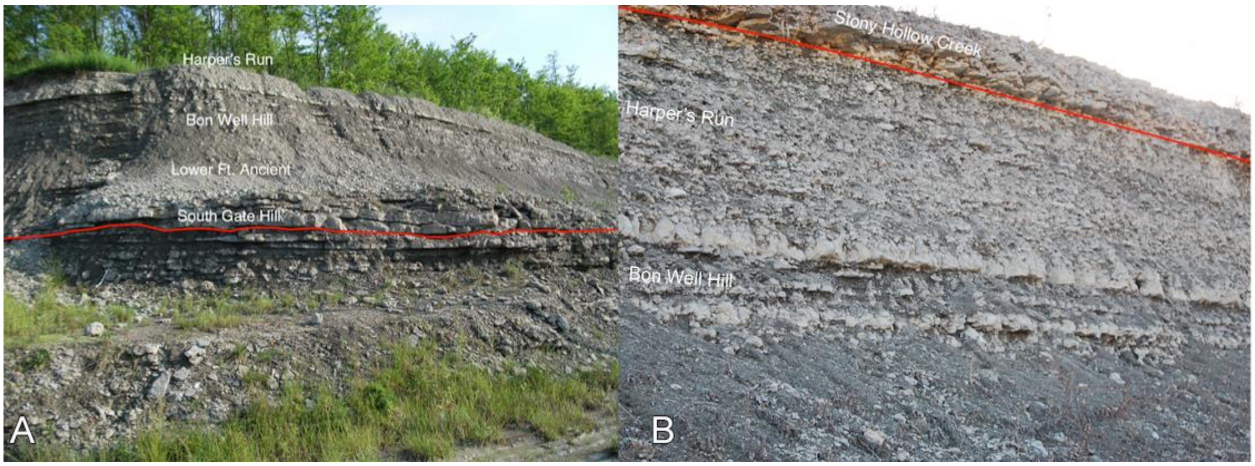


Figure 71. *Photographs of the lower (A) and upper (B) sections of the roadcut along the I-64 exit 123 offramp to US Highway 60 east of Owingsville, Kentucky, showing lithostratigraphic interpretation/correlation. Sequence boundary shown in red.*

This is an exceptionally fossiliferous though somewhat problematic succession of the Arnheim and Drakes Formations (in the mid Richmondian; Figure 71). The lowest beds near the intersection with US 60 are coarse pelmatozoan, bryozoan pack and grainstone beds up to 40 cm thick. A distinctive series of low angle clinoforms in thin-bedded packstone bed on the north side of the exit lane appears to represent the fill of a broad shallow submarine channel. This channel fill is in the same position as the grainstone channel fill seen at KY 111 and apparently records the same (C4-C5A) sequence boundary on underlying shale rich packstones of the upper Arnheim (Oregonia Member). On the south side of the lane the same beds form thick-bedded grainstones; this unconformable relationship was previously noted by Wier et al. (1965) and Holland and Patzkowsky (2009), who interpreted it as the basal C4 unconformity. These rudstones and grainstones contain abundant nodular solenoporids, less common stromatoporoids and tubular sponges (*Heterospongia*), plus well-preserved gastropods (*Loxoplocus* and large bellerophontids) and bivalves.

Overlying lower Rowland/lower Waynesville facies show rhythmically bedded wackestones and dark gray shales (Fisherville beds), which, again, yield carbonized algae as at the KY 111 (Stop 11) and I-64 fault (Stop 13B) outcrops. Outcrops continue up the ramp through the overlying succession of pale gray weathering, thin regularly banded nodular limestones and shales. This interval, the *Cyphotrypa* shale, is sharply overlain by 2 meters of richly fossiliferous beds of pack and rudstone that include pale orange weathering grainstones and rudstones full of solenoporid nodules and coquinas and prolific large articulated specimens of the orthid brachiopod *Hebertella*. This zone has recently been correlated to the Clarksville Member of the Waynesville Formation in Ohio by tracing transitional outcrops along the east side of the Cincinnati Arch (Brett et al., 2015b; Schwalbach, 2017).

The latter "*Hebertella* beds" are overlain at a sharp, irregular contact by an extraordinary double bed of large pinkish stromatoporoids and corals (*Cyathophylloides*, etc.), many inverted. The correlation of this bed, herein informally named the Owingsville bed for prominent exposures in this area, has been debated. We presently regard this horizon as equivalent to the basal Blanchester "lower *Glyptorthis"* bed to the north and the basal upper Rowland vuggy bed seen at Preston and elsewhere to the southwest (Brett et al., 2015b). Less concentrated stromatoporoids and *Tetradium* corals occur in the overlying 1.2 m biostromal interval. This latter package passes upward into an interval of thin bedded packstones and dark shales up to the upper bench. The highest beds in this outcrop (not easily accessible) are the pale greenish gray dolomitic shales and orange weathering dolostones of the undifferentiated Drakes Formation.

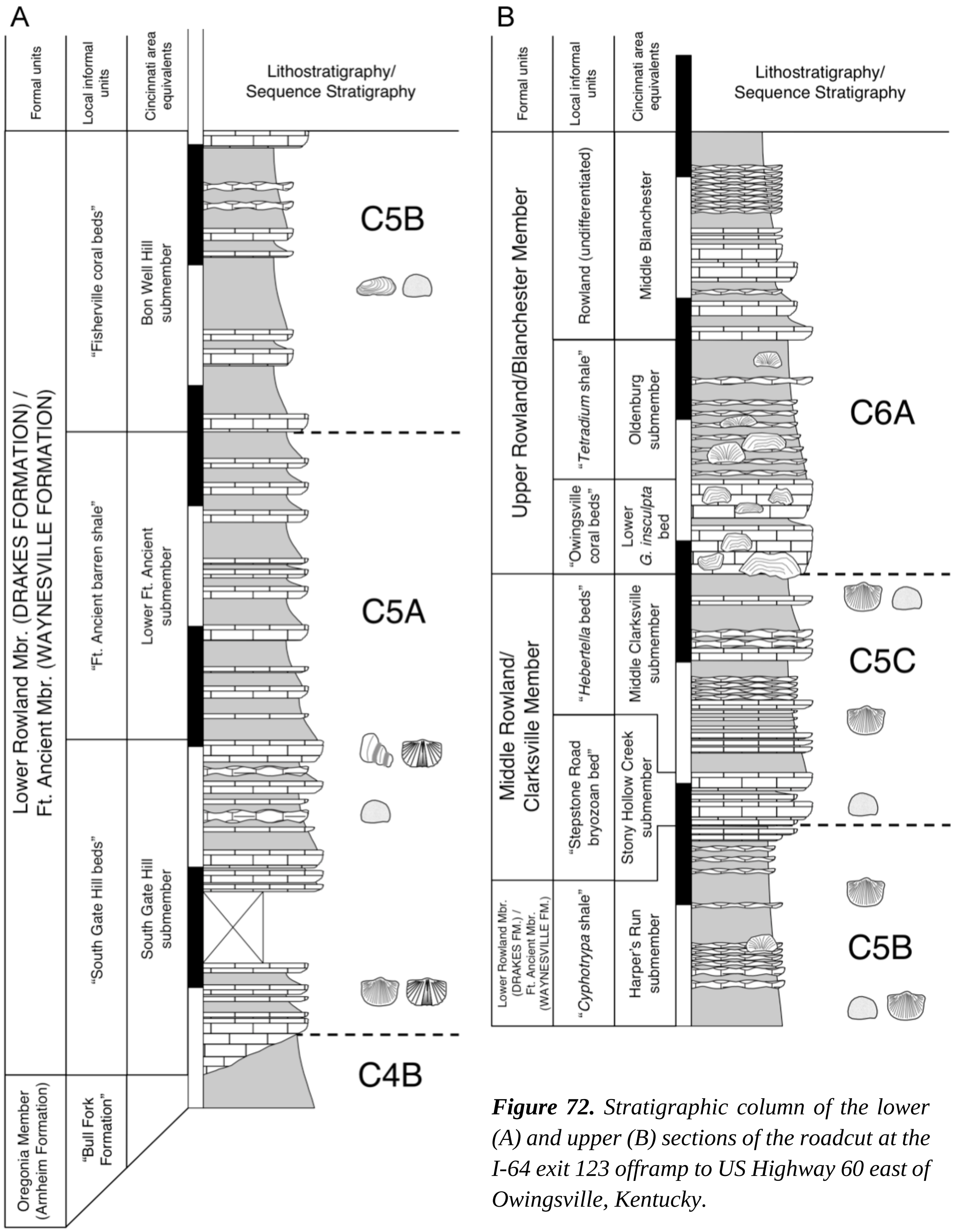


Figure 72. *Stratigraphic column of the lower (A) and upper (B) sections of the roadcut at the I-64 exit 123 offramp to US Highway 60 east of Owingsville, Kentucky.*

NOTES

Day 2: Mohawkian and Cincinnatian (Sandbian to Katian) Strata of Central Kentucky

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This portion of the field trip is intended to provide a cross section from some of the oldest rocks exposed in Kentucky to the basal Cincinnatian in the vicinity of Lexington and Frankfort, Kentucky. The lowest strata exposed in fault blocks along the gorge of Kentucky River belong to the middle Mohawkian Series, Turinian Stage ("Blackriveran" of older workers; mid-upper Sandbian) High Bridge Group. These are shallow subtidal to peritidal facies, including classic "birdseye" and desiccation cracked micrites, deposited in the still-stable interior carbonate platform of Laurentia. The faunas of these shallow water facies are generally sparse but include ostracodes, leperditians, a low diversity of brachiopods and small gastropods, bivalves, and nautiloids. A few beds show biostromes of *Tetradium*.

Several extremely widespread K-bentonites within these otherwise clean limestones not only provide absolute dates but are harbingers of collision of volcanic arcs along the eastern craton in the Taconic region. Much further to the southeast, in Tennessee, these clean carbonates interfinger with reddish muddy limestones and siliciclastics of the Moccasin Formation signifying overfilling of an earlier Taconian (Blountian) tectophase. These High Bridge carbonates constitute sequences M3 and M4 of Holland and Patzkowsky (1996).

A sharp, erosional sequence boundary, the M4-M5 sequence boundary, separates the pale micrites of the Tyrone Formation (upper High Bridge Group) from the grainstones of the basal Trenton Group, Lexington Formation, Curdsville Member which pass upward into shaly calcisiltites of the Logana Member, forming sequence M5A (Figure 73). These record the onset of and possibly a change from warm water lime mud-dominated deposition to shoal grainstones and deeper shelf carbonates. An increase in calcareous shale indicates increased influx of siliciclastics from Taconic source areas. This interval is also associated with one of the strongest isotopic carbon shifts in the Ordovician, the globally recognized Guttenberg excursion (GICE). We note that this excursion can be broken into the lower Logana Excursion and upper Macedonia Excursion (Young et al., 2015; see chemostratigraphy portion of Figure 73).

The Lexington Limestone, approximately 100 m thick was deposited on and adjacent to an elevated region, the Lexington Platform which experienced far field tectonic movements suggested by a mosaic of variable tidally influenced shoal grainstones and deeper shelf nodular shaly packstones, shales, and calcisiltites (Ettensohn and Lierman, 2015). Several widespread deformed zones interpreted as seismites have been traced across the region (McLaughlin and Brett, 2007). The Lexington was deposited during the time of extensive emplacement of major allochthons. However, the persistence of two major (3^{rd} order sequences) and some six smaller (4^{th} order) sequences as well as a detailed stratigraphic framework based on correlation of key surfaces, distinctive meter-scale cycles, demonstrates the through-going nature and a pervasive allocyclic signature, probably driven by eustasy (McLaughlin et al., 2004, Young et al., 2015). The distinctive meter to decameter scale cycles suggest the possibility of Milankovitch-forced glacioeustatic cycles as has been partially supported by oxygen isotopic studied of conodonts (Elrick et al. 2009).

In stark contrast to the often barren micrites below, the Lexington contains a more diverse fauna of ramose and domal bryozoans, brachiopods, crinoids, mollusks and trilobites. Distinctive taxa, such as the "gumdrop" bryozoan *Prasopora*, provide regionally extensive epiboles suggesting distinct bioevents during deposition. Particularly noteworthy are three distinct intervals characterized by proliferation of stromatoporoids (*Labechia*), solenoporids, *Tetradium* and colonial rugosans in the upper Perryville, Stamping Ground (especially Strodes Creek submember), and Devils Hollow. These large clonal organisms are accompanied by the influx of warmer water taxa comparable to those seen in the Richmondian invasion and suggest an earlier period of warming and immigration. These faunas will be seen in several sections.

Finally, the transition upward into the Point Pleasant and basal Kope Formation, seen in the later stops, shows evidence of overall deepening trends and an increased influx of siliciclastic sediments. These beds pass northward into dark gray shales often termed "Utica" in the deeper basins of the Point Pleasant Basin and Sebree Trough, areas of subsidence that may have been reactivated by far-field tectonics. The broad spread of organic rich clays and silts during the late Chatfieldian to early Cincinnatian (Edenian) times may signal a new phase of tectonism in the Taconic foreland. Ettensohn and Lierman (2015) summarize evidence that this widespread shale facies coincides with change in polarity of subduction and the shift from a peripheral to a retroarc basin. These tectonic and sedimentological changes also coincide with incursion or proliferation of a large number of fossil taxa including a suite of some 50 new bryozoans, brachiopods, especially *Eridorthis*, *Dalmanella emacerata*, *Sowerbyella rugosa*, echinoderms, including *Merocrinus* and *Ectenocrinus*, trilobites, including *Cryptolithus* and *Triarthrus*. The rarity of corals and stromatoporoids in the Point Pleasant and Kope Formations has been suggested to indicate cooler, more turbid and possibly nutrient rich water (Patzkowsky and Holland, 1996). However, see Harris et al. (2018) for a report of a colonial rugose coral from the lower Kope; these Edenian corals have also been reported anecdotally by other local collectors. Although this faunal turnover has not been studied as intensely as the later Richmondian invasion, it shows parallels that indicate significant environmental change, immigration and changes in community patterns.

This field day is intended to highlight these sequence, cycle, and stratigraphic events through study of the stratigraphic, sedimentological, and paleobiological aspects of the High Bridge Group, Lexington Formation, and Kope Formation recording about 4-5 million years during a critical interval of physical and biotic change.

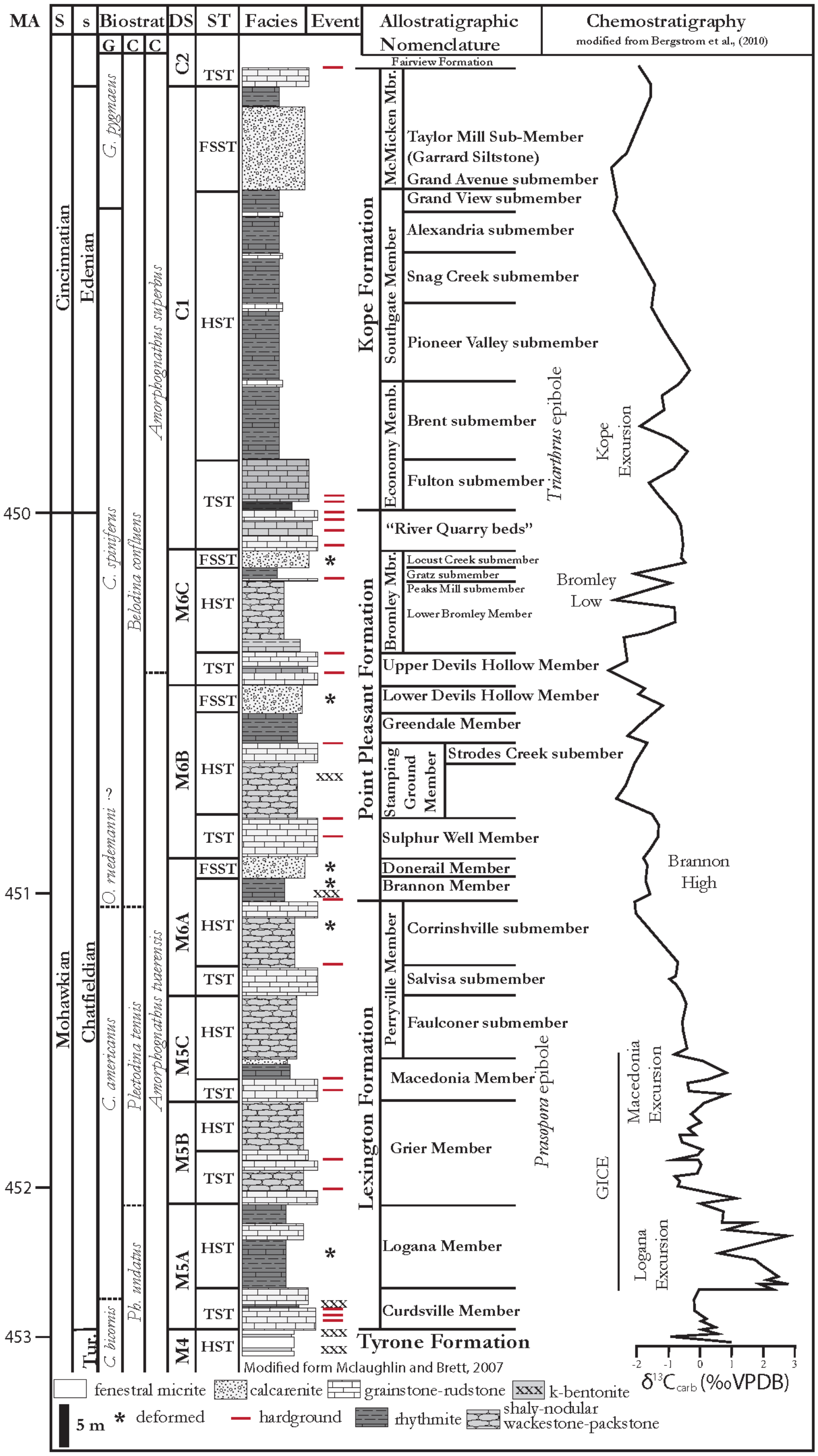


Figure 73*. Overview of the sequence, bio-, litho- and chemostratigraphy of the Lexington Limestone in its type area.*

Road Log for Post-Meeting Field Trip Day 2

The following road log starts at the I-64 junction with Kentucky Route 11 (i.e. exit 110), just north of Mount Sterling, Kentucky. As before, critical driving directions are **bolded** and all distances are in miles.

Total	*Increment*	*Description*
0.0	0.0	**Turn onto the interstate entrance ramp for I-64 westbound; head west on I-64**
0.6	0.6	Weathered, overgrown low outcrops
0.9	0.3	Weathered, overgrown low outcrops
1.5	0.6	Roadcut showing contact of Calloway Creek Limestone (Fairview equivalent) with the greenish laminated dolosiltites of the Tate Member of the Ashlock Formation (equivalent to the Bellevue Member of the Grant Lake Formation)
1.7	0.2	Outcrop of upper Calloway Creek Limestone along (closed) rest stop ramp
2.3	0.6	Another outcrop of Calloway Creek Limestone at the Grassy Lick Road overpass
2.7	0.4	Weathered outcrop of Calloway Creek Limestone
3.7	1.0	Overgrown exposure of Calloway Creek Limestone
4.3	0.6	Exposure of Calloway Creek Limestone on south side of I-64
5.4	1.1	Montgomery-Clark County line
5.6	0.2	Just before the Wades Mill Road overpass, an outcrop of Garrard Siltstone (uppermost Kope equivalent) with ball and pillow structures, overlain by basal Calloway Creek Limestone showing the "Z bed" limestone and "2-Foot shale", beds also characteristic of the basal Fairview Formation to the north
6.1	0.5	Weathered slope of an old outcrop, probably Kope Formation (Clays Ferry facies)
6.6	0.5	Roadcut of Kope Formation (Clays Ferry facies)
6.7	0.1	Roadcut of Kope Formation (Clays Ferry facies)
7.2	0.6	US Highway 60 overpass; overgrown roadcuts along north side of I-64
7.6	0.4	Low roadcuts of Kope Formation (Clays Ferry facies)
8.1	0.5	Cut of Point Pleasant Formation overlain by Kope Formation (Clays Ferry facies)
8.5	0.4	Low, overgrown outcrop, probably Kope Formation (Clays Ferry facies)
9.0	0.5	Another low outcrop, on the south side of I-64
9.3	0.3	Roadcut of Kope Formation (Clays Ferry facies)
11.2	1.9	Bert T. Combs Mountain Parkway to the left (only accessible from I-64 eastbound); leads toward Red River Gorge and Natural Bridge State Resort Park, both featuring excellent exposures of Mississippian and Pennsylvanian strata

12.4	1.2	**Take exit 96 for Kentucky Route 627 (toward Paris)**; note wonderful exposure of the upper Lexington Limestone, particularly the Stamping Ground Member, which here contains an extremely dense stromatoporoid biostrome at the base of the cut; the upper part of the exposure comprises the Strodes Creek, “unnamed”, and Greendale Members, which we will examine at the next stop
12.7	0.3	**Turn left (south) onto KY 627 at the end of the exit ramp**
12.9	0.2	Cross I-64 and continue south on KY 627 (Paris Road or Maple Street)
13.1	0.2	**Turn left (east) onto Veterans Memorial Parkway (Kentucky Route 1958)**
13.4	0.3	Outcrop on north side of the parkway, perhaps the “unnamed” member of the Lexington Limestone based on elevation (about in the middle of the next cut)
13.5	0.1	Pass junction with US Highway 60
13.9	0.4	Prominent roadcuts of Lexington Limestone on both sides of the parkway; **pull off onto shoulder near the small driveway cuts about half way through the outcrop**

Stop 15A: Veterans Memorial Parkway north of Winchester, Kentucky

Extraordinary section of the Strodes Creek Member and “unnamed” member (Tanglewood facies) of the upper Lexington Limestone, featuring a biostrome of large stromatoporoids and *Solenopora*.

14.3	0.4	Continue east on Veterans Memorial Parkway, passing Kentucky Route 1960
14.7	0.4	**Carefully make a U-turn at the junction with Ironworks Road and return west**
14.9	0.2	Outcrop of ledgy limestones on north side of the parkway; **pull off for a brief stop**

Stop 15B: Veterans Memorial Parkway west of Ironworks Road

This low roadcut is in the “unnamed” member (Tanglewood facies) and overlying Greendale Member (shaly fossiliferous packstones). Coarse skeletal grainstones/rudstones have prolific *Rafinesquina winchesterensis* brachiopods in edgewise-stacked masses.

16.5	1.6	**Continue west to the junction with KY 627 (Maple Street) then turn left (south)**
17.2	0.7	Railroad bridge overpass; once a classic and important locality with spectacular coral and *Solenopora* biostromes, this outcrop is now mostly covered by concrete
17.8	0.6	**Turn right (west) onto Boone Avenue to continue following KY 627**
19.1	1.3	Pass junction with Kentucky Route 1958 (Bypass Road)
19.9	0.8	Large cut of Lexington Limestone on both sides of KY 627; stromatoporoids are present in the Strodes Creek-equivalent zone above a shaly Stamping Ground Member
20.3	0.4	Outcrop of Lexington Limestone near junction with Augusta Drive
21.7	1.4	Pass turnoff leading to with Kentucky Route 1923
22.8	1.1	Cut in the Sulphur Well-Stamping Ground with oddly fractured “light bulb” structure
23.3	0.5	Long roadcut of Lexington Limestone just east of Quisenberry Lane

24.2	0.9	Roadcut of Lexington Limestone
24.5	0.3	Junction with Old Boonesboro Road (Providence School) and start of a large roadcut; optionally pull off for a brief examination of a famous deformed zone (Cane Run bed) in the Brannon Member of the Lexington Limestone, and the overlying massive Sulphur Well Member grainstones (Tanglewood facies)
24.6	0.1	Continuing down the roadcut, the outcrop exposes the Grier Member of the Lexington Limestone, including the argillaceous Macedonia bed
24.8	0.2	Pass Lisletown Road at the south end of the cut
25.1	0.3	Outcrop of Tyrone Formation, with Deicke K-bentonite near road sign
25.4	0.3	Junction with Kentucky Route 1924; **pull off on shoulder and exit vehicles**

Stop 16: KY 627 just north of the Kentucky River at Boonesborough, Kentucky

This succession provides an overview of some of the oldest rocks exposed in Kentucky: the Sandbian-age High Bridge Group. Here we can inspect the Oregon and Tyrone Formations, both composed of peritidal to shallow subtidal micritic limestones, and the important and well-exposed Boonesborough K-bentonites.

25.6	0.2	Proceed south on KY 627, crossing the Kentucky River (Madison-Clark County line); note major limestone quarry on the right (west) side
25.9	0.3	**Turn left (east) onto Kentucky Route 338 (Boonesborough Road) towards Fort Boonesborough State Park**; note cross-bedded limestones across from junction
26.1	0.2	Pass campground entrance
26.2	0.1	**Turn left (north) into Fort Boonesborough State Park**
26.4	0.2	**Bear left to restrooms and picnic area for a brief rest stop**
26.6	0.2	**Return south to park entrance and turn right (west) KY 338**
26.9	0.3	**Go back west to junction with KY 627 and turn left (south) onto KY 627**
27.0	0.1	Outcrop on the north side of the road exposing the shaly nodular limestones of the Bromley Member (Millersburg facies) of the Lexington Limestone
27.1	0.1	A fault brings the upper Kope Formation into contact with the basal Kope; note Point Pleasant massive grainstones on the right (west)
27.2	0.1	Upper end of the large cut in the upper Kope Formation (Clays Ferry facies), transitional into the Garrard Siltstone
27.3	0.1	Entrance to Fort Boonesborough on the left (east); this is a reconstruction of one of the oldest forts in Kentucky; the original was established in 1775 as a frontier settlement by famous American pioneer Daniel Boone
27.4	0.1	Roadcut exposing the upper Garrard Siltstone (upper Kope equivalent) and its characteristic large ball and pillow structures, sharply overlain by the 0.5 m “Z bed” and “2-Foot shale” at the base of the Calloway Creek Limestone (Fairview Formation)

28.0	0.6	Exposure of Calloway Creek Limestone on west side, north of Combs Ferry Road
29.1	1.1	Roadcut on Calloway Creek Limestone(?) on west side of KY 627
31.5	2.4	Overgrown outcrops along both sides of road (Calloway Creek Limestone?)
32.4	0.9	**Turn right (north) onto the entrance ramp to I-75 northbound**
32.8	0.2	Merge from entrance ramp onto I-75 northbound
33.2	0.4	Low outcrop on east side showing Tate Member of the Ashlock Formation (probably equivalent to the Bellevue Member of the Grant Lake Formation further north); another cut on the west side shows the sharp contact (sequence boundary) between ~1 m *Vinlandostrophia*-rich grainstone of the uppermost Calloway Creek Limestone and the overlying Tate Member
33.5	0.3	Outcrop on west side exposing the Calloway Creek Limestone
33.8	0.3	Outcrop on east side exposing the Calloway Creek Limestone
34.0	0.2	Roadcuts of Calloway Creek Limestone on both sides of the highway
34.2	0.2	Series of cuts on both sides of the highway exposing the Calloway Creek Limestone
35.0	0.8	US Highway 25 / US Highway 421 overpass; note roadcuts on both sides of the highway just north of the bridge, which expose the heavily deformed Garrard Siltstone; the northbound entrance ramp also contains excellent ball and pillows
35.3	0.3	Large roadcut on both sides of the highway; this is the type locality for the upper Clays Ferry Formation (herein regarded as a southern facies of the Kope Formation), with characteristic thin limestones, siltstones, and lesser shales (Stop 3-4C)
35.5	0.2	Cross the I-75Clays Ferry Bridge over the Kentucky River and enter Fayette County
35.8	0.3	North side of the bridge; put on hazard lights and prepare to pull off
35.9	0.1	**Pull off onto right shoulder at a low outcrop of pale limestone**

Stop 17: Roadcut on I-75 northbound just north of the Kentucky River bridge
Outcrop in the upper Tyrone Formation at and above the shaly Herrington Lake member.

36.5	0.6	**Take I-75 exit 99 to US Highway 25 / Kentucky Route 2328**; note outcrops of Lexington Limestone along the ramp
36.6	0.1	Turn right (south) onto US 25 / KY 2328 (Old Richmond Road)
37.3	0.7	Road descends into the gorge of the Kentucky River; scattered outcrops of High Bridge Group down to river level (but only on the north side of the River)
37.7	0.4	**Pull off into gravel lot directly underneath the I-75 bridge for a brief review of the geology of the Kentucky River Gorge**; note High Bridge Group limestones
37.9	0.2	Continue to the small, narrow bridge over the Kentucky River; cross carefully

38.0	0.1	South side of the Kentucky River, back in Madison County; note exposures of massive Camp Nelson Formation (lower High Bridge Group) in fault contact with Grier Member of the Lexington Limestone, showing drag folding; displacement of this down-to-the-south Kentucky River fault is about 100 m
38.3	0.3	South overpass of the I-75 bridge; **pull off on shoulder**

Stop 18A: South wall of the Kentucky River Gorge directly below I-75 Clays Ferry Bridge
Exposure of the middle Lexington Limestone (Brannon, Sulphur Well, and Stamping Ground Members) showing the M6A-M6B sequence boundary between the Brannon and Sulphur Well

38.4	0.1	**Continue south then pull along shoulder to examine another roadcut on the left**

Stop 18B: KY 2328 (Old Richmond Road) south of the I-75 Clays Ferry Bridge
The type section for the lower Clays Ferry Formation, exposing the Bromley Shale (M6C highstand), Locust Creek deformed beds (M6C falling stage), and Point Pleasant Formation (basal C1 TST).

39.6	1.2	**Continue uphill around several sharp switchbacks, then turn left (east) at the junction with US 25 / US 421 (Old Lexington Road)**
39.9	0.3	**Cross I-75 and turn left (north) onto the entrance ramp for I-75 northbound**
40.1	0.2	Note previously mentioned outcrops of Garrard Siltstone with prominent ball and pillow structures along the exit ramp
40.4	0.3	Turn on hazard lights and pull over at the north end of the large, fence-covered outcrop

Stop 18C: I-75 south of the Clays Ferry Bridge over the Kentucky River
Type section of upper Clays Ferry Formation (here equivalent to the Kope Formation); highly fossiliferous shale and limestone.

40.5	0.1	Proceed north, crossing the Clays Ferry Bridge with new appreciation of its context
40.9	0.4	Pass outcrop of Tyrone Formation (Stop 3-3)
41.5	0.6	Pass exit 99, noting faulted lower Lexington Limestones in the exit cut
42.4	0.9	Outcrops on both sides of I-75 in the lower Lexington Limestone (Grier Member)
42.6	0.2	Outcrop of lower Lexington Limestone
43.0	0.4	Outcrops of Lexington Limestone on both sides of I-75
43.3	0.3	Outcrop of Lexington Limestone on the east side of I-75
43.5	0.2	Minor outcrops of Lexington Limestone before bridge over Bird Hill Lane, which leads west to the Richmond Road Quarry (not visible)
43.7	0.2	Outcrop of Lexington Limestone on the east side of I-75
44.2	0.5	Outcrop of Lexington Limestone on the west side of I-75
44.5	0.3	Outcrop of Lexington Limestone on the east side of I-75

45.3	0.8	Low outcrop of Lexington Limestone on the east side of I-75
45.8	0.5	Outcrop of Perryville and Brannon Members with possible bentonite
46.6	0.8	Outcrop of Lexington Limestone on the west side of I-75
46.9	0.3	Kentucky Route 418 overpass (exit 104), with outcrops underneath and along ramps; these expose Stamping Ground Member of the Lexington Limestone (the shaly Millersburg facies, showing that this area lies on the south side of the Lexington Platform)
47.4	0.5	Outcrop of Lexington Limestone on the east side of I-75
51.2	3.8	Pass exit 108 for Man O' War Boulevard (named after the famed racehorse); the ramps have excellent exposures of the Stamping Ground Member of the Lexington Limestone with large stromatoporoids
52.7	1.5	Pass exit 110 for US 60 (leads east back to Winchester, or west to Lexington)
53.8	1.1	**Stay on I-75 north as I-64 westbound merges with I-75 northbound at exit 111**; shaly Stamping Ground Member (Millersburg facies) at the underpass
56.0	2.2	**Take exit 113 for US Highway 27 / US Highway 68**
56.4	0.4	**Follow exit ramp and turn right (southwest) onto US 68 towards Lexington**
57.6	1.2	Turn right (northwest) onto New Circle Road (Bypass 421)
58.2	0.6	Weathered Lexington Limestone in front of Lexmark plant on left (south)
59.3	1.1	Outcrops of Lexington Limestone (possibly Brannon Member, with deformed beds) near US 25 overpass
62.4	3.1	Relatively new outcrops of Lexington Limestone on right (north)
63.3	0.9	**Take exit 5 for US 60 west (to Bluegrass Parkway)**
63.6	0.3	Turn right (west) onto US 60 (Versailles Road) westbound
65.1	1.5	Pass Man O War Boulevard just north of Lexington Blue Grass Airport (LEX)
67.0	1.9	Outcrop of massive Lexington Limestone on south side of US 60
68.2	1.2	Small bridge over Shannon Run marks the Fayette-Woodford County line
68.5	0.3	Somewhat incongruous Kentucky Castle hotel and restaurant on the right (north)
69.6	1.1	**Bear right onto entrance ramp to Kentucky Route 9002, the Martha Layne Collins Blue Grass Parkway (henceforth the Bluegrass Parkway)**
70.2	0.6	Merge onto the Bluegrass Parkway, heading southwest
72.9	2.7	Pass junction with Kentucky Route 33 (heads north to Versailles)
73.3	0.4	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway
73.7	0.4	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway
74.1	0.4	Low outcrops of Lexington Limestone

75.2	1.1	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway
75.4	0.2	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway at the McCowans Ferry Road overpass
75.8	0.4	Weathered outcrop of Lexington Limestone on south side of the Bluegrass Parkway
76.3	0.5	Weathered cuts of Lexington Limestone on both sides of the Bluegrass Parkway
76.9	0.6	Outcrop of Lexington Limestone on south side of Bluegrass Parkway
77.1	0.2	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway
77.3	0.2	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway
77.5	0.2	Outcrops of Lexington Limestone on both sides of the Bluegrass Parkway, with strongly deformed bed in the middle (Donerail Member?)
77.9	0.4	Outcrop of shaly Brannon Member of the Lexington Limestone
78.2	0.3	Long series of outcrops of Lexington Limestone (Perryville and/or Grier Member) descending the valley to the Kentucky River
79.0	0.8	Weathered outcrops of Lexington Limestone just west of Scotts Ferry Road overpass
79.5	0.5	Bridge over the Kentucky River
79.6	0.1	West side of the Kentucky River; the Woodford-Anderson County line
79.7	0.1	**Pull off onto shoulder at the low end of a long, vertical roadcut**

Stop 19A: Lower end of Bluegrass Parkway roadcut west of the Kentucky River bridge

This end of the cut exposes a section near the base of the Lexington Limestone, including the Logana Member (M5A highstand) with prominent middle limestone bundle capped by a hardground, and basal Grier Member (M5B transgressive package), comprising limestones with common *Prasopora* bryozoans.

80.3	0.6	**Continue west and pull off opposite large shaly exposures at upper end of the cut**

Stop 19B: Upper end of Bluegrass Parkway roadcut west of the Kentucky River bridge

Spectacular views of middle Lexington Limestone. The grainstones of the upper Perryville Member, with rusty hardgrounds in the Cornishville submember (M6A transgressive systems tract), are sharply overlain by the dark gray shales and calcisiltites of the Brannon Member. The south wall shows a prominent deformed channel fill tentatively assigned to the Donerail Member (interpreted as the M6A falling stage), itself overlain by Sulphur Well Member grainstones at the M6A-M6B sequence boundary

81.3	1.0	**Continue west on the Bluegrass Parkway; pull off next to a rather shaly outcrop**

Stop 19C: Bluegrass Parkway about 2 miles west of the Kentucky River

Brief stop to examine the ball and pillow structures and deformed channel fills in the upper Brannon and Donerail Members of the Lexington Limestone. The limestones of the Sulphur Well are locally exposed at the top of the cut, offering another look at the M6A-M6B sequence boundary, as well as strata below.

81.8	0.5	Low roadcut exposing undeformed shales and siltstones of the Brannon Member of the Lexington Limestone
82.4	0.6	**Continue west on the Bluegrass Parkway and take exit 59B for US Highway 127 north**
82.7	0.3	**Turn right (north) onto US 127 north**
85.1	2.4	Outcrop of Lexington Limestone
86.5	1.4	Pass junction with US 62
87.1	0.6	Outcrops of weathered, rubbly Lexington Limestone on both sides of US 127
87.3	0.2	Pass junction with Kentucky Route 44 (Glensboro Road)
88.4	1.1	Outcrop of Lexington Limestone north of Emma B. Ward Elementary School
88.6	0.2	Outcrops of Lexington Limestone north of Briarwood Way
88.8	0.2	Outcrops of Lexington Limestone
89.1	0.3	Outcrops of Lexington Limestone near Alton Baptist Church
89.7	0.6	Pass junction with Business 127
91.4	1.7	Outcrops of Lexington Limestone
91.6	0.2	Outcrops of Lexington Limestone (massive grainstones) on both sides of US 127
91.8	0.2	Anderson-Franklin County line
96.3	4.5	Junction with I-64, welcome to Frankfort, Kentucky; note middle Lexington Limestone nearby, including a micritic, shaly exit ramp cut with leperditian-rich limestone
97.1	0.8	Pass Kentucky Route 420 / Kentucky Route 676 (East-West Connector); several major outcrops of Lexington Limestone are on this road to the east
97.7	0.6	Roadcuts in upper Lexington Limestone(?) on US 127 near Century Plaza
98.0	0.3	Pass junction with US 60 and continue straight (north)
99.0	1.0	Pass intersection with Devils Hollow Road; heading west on this local route leads to the type section of the Devils Hollow Member of the Lexington Limestone
99.5	0.5	Upper end of the very large "Frankfort West" roadcut; upper section is in the Greendale Member, sharply overlain by Devils Hollow grainstones; lower beds are rich in well-preserved leperditians
99.7	0.2	Middle of the "Frankfort West" roadcut, showing shaly Brannon with ball and pillows, overlain by the Sulphur Well (massive grainstones) and Stamping Ground Members
99.9	0.2	Lower end of the "Frankfort West" roadcut, in the Grier Member and well-defined shaly Macedonia beds
100.3	0.4	Continue east past junction with US 421; a left (north) turn here leads a series of spectacular exposures on US 421 exposing almost the entire Lexington Limestone

100.7 0.4 Cross bridge over the Kentucky River on combined US 127 / US 421 and **take a left at the next intersection (Wilkinson Boulevard) near downtown Frankfort, staying on US 127 / US 421 north**

102.8 2.1 Continue north to a junction where US 127 splits from US 421; **take ramp to the right to stay on US 127 north**

102.9 0.1 **Turn left (north) onto US 127 north, but be prepared to turn right again soon**

103.1 0.2 **Turn right (east) onto Cove Spring Road**

103.2 0.1 **Turn left (east), following signs for Cove Spring park**

103.4 0.2 **Park in parking lot at Cove Spring park along Penitentiary Branch**

Stop 20A: Cove Spring Park (lunch stop)

This small park provides opportunities for both a picnic lunch and casual geologizing in the upper Sandbian. The local outcrops are in the middle part of the Tyrone Formation (upper High Bridge Group) and show massive burrowed micrites with some thinner, shalier successions. A few beds contain silicified fossils, principally gastropods.

103.6 0.2 **Return west towards US 127; pull off at the junction of Deadhorse Road and Cove Spring Road near an old quarry**

Stop 20B: Deadhorse Road Quarry

This small old quarry exposes the micrites of the upper Tyrone Formation, including an excellent succession that contains the Diecke K-bentonite.

103.7 0.1 **Drivers may proceed back out to US 127 and turn right (north)**; passengers may proceed on foot out to the nearly adjacent roadcut on US 127

103.9 0.2 **Turn left into the parking area for Cove Spring Wetland Park and park**

Stop 21A: Lower end of the main "Frankfort North" roadcut on US 127

Section shows the uppermost Tyrone Formation, including a possibly unnamed K-bentonite, and the M4-M5 sequence boundary (roughly the Turinian-Chatfieldian Stage boundary). This is followed by the lower Lexington Limestone, including the Curdsville, Logana, and lower Grier Members.

104.1 0.2 **Return to vehicles (passengers may walk if they wish and time allows) and proceed up the hill to the northern end of the main roadcut**

Stop 21B: Upper end of the main "Frankfort North" roadcut on US 127

Brief stop to examine the Macedonia beds/member of the Lexington Limestone. Note its argillaceous character, resembling the Logana, but with abundant in situ *Prasopora* bryozoans.

104.3 0.2 **Continue up the hill and pull off at the southern end of the second major cut**

Stop 21C: Upper "Frankfort North" roadcut on US 127

This roadcut starts (on the east side, off-road) in the Brannon-Donerail Member succession (upper M5A) with a very dirty but distinct ball and pillow zone visible. Cross the road to view the lower end of the west cut, starting in the Sulphur Well Member with small scale tidal channels infilled with rhythmic, heterolithic, tidally bedded grainstone. Note stromatoporoid conglomerate near the Sulphur Well-Stamping Ground contact. Higher parts of the roadcut show the "unnamed" (Tanglewood facies grainstones), Greendale, and Devils Hollow Members.

104.4	0.1	Return to vehicles and continue north, passing the junction with Kentucky Route 1900 (Peaks Mill Road)
106.1	1.7	Large roadcut on the east side ("Peaks Mill South") shows a succession of deformed laminated calcarenites, the Locust Creek beds, sharply overlain by crinoid and bryozoan rich rudstones at the base of the upper Point Pleasant "River Quarry" beds (sometimes called the uppermost tongue of the Tanglewood, or Point Pleasant *sensu stricto*)
106.8	0.7	Bedding plane exposure of the uppermost Point Pleasant Formation or basal Kope (Fulton Submember) on the east side of US 127; *Merocrinus* columnals present
107.3	0.5	Outcrop of upper Point Pleasant Formation
107.6	0.3	Outcrop of Point Pleasant Formation
107.9	0.3	Series of outcrops of Point Pleasant Formation on both sides of the road
108.3	0.4	**Pull off on shoulder at a series of outcrops before entrance to gas station (presently a BP station)**

Stop 22: "Peaks Mill North" roadcut on US 127 (optional)

Excellent exposure of the Locust Creek beds, with deformed, "pinstriped" fine calcarenites (M6C falling stage) sharply overlain by the upper Point Pleasant River Quarry beds (C1 basal transgressive facies), here with a middle shaly zone rich in bryozoans and Cyclonema gastropods.

108.5	0.2	Gas station (possible rest stop if necessary)
110.2	1.7	**Pull off on shoulder at roadcut near Old Owenton Road**

Stop 23A: Upper roadcut on US 127 near Old Owenton Road ("Elkhorn South")

This cut provides a further look at the Point Pleasant (*sensu lato*) succession, beginning with the nodular Bromley Shale, the Peaks Mill white grainstone bed, the Gratz Shale, the Locust Creek deformed laminites, the "River Quarry" beds, and the lower Kope Formation, many rich in fossils.

110.5	0.3	**Continue north and pull over in the middle of a large faulted roadcut**

Stop 23B: Lower roadcut on US 127, just north of the Elkhorn Creek bridge ("Elkhorn North")

This steep-sided roadcut displays massive Sulphur Well grainstones, shaly, nodular Stamping Ground, the "unnamed" member with abundant small stromatoporoids and bryozoans (offset at near-vertical northwest trending normal faults), the shaly Greendale Member, and overlying Devils Hollow through Bromley exposed high in the butte on the east side.

110.7	0.2	Return to vehicles and cross bridge over Elkhorn Creek
111.1	0.4	Pass junction with Strohmeier Road
111.5	0.4	Pass junction with Swallowfield Road (Kentucky Route 2919)
111.7	0.2	South end of the "Swallowfield South" roadcut, a long and rather weathered cut that starts in the upper Perryville Member (Cornishville beds) with small ball and pillows structures overlain by the here-undeformed Brannon Member; the road ascends and the cut is in the Sulphur Well and Stamping Ground Members at the top
112.4	0.7	North end of the "Swallowfield South" roadcut; possibly Donerail Member?
112.7	0.3	**Pull off at the first outcrop immediately north of Long Branch Creek**

Stop 24A: US 127 at Long Branch (east roadcut of "Swallowfield North")

Cut in the Brannon Member, with the Cane Run deformed bed showing strongly brecciated limestone in marly matrix.

112.8	0.1	Cross Long Branch, encountering the start of a major roadcut on the northwest side; note Donerail, Sulphur Well, and Stamping Ground Members
113.1	0.3	**Pull off in the middle of a section of the roadcut with exposures on both sides**

Stop 24B: US 127 about 0.4 miles northwest of Long Branch ("Swallowfield North")

Exposure of the Upper Stamping Ground, Strodes Creek (with thin K-bentonite), "unnamed", and Greendale Members of the Lexington Limestone.

113.5	0.4	Upper end of the roadcut in the Point Pleasant (Bromley, Locust Creek, and River Quarry beds)
114.0	0.5	Franklin-Owen County line
117.3	3.3	Junction with Frank Clark Road; begin section of Lexington Limestone (Sulphur Well, Stamping Ground, "unnamed", and Greendale Members)
118.5	1.2	Cuts in Sulphur Well grainstones on both sides of the road near junction with Sawdridge Creek Road
118.9	0.4	Middle of a high, amphitheater-like roadcut on the west side of the road, which exposes the Donerail/Sulphur Well through Devils Hollow Members of the Lexington Limestone
119.5	0.6	High bridge over the Cedar Creek gorge, just above the town of Monterey, Kentucky

119.6 0.1 North end of the bridge; **pull off on shoulder at the start of large cuts on both sides**

Stop 25A: US 127 just north of Cedar Creek ("Monterey South")
This large, relatively fresh roadcut displays the "unnamed", Greendale, and Devils Hollow Members of the Lexington Limestone, and overlying Bromley Shale (sometimes assigned to the Point Pleasant Formation)

119.7 0.1 Continue north, passing the junction with Kentucky Route 335 on the left (west)

119.9 0.2 Lower end of a somewhat weathered roadcut; **pull off near sign for junction**

Stop 25B: US 127 near junction with KY 335 ("Monterey North")
A full section of the Point Pleasant *sensu lato*, including the upper Bromley, Peaks Mill, Locust Creek, River Quarry, as well as the basal Kope Formation (Fulton Submember)

120.7 0.8 Small outcrop of Kope Formation; cross fault nearby

121.2 0.5 Richly fossiliferous outcrop of the Bellevue and/or Corryville Members of the Grant Lake Formation; **pull over for an optional stop if time and stamina allow**

Stop 26: US 127 north of Burkes Lane ("Brachiopod Heaven")
Roadcut of middle Grant Lake Formation with *Vinlandostrophia ponderosa*, bryozoans, and other fossils.

121.6 0.4 Outcrop of Fairview and Grant Lake Formations south of junction with KY 845

123.6 2.0 Outcrop of Fairview Formation near A Hammond Road

127.7 4.1 **Turn right (east) at the junction with Main Street in Owenton, Kentucky**

128.8 1.1 **Dinner stop: The Smith House Restaurant (delicious barbecue; 1640 State Hwy 22, Owenton, KY 40359)**

129.9 1.1 **Turn right (west) and return to US 127, which goes north through Owenton**

139.2 9.3 **Follow US 127 for about 9 miles and continue straight on Kentucky Route 35; do not follow US 127 east at the split**

142.3 3.1 Large roadcut of lower Cincinnatian strata (Kope Formation?)

143.3 1.0 Bridge over Eagle Creek; Owen-Gallatin County Line; enter Sparta, Kentucky

144.1 0.8 Weathered and overgrown large roadcuts of Kope Formation on road bends

145.3 1.2 **Turn right (east) onto I-71 eastbound onramp (exit 57)**

165.0 19.7 **Merge onto I-71 / I-75 north toward Cincinnati**

187.1 12.1 **Take exit 184 for I-275 westbound towards the Cincinnati/Northern Kentucky International Airport (CVG);** passengers will be taken to hotels as necessary

<u>End road log for post-meeting field trip day 2</u>

Post-Meeting Field Trip Day 2 Stop Descriptions

Stop 15: Veterans Memorial Parkway northeast of Winchester, Kentucky

Contributors: Allison L. Young, Carlton E. Brett, Alex J. Reis

Location: Roadcuts along the Kentucky Route 1958 (Veterans Memorial Parkway) north of Winchester in Clark County, Kentucky; the first cut is just west of US Highway 60; the largest cut is east of US 60; the eastern cut is between Ecton Road and Kentucky Route 15

Coordinates: Main cut at 38° 00' 64.5" N, 84° 15' 69.9" W

Elevation: Lower end at ~235 m (~770 ft), upper end at ~262 (~860 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6B): a mostly complete succession of the Stamping Ground (lower Millersburg submember and upper Strodes Creek submember), “unnamed”, and Greendale members of the Lexington Formation

The four outcrops exposed on the Veterans Memorial Parkway provide a detailed look at the Stamping Ground Member and “unnamed” member of the Lexington Formation and its subdivisions (Figure 74). The outcrops are an easily accessible “four-corners” style roadcut divided by inclined access roads. Thus, in addition to inspecting the main cut, the units can be seen up-close by walking up the side roads.

The Stamping Ground Member of the Lexington Formation is a highly fossiliferous interval within the upper Lexington Formation, famous for its abundant stromatoporoids. The stromatoporoids in this interval are some of the largest seen in all of the Lexington Formation reaching over 80 cm wide. Their varied orientation, seen well here and at the Donerail Travel Center off Iron Works Pike at I-75 exit 120 south of Georgetown, Kentucky, indicators of strong storm activity.

The maximum flooding zone of the 4^{th} order Sulphur Well-Stamping Ground sequence occurs within the middle Stamping Ground. The upper Stamping Ground, essentially synonymous with previously proposed Strodes Creek Member (Black and Cuppels, 1973), carries the main epibole of the stromatoporoid *Labechia* and, locally, *Tetradium* corals. The Strodes Creek sub-member represents a 4^{th} order late highstand and shows a roughly shallowing upward succession. A stromatoporoid "conglomerate" comprising brecciated and reoriented stromatoporoids and/or tetradiid corals near the top record a period of reworking, likely by a major storm event. The “unnamed member”, a previously unrecognized but widespread grainstone package represents a 4^{th} order TST on a 3^{rd} order late TST/HST with two or three internal 5th/6th order cycles; this interval, previously conflated with the Strodes Creek Member, warrants status as a new member of the Lexington Limestone, and will be described in future publication. The shaly Greendale Member, seen at other localities nearby (such as the outcrop on Veterans Memorial Parkway just north of KY 15), is recognized as a 4^{th} order HST.

The proliferation of stromatoporoids and corals in the upper Lexington Formation strongly suggests a temporary warming event associated with the Sulfur Well-Stamping Ground cycle (i.e. lower M6B). Overall the Sulphur Well through Greendale interval is interpreted to represent a period of warming and relative transgression in the late Chatfieldian (early Katian) that shows some parallels with the later Katian Richmondian warming and invasion episode(s).

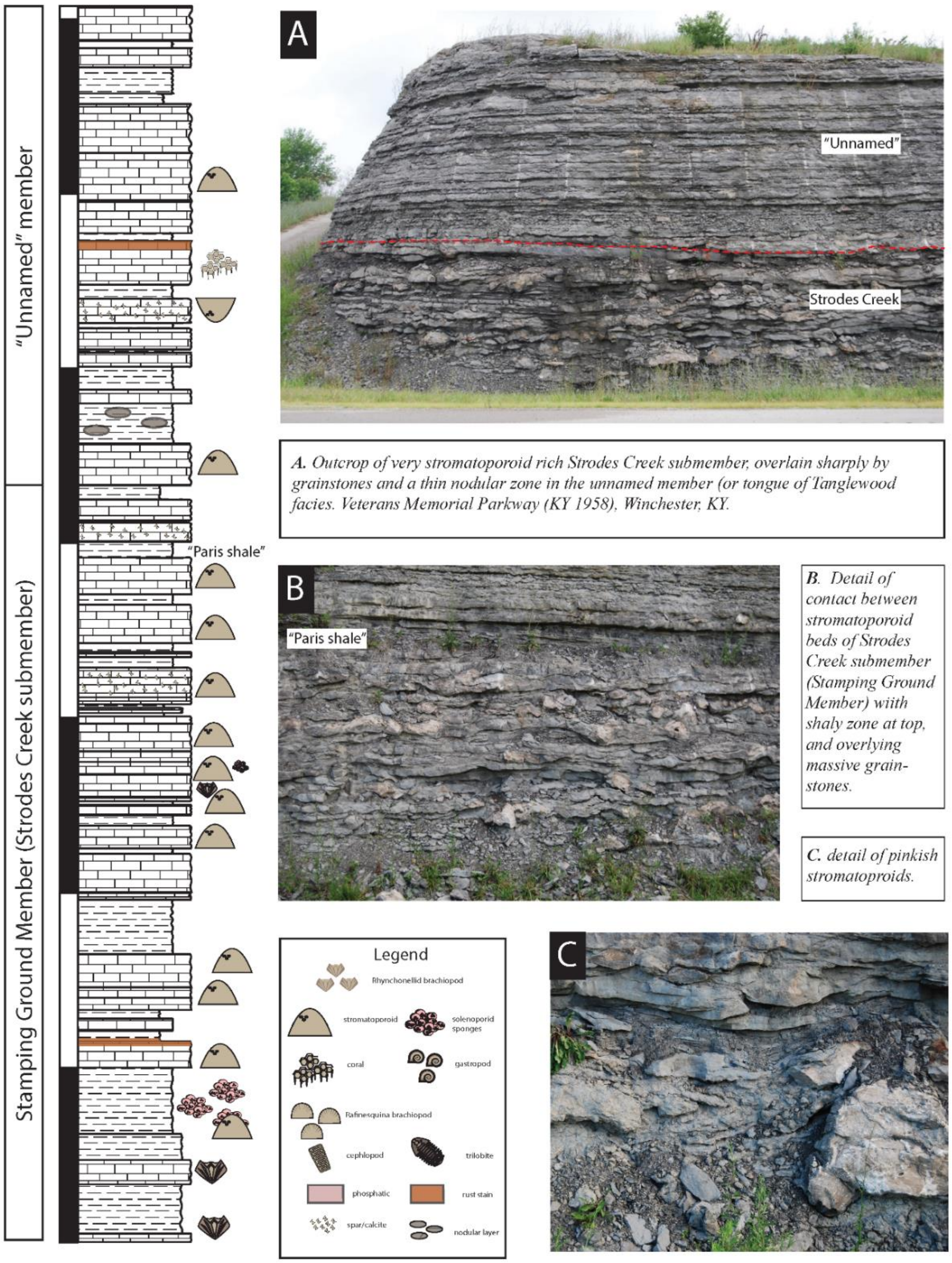


Figure 74. *Overview of the Veterans Memorial Parkway roadcut north of Winchester, Kentucky, which provides an excellent exposure of the Stamping Ground Member of the Lexington Limestone (especially the Strodes Creek submember), with abundant "lagoonal" fossils, including* Solenopora*, stromatoporoids, and putative algae.*

Stop 16: KY 627 just north of the Kentucky River at Boonesborough, Kentucky

Contributors: Carlton E. Brett, Thomas J. Schramm

Location: Roadcuts on both sides of Kentucky Route 627 immediately north of the Memorial Bridge over the Kentucky River in Clark County, Kentucky

Coordinates: South end at 37° 54' 24.0" N, 84° 16' 05.0" W;
north end at 37° 54' 31" N, 84° 15' 58.7" W

Elevation: ~204 m to ~224 m (~670 ft to ~736 ft)

Stratigraphy: Upper Ordovician (Sandbian, Sa2; Mohawkian, upper Turinian, M3-M4): High Bridge Group (Camp Nelson, Oregon, and Tyrone Formations)

These roadcuts provide an excellent section of over 30 meters of the Upper Ordovician (Sandbian; Mohawkian, Turinian or Blackriveran of North American terminology) Oregon and Tyrone Formations of the High Bridge Group. As such, this outcrop provides an excellent overview of the peritidal to shallow subtidal micrite-dominated facies that were so widespread in the Sandbian along the margin of eastern Laurentia, during the transition from the passive margin "Great American Carbonate Bank" and the development of the Taconic foreland basin. This long roadcut also exposes as many as 19 distinct K-bentonites, most of them very thin, but yielding probable phenocrysts (Conkin and Conkin, 1983), but including the extremely important and widespread 1st through 3rd Boonesborough, Deicke (Pencil Cave) and possibly the Millbrig (Mud Cave) horizons, the latter of which has been fingerprinted, dated and traced widely across eastern North America (Kolata et al., 1996). The Boonesborough section is discussed in detail by Cressman and Noger (1976), Kuhnhenn et al., (1981), Conkin and Conkin (1983), Kolata et al. (1996), and Bergström et al. (2010).

The section begins with a cut at the intersection of Kentucky Route 1924 (Four Mile Road) and extends along the southeast side of KY 627 up to the intersection of Old Boonesborough Road. From that corner a steep private drive leads uphill directly above the end of the KY 627 exposure; a cut along this drive exposes the middle portion of the Tyrone Formation. Just north of this intersection, the Tyrone is also exposed in cuts along both sides of KY 627 upward to just below its upper contact of with the Lexington.

The lowest exposures along KY 1924 show the uppermost Camp Nelson Formation with two cycles of burrow mottled micrites and thin, microbially ("cryptalgal") laminated and somewhat argillaceous dolomicrites. It should be noted that a splay of the Kentucky River fault zone is exposed as a brecciated zone at the southeast end of the exposure.

About 10 meters of pale orange dolomicrite assigned tentatively to the Oregon Formation is exposed in the lower part of the main roadcut southeast of KY 627. These comprise dolomitized micrites showing meter-scale cyclicity. Cycles comprise lower bioturbated massive lime-mudstones that pass upward into slightly recessive, buff weathering, fine microbially laminated, argillaceous dolostones with desiccation cracks, including prism cracks. A distinctive feature of this diagenetically altered facies, sometimes termed the Kentucky River marble, are the so-called "leopard-spots" (Figure 75C); these are irregular, sometimes labyrinthine dark gray mottles in a pale orange buff dolomicrite background. The origin of this mottling is still a matter of debate. They may be an accentuation of burrow mottling, bedding, desiccation cracks and other primary features, although some workers have claimed a largely diagenetic origin for the spots. It is evident that this process occurred early in diagenesis as the spots are unaffected by subsequent dolomitization and are crosscut by stylolites (Kuhnhenn et al., 1981).

A. Middle shaly zone or "Herrington Lake" member overlain sharply by massive upper member of Tyrone Formation; KY 627 cut, Boonesborough, KY

B. Deicke K-bentonite within Tyrone Formation; overlain by fenestral micritic limestone. Rte. 27 roadcut, Camp Nelson, KY.

C. Typical "leopard spot" lithology of Oregon Formation or "Kentucky River marble"; KY 627 cut, Boonesborough, KY

***Figure 75**. Overview of the upper High Bridge Group (upper Camp Nelson, Oregon, and Tyrone Formations, particularly the latter).*

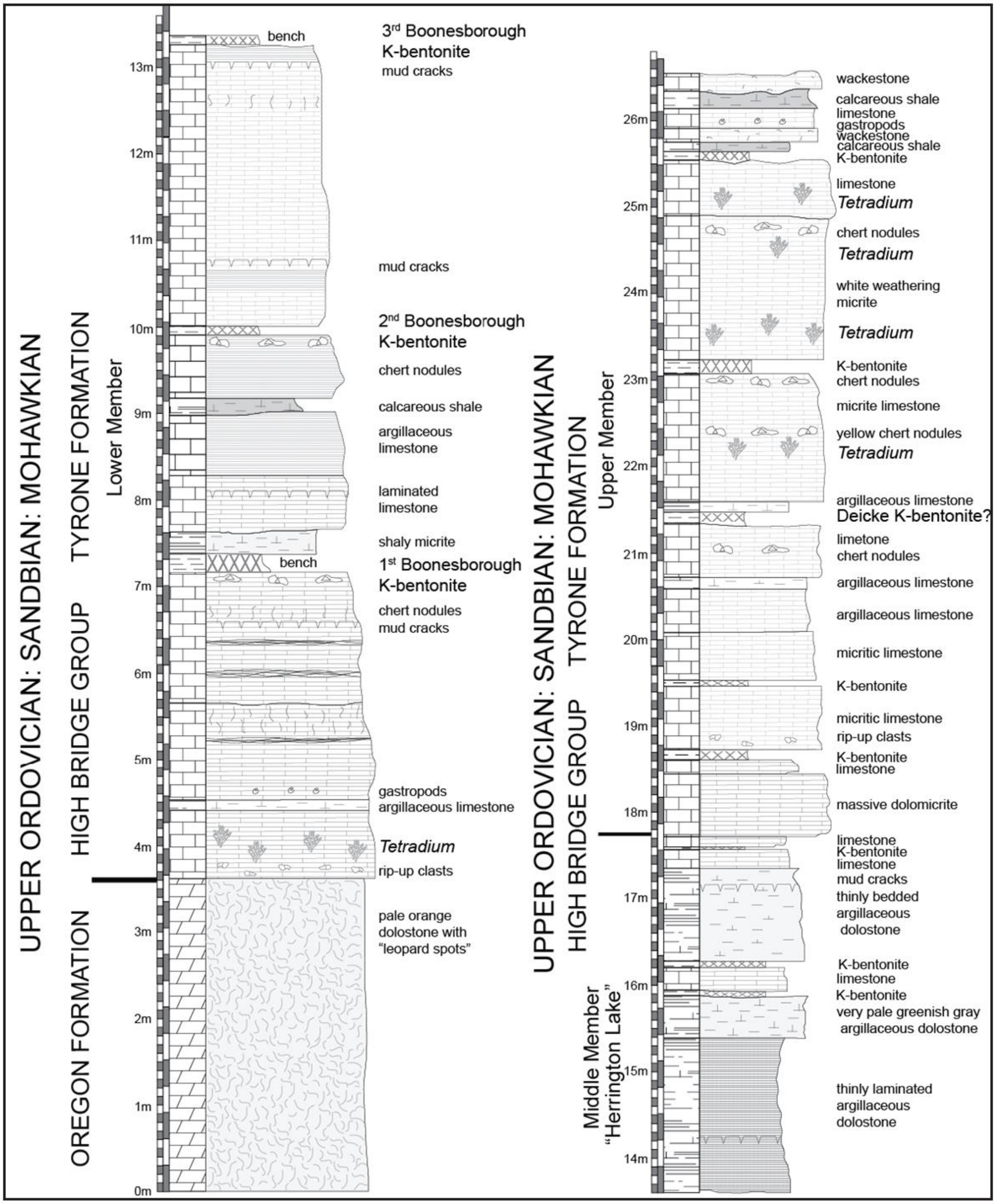


Figure 76. *Stratigraphic section of the Kentucky Rouge 627 roadcuts, featuring the High Bridge Group (upper Camp Nelson, Oregon, and Tyrone Formations.*

A relatively abrupt change to pale gray micrites is herein used to mark the base of the Tyrone Formation, the upper of three units of the High Bridge Group. This Oregon-Tyrone boundary is somewhat arbitrary and may simply reflect a diagenetic front. It should be noted that Cressman and Noger (1976) and (Kuhnhenn et al., 1981) included the overlying 6 m in the Oregon Formation because of the recurrence of "leopard spotted" dolomitic facies at about 5 m. However, this is a minor bed and most of the succession consists of limestone, or argillaceous dolostone and dolomitic mudstone facies atypical of the Oregon. Following the definition of Conkin and Conkin (1983), the Tyrone at this locality is about 23.5 m thick and divisible into three major units, herein designated as informal lower and upper micritic limestone members, separated by a distinctly argillaceous middle or Herrington Lake member.

The lower Tyrone is about 10 m thick and consists mainly of pale gray hard micritic limestone (lime mudstone to wackestone) with a middle interval of argillaceous, bentonitic dolostone with a basal K-bentonite. The first unit of the lower member is about 3.6 m thick and comprises relatively massive pale gray to slightly pinkish gray micritic limestone with minor dolomitization; it is subdivided into seven half-meter scale sub-equally spaced cycles, set off from one another by darker argillaceous partings. Again there are subtle meter-scale cycles within this interval that show alternations between of pale gray sub-laminated fenestral micrite, some vertical and horizontal burrows and pale pinkish gray burrow mottled wackestones. The latter yield fragmentary fossils including small *Tetradium*. rare solitary rugose corals, bryozoans, gastropods, nautiloids, leperditian ostracods, and minor pelmatozoan debris. These clearly record shallow subtidal facies. Also distinctive are beds of thin, lenticular intraclastic breccia/conglomerate, possibly transgressive lags at the bases of shallowing upward cycles (Figure 77).

A notable feature in the upper half meter of this unit is the presence of two layers of pale cream to gray colored chert that lie below the sharp upper contact of the unit with overlying bentonite and bentonitic shale. This interval shows abundant vertical burrows that terminate at the top surface, which is exposed to good advantage on the large bench near the upper end of this part of the cut. A large surface area of this contact is exposed on the main bench near the top of the outcrop and it shows features of a firmground with abundant sharply defined burrows.

This firm-ground platform is immediately overlain by a 45-50 cm recessive zone, which can be exposed by digging, the lower 25 cm consists of a pale yellowish, unctuous clay, evidently a K-bentonite bed designated the "lower Boonesborough metabentonite" (or K-bentonite) by Conkin and Conkin (1986). As is typical of many bentonites, this clay is overlain by about 30 cm of soft, laminated calcareous shale/platy argillaceous limestone, which yields well preserved darkened burrows. This shaly zone passes up into a desiccation cracked, laminated dolomicrite, a bed of pale orange "leopard spotted" dolostone, and finally a second desiccation cracked and microbially laminated argillaceous zone.

A second interval of cream-colored chert nodules occurs ~10 cm below the top of an overlying 85 cm micritic limestone. This chert zone again underlies a yellow weathering clay, recording a second Boonesborough K-bentonite (Conkin and Conkin, 1983). The second K bentonite is followed by a 330 cm-thick massive bed of buff-weathering dolomitic carbonate, which forms a cliff and terminates at an upper platform. This section is mostly inaccessible but is exposed above the second platform and to best advantage at the base of a cut along the paved private driveway off Old Boonesborough Road, just above the KY 627 cut, and it shows wavy microbial laminae, and minor scour and fill channels.

The massive bed is followed by a ~4 m thick interval of pale greenish gray, buff weathering, sub-laminated, silty argillaceous dolostone and dolomitic mudstone with minor microbialites. This interval, identified as unit V of the middle member by Conkin and Conkin (1983), is sparsely fossiliferous, with rare leperditians. This shaly zone is a distinctive marker interval that has been traced widely in central Kentucky;

it is informally named the Herrington Lake member of the Tyrone for exposures along Kentucky Route 34 just northeast of the bridge over Herrington Lake (south of Dix Creek Dam) near Marcellus, Kentucky.

The Herrington Lake interval is sharply overlain by hard, white weathering micrites that represent the upper member of the Tyrone Formation. These are best exposed in the (now somewhat overgrown) upper exposures of this roadcut. These beds show wavy, ("cryptalgal") microbial laminae as well as horizons of vertical and lesser horizontal burrows and thin recessive intervals of laminated and desiccation cracked shaly micrites. A distinctive yellowish clay, nearly 17 cm thick, apparently representing a third K-bentonite horizon, occurs about 4 m above the base of the upper member of the Tyrone. Again, nodular, cream-colored chert nodules occur about 30 cm below this K-bentonite and the clay is overlain by a recessive interval of burrowed argillaceous micrites.

A soft, yellow weathered clay horizon also about 15 cm thick is separated from the third by about 170 cm of wavy laminated micrite; a zone of thin chert nodules occurs again about 30 cm below the clay. This highest clay bed is identified as metabentonite-12 or the Pencil Cave by Conkin and Conkin (1983); as such it would be equivalent to the very widely correlated Deicke K bentonite horizon (Kolata et al. 1996), although it is not notably thicker than the others. In this case, the clay is not overlain by a shaly horizon but rather it is sharply overlain by 183 cm of massive, light gray burrow mottled micrite with leperditian ostracodes and a horizon of black chert nodules below a parting (K-bentonite?). This latter horizon is very tentatively correlated with the Mud Cave or Millbrig K-bentonite by Conkin and Conkin (1983). It is anomalous that the Millbrig, normally one of the thickest bentonite horizons is so poorly developed here that it has not been identified with certainty.

This is overlain by a distinctive, 70 cm-thick, white-weathering fenestral micrite bed. The upper 1.5 m of the Tyrone Formation exposed at the very top of the outcrop southeast of Kentucky Route 167 is thinner bedded, with shaly wacke- to packstone beds that are more highly fossiliferous than the rest of the unit and contains abundant gastropods, nautiloids, and *Tetradium* corals.

The M4-M5 unconformity with the overlying basal Lexington Curdsville Member is not exposed at this locality; however, it must lie just above this outcrop. The Curdsville is well exposed nearby on the downthrown fault block south of the Memorial Bridge over the Kentucky River in the Boonesborough limestone quarry where it is a massive, well sorted pelmatozoan grainstone.

This is an unusually complete section of the upper High Bridge Group and one of the few exposures that features such a large number of bentonites including both Deicke and possibly the Millbrig in a single outcrop. It is also unusual in showing a relatively thick interval limestone overlying the putative Millbrig bentonite; in most localities this horizon lies at or slightly below the M4-M5 unconformity. Hence, there is relatively more section preserved below the unconformity. Surprisingly, this succession appears to show a deepening upward pattern with more fully marine fossiliferous facies than the majority of the Tyrone. This suggests that even more section, recording the falling stage once lay below the level of the unconformity.

Figure 77. *Intraformational conglomerate within the Tyrone Formation at Boonesborough along Kentucky Route 627. Large chunks of white birdseye micrite are embedded in fine grainstone matrix, suggesting erosion within the Tyrone depositional system, perhaps during lowstand, with deposition during early transgression as a lag.*

Stop 17: Roadcuts on I-75 northbound north of the bridge over Kentucky River Gorge

Contributors: Carlton E. Brett, Kyle R. Hartshorn

Location: Exposures along north-bound lane of I-75 roughly 0.3 to 0.5 km (0.2 to 0.3) miles north of the Clays Ferry bridge over the Kentucky River Gorge and ~0.5 km (0.3 miles) south of I-75 exit 99 for Clays Ferry, Fayette County, Kentucky

Coordinates: 37° 53' 13.3" N, 84° 20' 35.6" W

Elevation: ~236 m to ~240 m (~774 ft to ~788 ft)

Stratigraphy: Upper Ordovician (Sandbian, Sa2; Mohawkian, uppermost Turinian); High Bridge Group, Tyrone Formation

These exposures display the shaly middle member (Herrington Lake) of Tyrone Formation with well-developed desiccation cracks in pale yellowish weathering dolomitic shales and overlying micritic limestones (Figure 78). Note well-developed small scale peritidal cyclicity, white-weathering fenestral ("birdseye") micrites, and vertical burrows overlain by desiccation-cracked, pale, shaly micrites. Sparse fossils include ostracodes, leperditians, and, rarely in the upper beds, gastropod coquinas (some silicified) and *Tetradium*.

The subsequent exit ramp (I-75 exit 99) shows dipping beds of the lower Lexington Limestone (Grier Member). Departing the interstate and taking Kentucky Route 2328 (Old Richmond Road) allows one to descend into the Kentucky River Gorge and access additional outcrops. At the river, KY 2328 crosses a small one lane bridge and ascends a road on the south side. Massive carbonates at river level near the viaduct of the I-75 Clays Ferry bridge belong to the Camp Nelson Formation (lower High Bridge Group), among the oldest rocks exposed in the commonwealth of Kentucky and previously seen at Boonesborough. These lime mudstones and wackestones record late Sandbian sequences (M2-M3) and are subjacent to the succession of Tyrone (sequence M4) exposed on I-75.

Shortly after crossing the bridge, note the massive Camp Nelson carbonates in fault contact with drag-folded lower Lexington Limestone (Grier Member), comprising the noticeably different lithology of thinly bedded limestones and shales.

Stop 18A: Cuts along KY 2328 immediately below the I-75 bridge, Kentucky River Gorge

Contributors: Carlton E. Brett

Location: Outcrop immediately below the deck of I-75 Clays Ferry bridge on south side of Kentucky River; Madison County, Kentucky

Coordinates: 37° 52' 57.3" N, 84° 20' 16.2" W

Elevation: Very roughly ~218 m to ~238 m (~716 ft to ~782 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6A): Lexington Limestone (Brannon, Sulphur Well, Stamping Ground, and Devils Hollow Members)

This outcrop exposes particularly shaly facies of the Brannon Member of the Lexington Limestone with dark gray shales and thin calcisiltites in sharp contact with massive cross-bedded grainstones of the overlying Sulphur Well Member (Figure 79). This is the M6A-M6B (sub-Sulphur Well) sequence boundary of Brett et al. (2004), a regional erosion surface that is known to truncate parts of the Brannon.

Figure 78. *Field trip participants inspect the Tyrone Formation along I-75 just north of the Clays Ferry bridge. Note the shaly zone at about eye height; this is part of the Herrington Lake member near the middle of the Tyrone.*

Figure 79. *The Brannon-Sulphur Well contact (M6A-M6B sequence boundary) beneath the I-75 Clays Ferry Bridge. Note the sharp facies change (mudstones beneath, crossbedded coarse grainstones above).*

Stop 18B: KY 2328 in the Kentucky River Gorge south of the I-75 bridge

Contributors: Carlton E. Brett

Location: Roadcuts along Kentucky State Route 2328 (Old Richmond Road) south of the I-75 bridge in the Kentucky River Gorge, Madison County, Kentucky

Coordinates: 37° 52' 52.2" N, 84° 20' 22.5" W

Elevation: ~235 m to ~258 m (~772 ft to ~847 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1-Ka2?; Mohawkian, Chatfieldian, M6C to Cincinnatian, basal Edenian, C1): lower Clays Ferry Formation (equivalent to the Bromley Shale, Point Pleasant Formation, and basal Kope Formation)

Pull off to examine part of the type section of the lower "Clays Ferry Formation" (Figure 80). The lower unit here is medium gray shale with interbedded calcisiltites and silty packstones correlative with the Bromley Member of the Cincinnati area. Note a zone of ball and pillow deformation in fine-grained grainstones of the informally named Locust Creek submember near the top of the exposure. This extremely widespread deformed zone has been interpreted as a series of seismites (McLaughlin and Brett, 2004). It is overlain sharply by coarse skeletal (pelmatozoan, brachiopod, bryozoans) packstones, rudstones and grainstones of the Point Pleasant Member (*sensu stricto*). This contact is a widespread erosion surface, identified by Brett et al. (2004) and McLaughlin et al. (2008) as the M6C-C1 sequence boundary. The Point Pleasant at this locality shows abundant *Rafinesquina*, in some cases as edgewise coquinas.

Figure 80. *The lower Clays Ferry Formation in the Kentucky River Gorge along Kentucky Route 2328.*

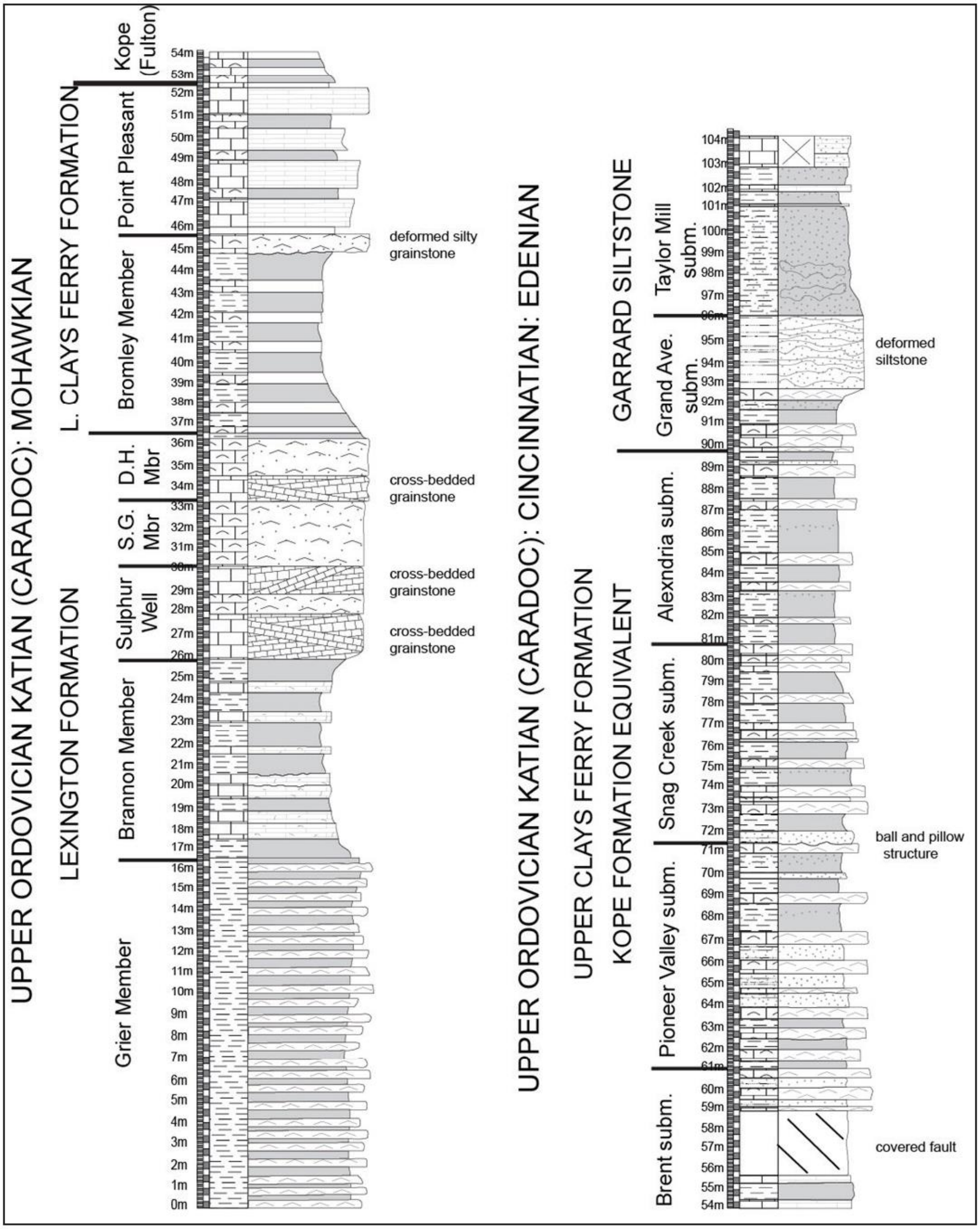


Figure 81. *Generalized stratigraphic section of the Lexington Limestone, Clays Ferry Formation, and Garrard Siltstone in the Kentucky River gorge and adjacent I-75 highway exposures at Clays Ferry, Kentucky*

Stop 18C: I-75 south of the Clays Ferry bridge

Contributors: Carlton E. Brett

Location: Section along north-bound lane of I-75, about 0.1 to 0.5 km south of Clays Ferry Bridge; Richmond township, Madison County, Kentucky

Coordinates: 37° 52' 54.2" N, 84° 20' 08.9" W

Elevation: ~255 m to ~276 m (~837 ft to ~905 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2?; Cincinnatian, Edenian): upper Clays Ferry Formation (Kope Formation equivalent here)

Here the downthrown block of the Kentucky River fault exposes the lower Cincinnatian (Edenian) upper Clays Ferry Formation (Figure 81). A southern facies of the Kope Formation, the Clays Ferry is notably more limestone rich than the Kope seen at Maysville and carries a very rich, slightly more proximal (upramp) fauna. The thin limestones and shales are rich in brachiopods, especially *Sowerbyella rugosa*, the dalmanellid *Cincinnetina*, *Rafinesquina*, and *Hebertella*. Mollusks are also abundant, including gastropods, bivalves, and nautiloids. Trilobites and trace fossils have also been reported. Siltstones are common and include beds up to 30 cm thick, some with soft sediment deformation.

The uppermost part of this outcrop, best exposed at the I-75 onramp from US Highway 25 to the south (exit 97), exposes the Garrard Siltstones, an uppermost Edenian unit correlated to the upper Kope Formation (largely the Taylor Mill submember). As its name suggests, the Garrard is very silty and likely represents falling stage deposits, with the silt resulting from strata being eroded upramp. As with the Hooke-Gillespie siltstones near Maysville, the Garrard is intensely deformed, with ball and pillow structures a meter or more in diameter. This horizon (or perhaps a combination of several discrete horizons) is traceable almost everywhere that the Garrard crops out. Typical Garrard with deformed bedding may be found as far south as Hustonville, nearly 70 km (40 miles) to the southwest of Clays Ferry.

Stop 19: Cuts along the Bluegrass Parkway west of the Kentucky River Gorge

Contributors: Allison L. Young, Ben Dattilo, Carlton E. Brett

Location: Large roadcuts on both sides of the Bluegrass Parkway (Kentucky Route 9002) starting just west of the bridge over Kentucky River and extending for about 0.5 km (0.3 miles) west, in Anderson County, Kentucky

Coordinates: Main cut (a) from 37° 59' 08.4" N, 84° 49' 29.9" W to 37° 59' 15.6" N, 84° 50' 17.4" W; supplementary outcrop (b) at 37° 59' 05.1" N, 84° 51' 13.9" W

Elevation: ~199 m to ~242 m (~652 ft to ~795 ft)

Stratigraphy: Upper Ordovician (uppermost Sandbian, Sa2 to lower Katian, Ka1; Mohawkian, Chatfieldian, M5A-M6B): Lexington Formation (Logana, Grier, Macedonia, Perryville, Brannon, "Donerail", and Sulphur Well Members)

This spectacular cut along the Bluegrass Parkway comprises the interval from the Curdsville Limestone (below the road level along river bluff) to the Sulphur Well mainly as sheer walls but most units are accessible by moving up the road slope (Figure 82). We will make stops briefly at the base and top of the outcrop. The lowest exposures feature a section of the upper Logana Member with recessive rhythmic beds of calcisiltite and shale; a rusty contact sets off the top of the mid-Logana limestone. This interval is overlain by a long section of the Grier, including Macedonia submember; this is a relatively monotonous succession of pack- and grainstones with minor shaly intervals about 20 cm thick; these beds are rich in the domal bryozoan *Prasopora* and will be seen also at Frankfort North (Stop 21).

Higher parts of the cut feature the complete sequence M6A: Perryville to Brannon and informal Donerail members. This sequence commences with massive crinoidal grainstones of the Salvisa beds, which pass upward through thinner bedded packstones and shales of the transitional, retrograding Cornishville beds. Marked by small stromatoporoids and distinctive, rusty weathering hardgrounds near the top, a sharp contact (flooding surface) separates the Cornishville from overlying Brannon Member with dark gray shale and thin siltstones/calcisiltites. Looking across the road spectacular high-wall views of the larger-scale soft sediment deformation in upper portions of the Brannon and a small, deeply incised and synsedimentarily faulted channel, filed with pack- or grainstones attributed to the Donerail member. Overall this succession shows a lowstand-early transgressive systems tract. Maximum starvation/maximum flooding surface, base of Brannon, highstand (Brannon), and falling stage channel fills, Donerail, beneath the next (sub-Sulphur Well; M6B) sequence boundary.

Stop 20: Cove Springs Park north of Frankfort, Kentucky

Contributors: Carlton E. Brett

Location: Exposures along stream (Penitentiary Branch) at Cove Springs Park, Deadhorse Road, off US Highway 127 0.2 km (0.1 mile) northeast of junction of US Highway 421 on the north side of Frankfort, Franklin County, Kentucky

Coordinates: Parking area at 38° 13' 06.7" N, 84° 50' 53.7" W

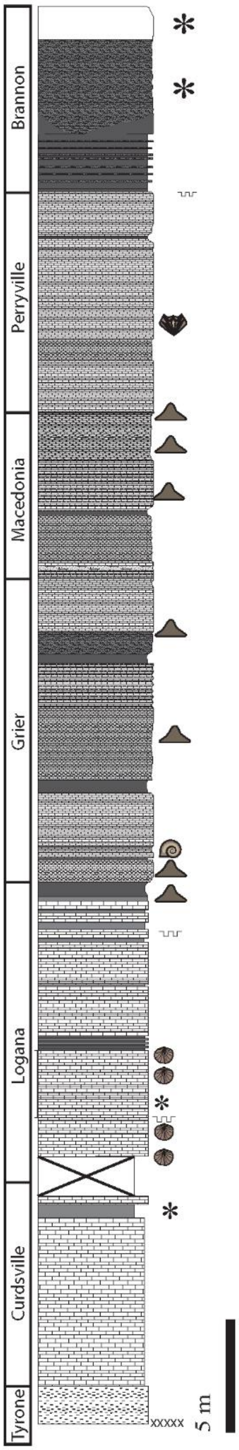
Elevation: ~155 m to ~168 m (~509 ft to ~550 ft; though not all well exposed; upper parts in woods)

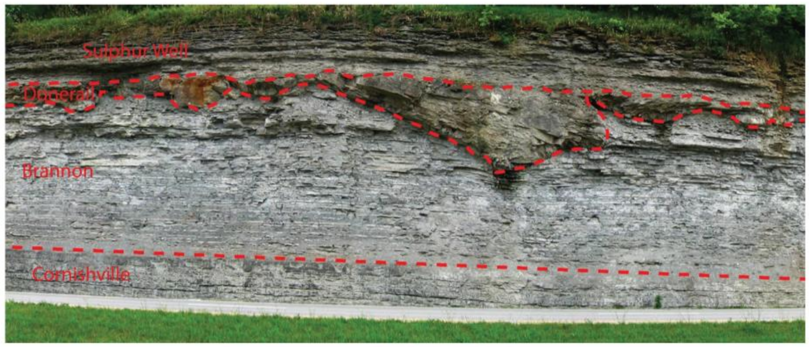
Stratigraphy: Upper Ordovician (upper Sandbian, Sa2; Mohawkian, uppermost Turinian, M4); High Bridge Group, Tyrone Formation

This sylvan nature center provides a lunch stop and an opportunity to examine strata of the upper member of the Tyrone Formation. A small old quarry just northeast of the junction of Deadhorse Road and Cove Spring Road (~100 m southeast of junction with US 127) provides access to the micritic limestones of the middle Tyrone Formation (Figure 83D). The Pencil Cave or Diecke K-bentonite-one of the two most widespread bentonites in eastern US is observable as a bright green clay in a recess at the level of the small access road. This K-bentonite has been traced very widely across the eastern and Midwestern United States (Kolata et al., 1996) and has recently been dated at 453.74 +/- 0.20 million years (Sell et al., 2015).

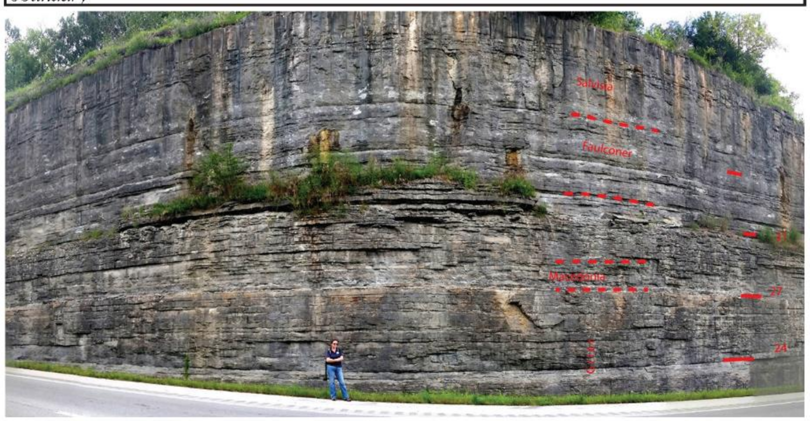
See www.frankfortparksandrec.com/Parks/Cove_Spring/cove_spring.html for more park information.

Bluegrass Parkway





A. Upper Perryville, Cornishville submember (late TST), overlain by gray shales and calcisiltites of Brannon Member (HST); the top of the latter is incised by a deformed channel filling grainstones of the Donerail falling stage. Dotted line at top indicates M6A-M6B sequence boundary'



B. Panorama of massive unnamed basal limestones of Macedonia member (M5C), overlain at rust-stained contact by thinner bedded argillaceous limestones and shale of upper member that pass upward into thicker bedded packstones. M5-M6 boundary is at base of massive Salvisa submember.

C. Vertical wall of main outcrop of showing relatively monotonous fac ies of Grier, Macedonia and Perryville along Bluegrass Parkway

Figure 82. *General description and stratigraphic column of the Bluegrass Parkway roadcut.*

Stop 21: US 127 northwest of Cove Springs Road, Frankfort, Kentucky ("Frankfort North")

Contributors: Carlton E. Brett, Patrick I. McLaughlin, Allison L. Young

Location: Series of large exposures along US Highway 127, starting a few meters north of junction of Cove Spring Road and extending for about 0.5 km (0.3 mile) to upper exposures at junction Kentucky Route 1900 (Peaks Mill Road); areas are opposite a small parking area for Cove Springs Wetlands, north of the junction with US Highway 421 north of Frankfort in Franklin County, Kentucky

Coordinates: Base (a) at 38° 13' 08.4" N, 84° 51' 07.6" W walk up the ditch to bench in Macedonia bed (b) at 38° 13' 22.2" N, 84° 51' 18.7" W; the base of the uppermost roadcut (c) starts at about 38° 13' 28.5" N, 84° 51' 15.1" W

Elevation: ~160 m to ~235 m (~524 ft to ~770 ft)

Stratigraphy: Upper Ordovician (upper Sandbian, Sa2 - Katian, Ka1; Mohawkian, uppermost Turinian – Chatfieldian, M4-M6); Tyrone Formation (of the High Bridge Group), Lexington Formation (Curdsville, Logana, Grier, Macedonia, Perryville, Brannon, Sulphur Well, Stamping Ground, "unnamed", Greendale, and Devils Hollow Members)

This classic, large roadcut is commonly referred to as "Frankfort North"; it is considered the primary reference section for the Lexington Formation and it exposes nearly every bed from the basal unconformity upward to Sulphur Well (Figure 83). The lowest outcrop exposes the uppermost Tyrone Formation, including an unnamed yellow-weathering K-bentonite above the Diecke seen around the corner in the old quarry (Figure 83D). The famed Millbrig K-bentonite is missing at this locality being truncated by erosion at the base of the Lexington Formation. This well-known M4-M5A sequence boundary is well exposed as a sharp but cryptic contact between somewhat fossiliferous wackestones in the Tyrone and pinkish gray, massive crinoidal grainstones of the basal Curdsville Member of the Lexington. Several meters above the unconformity there is a distinctive notch where a thin < 1m succession include a basal pale gray condensed bed full of the brachiopod *Sowerbyella curdsvillensis*, overlain by silty gray mudstone and siltstone with some small-scale ball and pillow deformation of silts. This is the Capitol shale interval but locally it is bentonitic, gives a very strong gamma ray kick and has been referred to as the Capitol metabentonite (Conkin and Dasari, 1986). This interval is sharply overlain by the upper 2 m of the Curdsville which then passes upward as a second small scale cycle in beds packed with dalmanellid shells for about 0.5 m.

These transition upward into medium gray calcareous shales and nearly barren rhythmically bedded subtabular fine grained calcisiltites of the Logana Member. Sparse fossils include dalmanellids, nuculid bivalves and rare conulariids and *Cryptolithus* trilobites. As at the Bluegrass Parkway, the Logana is subdivided by a meter-thick package of dalmanellid grainstones and the upper rhythmite package is in turn overlain by grainstones of the basal Grier. The Logana Member yields a strong positive C-isotopic excursion, which has been equated by Bergström et al. (2010) to the GICE, though may be best referred to as its own excursion, the Logana Excursion (A. Young et al., 2016). The Curdsville and Logana together form the TST and HST of 4th order sequence M5A (Brett et al., 2004).

The cut and low minor bench at the upper end of the first major cut (Stop 21B) show the upper Grier, including a package of crinoid-bryozoan grainstones that are overlain by a thin (~1 m) package of gray shale and thin, tabular calcisiltites closely resembling the Logana. This is the Macedonia bed (or beds) and it yields a second, slightly less prominent C isotope peak referred to by A. Young et al. (2016) as the Macedonia excursion. The bench on Macedonia shales exhibits in situ colonies of the bryozoan *Prasopora* cf. *simulatrix* (please leave these intact for the appreciation of future visitors).

Following a gap in the roadcut, exposures resume in the middle-upper Lexington (Stop 21C). At the upper curve, rather dirty exposures on the northeastern side of the road display deformed calcisiltite ball and pillow structures equated with the Brannon Member though decidedly much less shaly than the same interval at the Blue Grass Parkway. The opposite (west) side of the road commences in grainstones of the Sulphur Well (or middle tongue of Tanglewood). These show lenticular beds of flaser laminated, tidally laminated beds that appear to fill tidal channels and show lateral accretion. This interval is succeeded by a thin shaly zone (maximum flooding surface?) followed in turn by a "conglomerate" (rudite) of chaotically oriented stromatoporoids. Higher units are inferred to represent the Stamping Ground, unnamed member, Greendale Member and Devils Hollow Member. The bryozoan rich top of this interval with a distinctive zone of soft sedimentation is exposed at the junction of Kentucky Route 1900 at the hilltop.

Stop 22: Cuts on US 127 just south of BP gas station ("Peaks Mill North")

Contributors: Carlton E. Brett, Patrick I. McLaughlin, Allison L. Young

Location: Low roadcuts on both sides of US Highway 127 about 1.2 km (0.75 miles) north of Shadrick Ferry Road and 0.3 km (0.2 miles) south of a BP gas station at Steele Branch Road, 3.8 km (2.4 miles) southwest of Peaks Mill, in Franklin County Kentucky

Coordinates: 38° 16' 45.2" N, 84° 50' 53.2" W

Elevation: ~229 m to ~236 m (~750 ft to ~775 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6C-C1): upper Lexington Limestone (Locust Creek beds), Point Pleasant Formation (*sensu stricto*; the "River Quarry" beds)

This relatively small outcrop exposes a highly fossiliferous succession that starts in deformed (convoluted, overturned folds) thinly and tidally laminated fine grained grainstones assigned to the Locust Creek beds of the uppermost Lexington Formation of official usage (also termed the uppermost Tanglewood Member of Lexington by some Kentucky mappers). However, we feel that they may be better assigned to the Point Pleasant Formation and thus may refer to them as a part of the Point Pleasant Formation informally (Point Pleasant *sensu lato*). These calcarenites represent the falling stage systems tract of sequence M6C.

These beds are sharply overlain by fossiliferous coarse grainstones/rudstones of the "River Quarry" beds (the Point Pleasant *sensu stricto*) at an irregular possibly karstic contact that truncates folds in the underlying beds. This is the M6-C1 or basal Cincinnatian sequence boundary. The "River Quarry" beds are divided into a series of three packages of skeletal pack- and grainstones separated by recessive shaly packstones and shales. These shales, especially the lower are rich in fossils, notably robust, ramose bryozoans, brachiopods (*Rafinesquina*, dalmanellids) and abundant well-preserved specimens of the calcitic gastropod *Cyclonema*. Crinoids including *Anomalocrinus* and *Glyptocrinus* have also been obtained from this cut. The uppermost platform shows a heavy grainstone ledge with well-preserved symmetrical ripple marks. Nearby outcrops have yielded golf-ball-like cyclocrinitid algae.

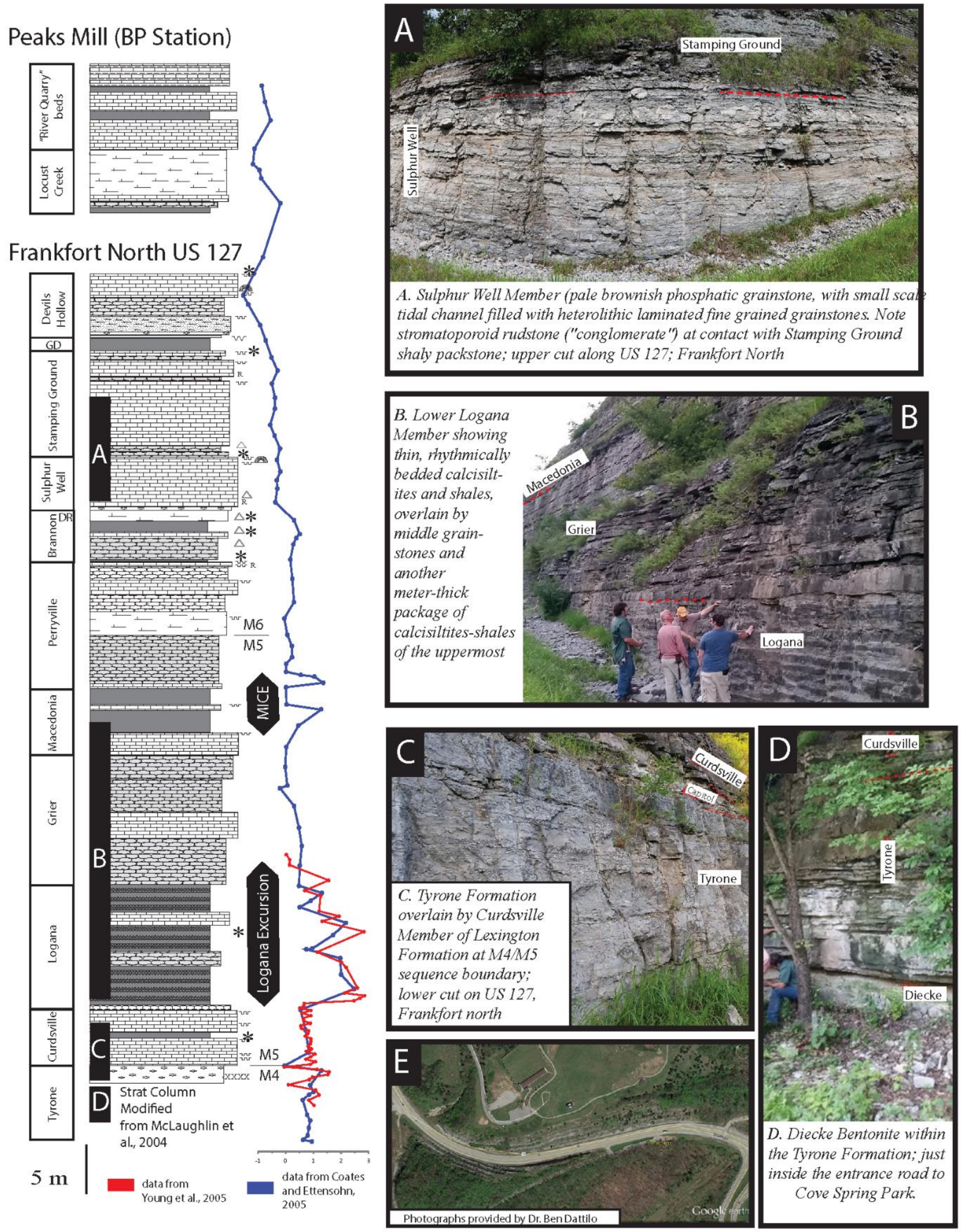


Figure 83. *Overview of the composite section formed by the US Highway 127 "Frankfort North" and Peaks Mill BP station roadcuts, which offers a complete view of the Lexington Limestone.*

Stop 23A: Cuts on US 127 at Old Owenton Road south of Elkhorn Creek

Contributors: Carlton E. Brett, Patrick I. McLaughlin

Location: Outcrop on east side of US 127, between Old Owenton Road and Strohmeier Road, south of the crossing of Elkhorn Creek, northwest of Peaks Mill in Franklin County, Kentucky

Coordinates: 38° 18' 11.8" N, 84° 50' 50.1" W

Elevation: Base at ~205 m (~675 ft), top at ~225 m (~739 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6 - Cincinnatian, Edenian, C1): upper Lexington Formation (Devils Hollow Member, Bromley Member, Peaks Mill submember, Gratz submember, Locust Creek submember), Point Pleasant Formation (“River Quarry” beds), and Kope Formation (Economy Member)

This large but somewhat weathered cut displays the upper Lexington, the Point Pleasant Formation, and the transition into the lower Cincinnatian (Edenian Stage) Kope Formation. Starting at the base and proceeding uphill, the following succession is seen: the pack- and grainstone beds of the Devils Hollow Member are sharply overlain by dark gray thin nodular bedded shaly packstones and shales assigned to the Bromley Member. These beds are rich in molluscan remains and fragments of the asaphid trilobite *Isotelus*. The Bromley is overlain by a distinctive 1 m thick white weathering sparry grainstone of the Peaks Mill beds, the condensed beds (likely a 5th order TST) that underlie the Gratz (shales) and Locust Creek calcarenites. As in the previous outcrop, the Locust Creek’s contorted beds of “pinstriped” fine grainstones are sharply overlain by coarse grainstones and rudstones of the “River Quarry” beds. These pass upward into a poorly exposed shaly slope in the Kope Formation. This slope is littered with slabs of thin packstone rich in the diagnostic Edenian brachiopod *Sowerbyella rugosa* and here the lithology makes a marked change into distinctly more shaly succession. The distinctive crinoid *Merocrinus* may also be found in the basal Kope at this locality, including complete calyces.

Stop 23B: Cuts on US 127 immediately south of Elkhorn Creek

Contributors: Carlton E. Brett, Patrick I. McLaughlin

Location: Roadcut on both sides of US Highway 127 between Old Owenton Road and Strohmeier Road, just south of the crossing of Elkhorn Creek, 3.2 km (2 miles) northwest of Peaks Mill in Franklin County, Kentucky

Coordinates: Middle of cut at 38° 18' 38.8" N, 84° 50' 54.0" W

Elevation: Base at ~172 m (~564 ft), top of west side at ~208 m (~681 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6): Lexington Formation (Sulphur Well, Stamping Ground, “unnamed”, Greendale, Devils Hollow, and Bromley Members) and Point Pleasant Formation

This high roadcut displays a succession of beds from the Sulphur Well Member through the Bromley Member. The distinctive white grainstones of the Peaks Mill beds cap the section at the top of a steep cliff. The section is cut by a distinct down-to-the-south normal fault and associated splays which offset the “unnamed” member by about 2 m.

Outcrops at road level provide access to the full succession of sequence M6B and its two subsequences. The lowest beds are in particularly massive Sulphur Well Member (middle Tanglewood), with stacked stylolitic(?) discontinuities and rust stained horizons overlain by the argillaceous rubbly packstones of the Stamping Ground. The 10 m Stamping Ground is itself capped by a massive unnamed 3 m thick rudstone/grainstone with abundant stromatoporoids and solenoporid sponges. This is overlain by the shaly beds of the Greendale. A series of skeletal packstones and grainstones with thin shale partings above the first bench mark in the Devils Hollow Member. These particular beds are highly significant as they yield rather well-preserved graptolites which are noted by the USGS as including specimens of *Diplacanthograptus spiniferus*, some of the only diagnostic graptolites recovered the Lexington. This occurrence suggests that beds of the upper Lexington or Point Pleasant may fall within the *D. spiniferus* Zone. However, the specimens are somewhat ambiguous; new graptolite material obtained in 2016 is presently under study by C. Mitchell (SUNY Buffalo).

Stop 24: Long roadcut on US 127 at Swallowfield, Kentucky

Contributors: Carlton E. Brett, Patrick I. McLaughlin

Location: Major roadcut on US Highway 127 commencing with a small outcrop just east of bridge over Long Branch creek and picking up with continuous outcrop on northeast side of the road for about a mile uphill, near Swallowfield in northern Franklin County, Kentucky

Coordinates: Lower outcrop east of Long Branch at 38° 20' 34.4" N, 84° 50' 54.5" W; middle of long cut at 38° 20' 36.9" N, 84° 51' 21.7" W

Elevation: Base at ~171 m (~560 ft), top at ~221 m (~725 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6): Lexington Formation (Brannon, Sulphur Well, Stamping Ground, “unnamed”, Greendale, Devils Hollow, and Bromley Members) and Point Pleasant Formation (to “River Quarry” beds)

This extensive cut, nearly a mile in length, has been described in detail in McLaughlin et al. (2008a, p. 207-209) and will not be a major focus of this trip, as it largely contains strata already seen at earlier stops. However, a few highlights are well worth discussion. The lowest cut, just east of the bridge over Long Branch Creek, is in the upper Brannon Member and shows a remarkable succession of deformed and highly broken beds. Near the base, the upper whitish weathering interval shows chaotically arranged clasts in a marly calcisiltite matrix. This illustrates the progression of deformation anticipated during propagation of seismic waves upward through layers of varying competence. This bed appears to correlate with the Cane Run bed, a distinctive marker in the upper Brannon near Lexington.

A brief stop in the middle of the main roadcut will examine the top of the Stamping Ground (Figure 84), including Strodes Creek submember, with a thin K-bentonite near its base, which has yielded zircons. A second shaly notch yields abundant small, marble-sized, chert-replaced solenoporids. This zone is overlain by a massive 2 m thick “unnamed” member with a profusion of bryozoans, solenoporids and occasional stromatoporoids. The sharp top of this bed shows a rusty stained hardground at its contact with the overlying shaly Greendale Member. The Greendale here is partitioned into two roughly equal subunits by a middle limestone bed. Higher parts of the roadcut display excellent outcrops of the Devils Hollow, Bromley, Locust Creek laminated grainstones (here notably *not* deformed). The “River Quarry” beds form the upper bluffs at the very top of this extraordinary outcrop.

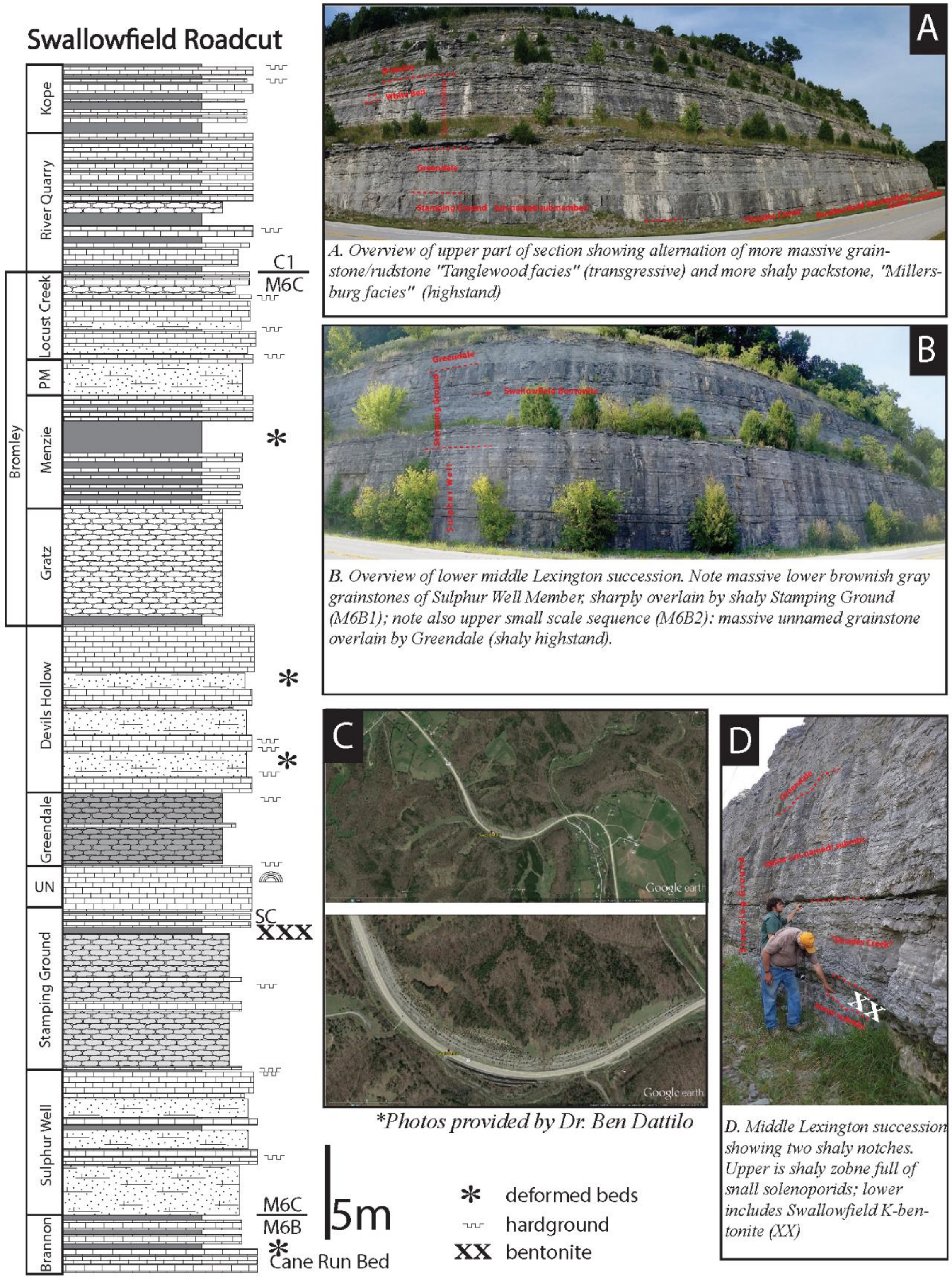


Figure 84. *Overview of the US Highway 127 roadcut near Swallowfield, Kentucky.*

Stop 25A: US 127 just north of Cedar Creek ("Monterey South")

Contributors: Carlton E. Brett, Patrick I. McLaughlin; Timothy R. Paton

Location: Large roadcuts on both sides of US Highway 127 immediately north of cliffs along Cedar Creek (sometimes called Sawdridge Creek) gorge at the north end of the US 127 bridge on the outskirts of Monterey in Owen County, Kentucky

Coordinates: 38° 25' 31.7" N, 84° 52' 01.0" W

Elevation: Cedar Creek at ~141 m (~463 ft), base of roadcut at ~171 m (~560 ft), top of roadcut at ~204 m (~670 ft)

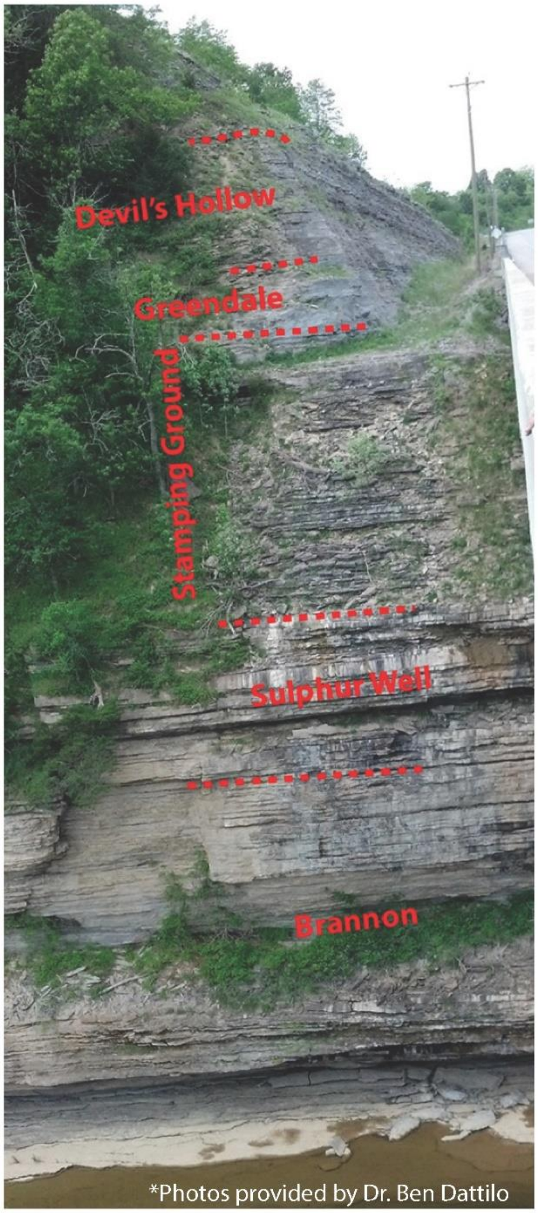
Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, Chatfieldian, M6-C1): Lexington Limestone ("unnamed", Greendale, Devils Hollow, and Bromley members), Point Pleasant Formation

These high cuts on both sides of the highway provide an excellent section of the upper Lexington (Figure 84) and were featured as Stop 1B ("Lower Monterey East") of McLaughlin et al. (2008a). The gorge below, not easily accessible, may expose the Brannon, Sulphur Well, and Stamping Ground Members. The roadcut itself starts with a sharp rusty hardground on top of massive grainstones of the "unnamed" member. Above this contact, the ashen gray calcareous mudstones of the Greendale Member contain abundant *Rhynchotrema* and locally show deformation such as ball and-pillow structures.

The overlying Devils Hollow (upper middle Tanglewood) is a highly varied set of grainstones, packstones and shales with several distinct rusty weathering phosphatic hardgrounds. Bluish chert nodules may be present locally. The upper portion of the cut provides an excellent section of the Bromley Member (also called the Millersburg Member of the Lexington Limestone for its rubbly facies) with medium gray shale nodular packstones rich in shell fragments, gastropods and small bivalves. These beds are show prolific remains of the trilobite *Isotelus* although they are almost entirely disarticulated and typically fragmentary.

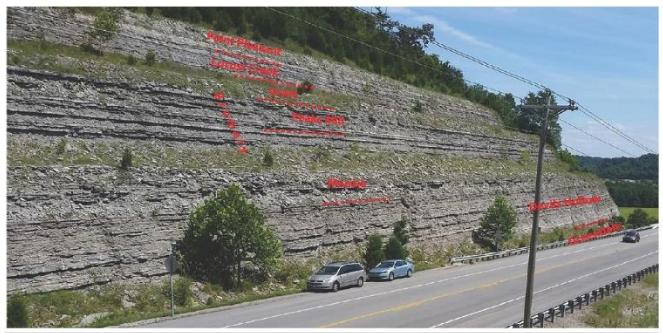
The uppermost slope-face exposes the Peaks Mill, Gratz, and Locust Creek beds, and perhaps the "River Quarry" beds.

Monterey South, Kentucky



A. *Section in cliff adjacent to US 127 bridge over Cedar Creek showing succession of Brannon-Donerail (M6A) sharply overlain by Sulphur Well-Stamping Ground-Greendale (M6B) and Devils Hollow (M6C)*

B. *Greendale-Devils Hollow contact. M6B-M6C.*



C. *Upper succession at Monterey South showing Devils Hollow sharply overlain by shaly Bromley Member at a major M6C flooding surface; high in the cliff the basal "River Quarry beds" (Point Pleasant s.s.) basal C1 show as light bands near top.*

D. *Satelite image of large Monterey South cuts along US 127*

Figure 84. *Overview of the southern roadcut on US Highway 127 at Monterey, Kentucky.*

Stop 25B: US 127 at KY 355 north of Monterey, Kentucky ("Monterey North")

Contributors: Carlton E. Brett, Patrick I. McLaughlin; Timothy R. Paton

Location: Roadcuts on the east side of US Highway 127 immediately north of intersection of Kentucky State Route 355 and extending northeast around a bend in the road for about 0.5 km (0.3 miles), 0.8 km (0.5 miles) northeast of Monterey, Owen County, Kentucky

Coordinates: South end at 38° 25' 38.9" N, 84° 52' 04.4" W;
north end at 38° 25' 54.2" N, 84° 52' 04.1" W

Elevation: Base at ~190 m (~624 ft), top at ~218 m (~715 ft)

Stratigraphy: Upper Ordovician (Katian, Ka1; Mohawkian, uppermost Chatfieldian, M6C to Cincinnatian, basal Edenian, C1): Lexington Formation (Bromley Member, Peaks Mill beds, Locust Creek beds), Point Pleasant Formation (*sensu stricto*; i.e. "River Quarry" beds), Kope Formation (Economy Member)

This is the northernmost outcrop of the upper Lexington-Point Pleasant along this transect and it illustrates an unusually distal facies in the "River Quarry" beds interval; it was Stop 1A of McLaughlin et al. (2008a). The upper Bromley, Peaks Mill, and Locust Creek are well displayed in the lower end of the outcrop (Figure 85). The deformed "pinstriped" calcisiltites of the Locust Creek are irregularly truncated beneath coarse skeletal rudstones that culminate in orange-weathering crumbly grainstone all in the lower package of the "River Quarry" beds. A distinctive bored hardground at the top of this package is sharply overlain by nearly barren, medium gray shale and siltstone in the middle "River Quarry" beds. Small chalky weathering concretions occur at several levels; these rarely contain fragments and even articulated specimens of *Isotelus* and rare enrolled *Flexicalymene* occur in the shales. An upper ledge-forming bed of packstone apparently records the upper River Quarry compact limestone. Hence, this section is exceptionally shaly, perhaps representing an embayment that developed on the ramp during later Point Pleasant deposition. In contrast, the overlying Fulton submember (basal Kope Formation) shows a series of relatively thick limestone ledges with very rich fossil assemblages. Float slabs yield a variety of brachiopods including dalmanellids and *Sowerbyella rugosa*, varied gastropods, bivalves, nautiloids, trilobites (especially *Flexicalymene granulosa* and *Cryptolithus tesselatus*), and crinoid columnals, including *Ectenocrinus*, *Cincinnaticrinus*, and the distinctive cylindrical *Merocrinus*, a local index fossil for the Fulton. Rare slabs with distinctive stellate plates of the glyptocystitid rhombiferan *Cheirocystis fultonensis* prove the presence of this highly restricted epibole species, which is normally restricted to the basal meter of the Fulton. Gypsum crystals are locally found in float. The highest beds exposed at the top of the section are silty shales rich in *Sowerbyella* typical of the Brent submember of the Economy Member (lower Kope Formation).

A. *Panorama of section on US127 at Monterey north showing anomalously shaly middle Point Pleasant ("River Quarry beds"), with thin upper limestone, overlain by shale and thin limestone of the lower Fulton submember of the Kope Formation.*

B. *thinly laminated and bindled (tidal?) bedding in the lower Locust Creek member.*

C. *lower grainstones of the "River Quarry" beds; note very rusty, phosphatic grainstone.*

D. *Sharp, irregular erosional contact of "River Quarry" (formerly Point Pleasant Member coarse rudstones on Locust Creek laminated grainstones. Note clast of Locust Creek grainstone in basal lag.*

Figure 85. *Overview of the northern roadcut on US Highway 127 at Monterey, Kentucky.*

Stop 26: US 127 north of Burkes Lane ("Brachiopod Heaven")

Contributors: Kyle R. Hartshorn

Location: Roadcut on both sides of US Highway 127, 3.1 km (1.9 miles) northeast of Monterey in Owen County, Kentucky; 0.9 km (0.7 miles) northeast of the junction with Burkes Lane

Coordinates: 38° 26' 43.9" N, 83° 51' 10.5" W

Elevation: Base at ~259 m (~850 ft), top at ~202 m (~863 ft)

Stratigraphy: Upper Ordovician (Katian, Ka2; Cincinnatian, Maysvillian, C2): Grant Lake Formation (Corryville Member?)

This outcrop serves as optional denouement to the field trip, ending roughly where the trip began (in a stratigraphic sense), back in the Grant Lake Formation (Figure 86). Here, as near Maysville, the Grant Lake is full of large brachiopods, particularly *Vinlandostrophia ponderosa* (Figure 87). Bryozoans are also common in this rubbly limestone and some of the globular bryozoans have clam molds preserved on the bottom, similar to the *Cyphotrypa* from the Rowland "Ball Bryozoan Bed" near Owingsville.

Figure 86. *Grant Lake Formation on US Highway 127. Note shaly/rubbly limestones (likely Corryville Member), with ledgy grainstones at the top of the cut, perhaps Flemingsburg bed or even Mount Auburn Member.*

Figure 87. *Brachiopod heaven on US Highway 127. Rest in peace,* Platystrophia ponderosa.