SERIES TO SEQUENCES: GEOLOGIC FIELD EXCURSIONS IN SOUTHWESTERN OHIO

Prepared for

American Institute of Professional Geologists

60th Anniversary Conference
"The Many Facets of Geology"
September 16–19, 2023
Radisson Hotel Cincinnati Riverfront
Covington, KY, U.S.A.

OHIO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES

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FRONT COVER: Photograph of a 2-meter-high waterfall along East Fork, Four Mile Creek in Preble County, Ohio.

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Field trips prepared by

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GEOLOGICAL
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ABBREVIATIONS USED IN THIS REPORT

Units of Measure

centimeter	cm
foot or feet	ft
inch	in
kilometer	km
meter	m
mile	mi
million years	myr
thousand years	kyr
thousand years ago	ka

Other

carbonate	carb
Digital Elevation Model	DEM
Falling Stage Systems Tract	FSST
Guttenberg Isotope Carbon Excursion	GICE
Highstand Systems Tract	HST
Hirnantian Isotopic Carbon Excursion	HICE
Last Glacial Maximum	LGM
Light Detection and Ranging	LiDAR
Lowstand Systems Tract	LST
Marine Isotope Stages	MIS
Transgressive Systems Tract	TST

AIPG 60th Anniversary Conference

Ohio Field Trip Schedule and Itineraries

Note: All distances are approximate.

Upper Ordovician and lower Silurian facies, cycles, and sequences in southern Ohio: A field and core workshop

Leaders: Christopher B.T. Waid, Ohio Geological Survey; Carlton E. Brett, University of Cincinnati; Cole Farnam, University of Cincinnati

Sunday, September 17

8:00 a.m. – Depart from Radisson Hotel Cincinnati Riverfront and travel to southern Ohio.

9:00–10:15 a.m. – View core of upper Cincinnati Group, Medina Group, and lower Clinton Group at ODOT Rest Area on OH-32 between Mount Orab and Sardinia, OH.

10:45 a.m.–12:15 p.m. – View outcrop sections on OH-41 north of West Union, Ohio.

12:30–2:00 p.m. – Lunch stop followed by viewing core of upper Clinton Group and Lockport Group units.

2:15–4:00 p.m. – View Measley Ridge outcrop sections along OH-32.

5:30 p.m. – Return to Radisson Hotel in Covington, KY.

Total Field Trip Time: 9.5 hours

Exploring the type Cincinnatian Series (Upper Ordovician) and its world-famous fossils at Hueston Woods State Park

Leader: Mark E. Peter, Ohio Geological Survey

Monday, September 18

8:00 a.m. – Depart Radisson Hotel Cincinnati Riverfront in Covington, Kentucky.

9:30–10:30 a.m. – View Upper Ordovician fossils at Limper Geological Museum in Oxford, Ohio.

11:00 a.m.–12:00 p.m. – View Acton Lake spillway exposure of Waynesville Formation.

12:15–12:45 p.m. – Picnic lunch at Hueston Woods State Park Nature Center.

1:30–3:30 p.m. – View East Fork, Four Mile Creek exposures of Liberty Formation and collect fossils.

5:00 p.m. – Return to Radisson Hotel Cincinnati Riverfront in Covington, Kentucky.

Total Field Trip Time: 9 hours

Revisiting the Wisconsin depositional history of the southernmost extent of the Scioto Sublobe, Ohio

Leaders: T. Andrew Nash, Ohio Geological Survey, Tyler A. Norris, Ohio Geological Survey;
Thomas R. Valachovics, Ohio Geological Survey

Tuesday, September 19

8:00 a.m. – Depart Radisson Hotel Cincinnati Riverfront in Covington, Kentucky.

9:00–9:30 a.m. – View the terminal moraine of the Scioto Sublobe in Warren County, Ohio.

9:35–10:35 a.m. – View an outcrop with different lithologic units and till facies on the western bank of Todd Fork.

10:55 a.m.–12:00 p.m. – View the Caesar Till at Melvin Stone Quarry.

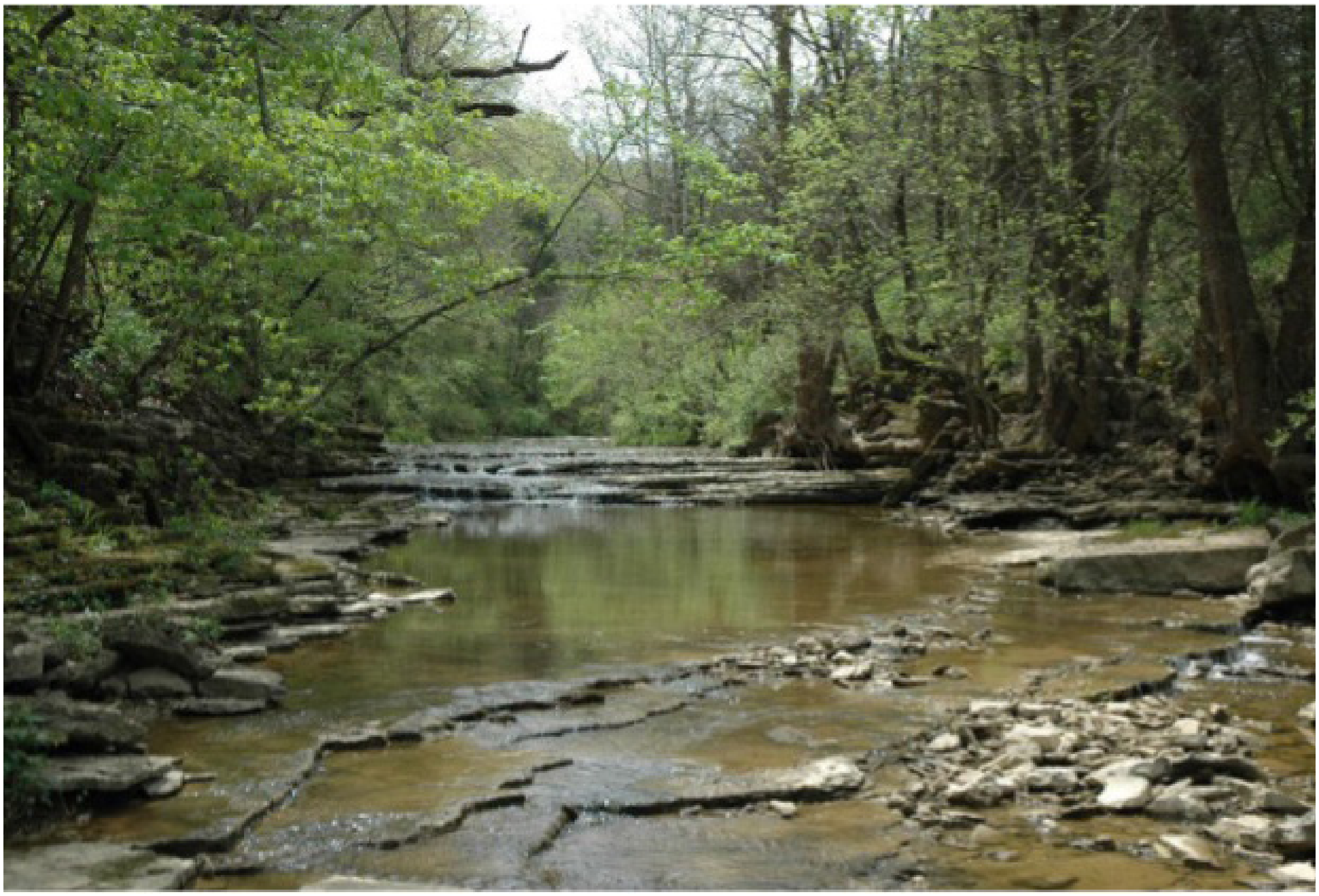
12:15–1:00 p.m. – Lunch stop at Richland Township Park.

1:20–2:20 p.m. – View the Darby Till near Rattlesnake Creek.

2:35–3:15 p.m. – View the Washington Esker, just south of Washington Court House, Ohio.

5:00 p.m. – Return to Radisson Hotel Cincinnati Riverfront in Covington, Kentucky.

Total Field Trip Time: 9 hours



CHAPTER 1

Upper Ordovician and lower Silurian facies, cycles, and sequences in southern Ohio: A field and core workshop

OHIO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES

University of CINCINNATI

American Institute of Professional Geologists
60th Anniversary Conference 2023

Geologic Field Trip

Upper Ordovician and lower Silurian facies, cycles, and sequences in southern Ohio: A field and core workshop

Field trip leaders: Christopher B.T. Waid[*,1,2], Carlton E. Brett[*,3], and Cole Farnam[*,3]

Ohio Geological Survey

*** Field trip guide author.**
[1]Ohio Department of Natural Resources, Division of Geological Survey
[2]The Ohio State University, School of Earth Sciences
[3]University of Cincinnati, Department of Geology
Field trip cover photo: A view of the Brassfield Formation along Lick Fork Creek south of Peebles, Ohio. Photograph by Charles R. Salmons (Ohio Geological Survey).

INTRODUCTION

The Cincinnati Group (Upper Ordovician; Katian–Hirnantian? Stages), and Medina and Clinton Groups (lower Silurian, Llandovery and Wenlock Series) in Ohio and adjacent regions form both a natural laboratory for the study of mixed siliciclastic and carbonate sequences and a valuable economic resource (figs. 1-1, 1-2). The Medina Group, in proximal sandy facies representing prograded clastic-wedge paleodepositional environments (northeastern Ohio), contains extensive oil and gas reserves that may be amenable for CO_2 enhanced oil/gas recovery and subsequent sequestration (Riley and others, 2011). Conversely, more distal carbonate-dominated facies in western Ohio are extensively quarried for aggregate and lime production (USGS, 2018). The overlying Clinton Group strata, (not to be confused with the driller's term "Clinton sands" which belong to the Medina Group), which are generally much more shale rich than the Medina Group throughout the basin, provide the cap rocks for the Medina Group hydrocarbon fields, so understanding their distribution is equally important for both hydrocarbon production and potential CO_2 sequestration. Moreover, certain carbonate units (notably the "Red Brassfield," Waco, and Dayton limestones), have long been used as paving and ornamental building stones. Finally, the interbedded fossil-rich limestones and clay mudrocks, especially in the Cincinnati and Clinton groups (fig. 1-1), provide some of the most accessible renowned and prolific fossil collecting localities in the world (e.g., Caesar Creek State Park, roadcuts around Cincinnati).

In addition to their economic value, these units record a dynamic time in both global climate and regional tectonics, notably the Taconian and early phases of the Salinic orogenies in the Appalachian foreland basin (fig. 1-3A) . The Cincinnati Group (fig. 1-2) was deposited during the transition from very warm greenhouse conditions to Late Ordovician icehouse conditions. The icehouse reached its apex during the Hirnantian Age and contributed to the major Late Ordovician mass extinction event. The overlying Medina and Clinton groups record the opposite—the slow transition from the peak ice conditions in the Hirnantian through warmer (but still icehouse transitional) conditions throughout much of the Silurian, and the recovery and diversification of marine life. Large-scale fluctuations in the global carbon system related to the climatic changes are evidenced by several globally recognized positive and negative stable carbon isotope ($\delta^{13}C$) excursions (fig. 1-1) in both carbonate and organic carbon. Changes from glacial to interglacial periods led to sea-level fluctuations of varying magnitudes and frequencies that may have corresponded to Milankovitch orbital oscillations (Munnecke and others, 2010; Ellwood and others, 2011; Sinesael and others, 2019; Sproson, 2020), which left a record of cyclical lithological change throughout the Cincinnati, Medina, and Clinton Groups. Amplitude modulation effects between the 100 and 400 kyr eccentricity and higher frequency obliquity (presently 41 kyr but estimated as 33 kyr for the Late Ordovician–early Silurian; Sinesael, pers comm. 2020) and precessional (~20 kyr present; ~16 kyr in mid Paleozoic) Milankovitch cycles created 10 to 100 kyr-scale climate (and likely sea-level) variations. A very large-scale 4.5-myr periodicity has been postulated (Sproson, 2020), caused by amplitude modulation effects of obliquity and eccentricity cycles.

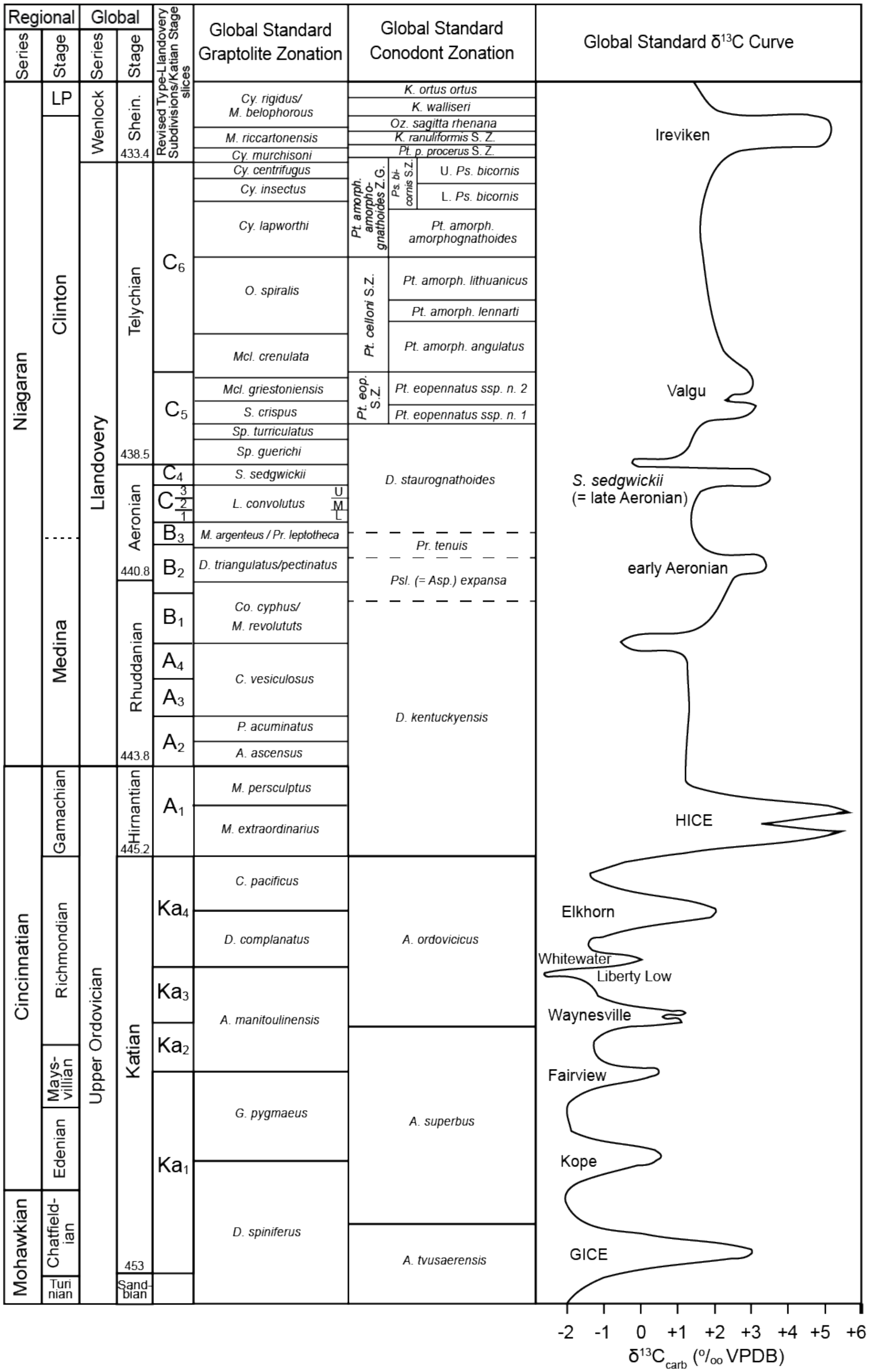


FIGURE 1-1. Chronostratigraphic diagram of the Katian through Sheinwoodian stages. LP=Lockport Group, L=lower, U=upper, Ord.=Ordovician, Shein. = Sheinwoodian, S.Z. = Superzone, Z.G.=Zonal Group. Global and regional series and stages, conodont zonation, and global standard δ13C from Cramer and others (2011), LaPorte and others (2009), and Sennikov and others (2015). Correlation of conodont and graptolite zones from Melchin and others (2012). Correlation of Type Llandovery subdivisions from Davies and others (2013, 2016). Katian stage slices from Bergström (2009). Figure modified from Waid and Cramer (2017).

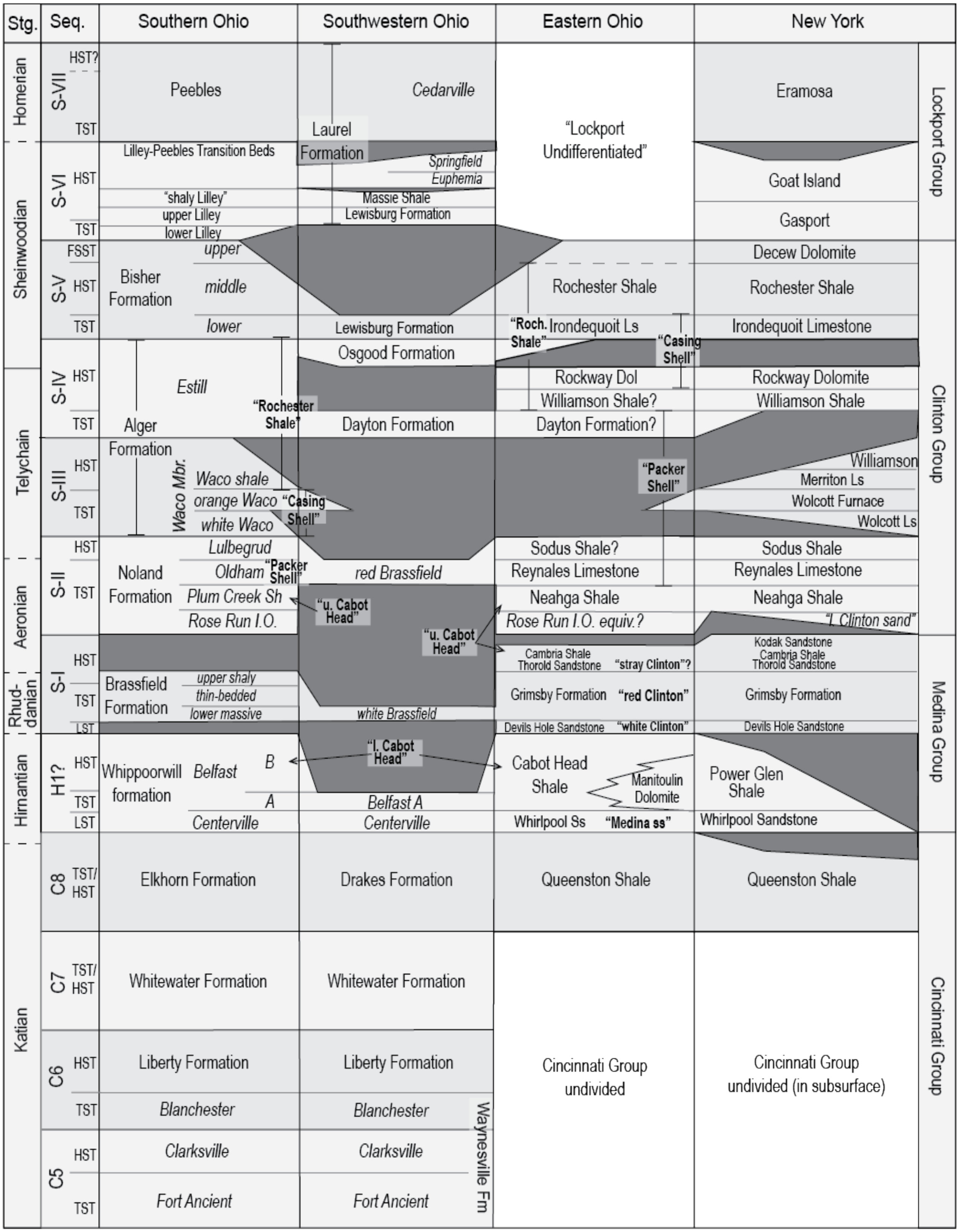


FIGURE 1-2. Semichronostratigraphic chart for Upper Ordovician through lower Silurian strata of the western and northwestern Appalachian Basin. Members are italicized. Bold units in quotes are subsurface terminology as used throughout Ohio and sometimes in surrounding states. Note that the same unit names refer to different formal strata depending on geographic location. Sequences are third-order stratigraphic sequences. Correlations and sequence stratigraphic interpretations mostly derived from data and interpretations in Brett and Ray (2005), Brett and others (1990, 1995, 2012), Castle (1998), Bergström and others (2011), McLaughlin and others (2008), Cramer (2009), Schröer and others (2016), Sullivan and others (2016), and Waid (2018). Figure modified from Waid and Brett (2019).

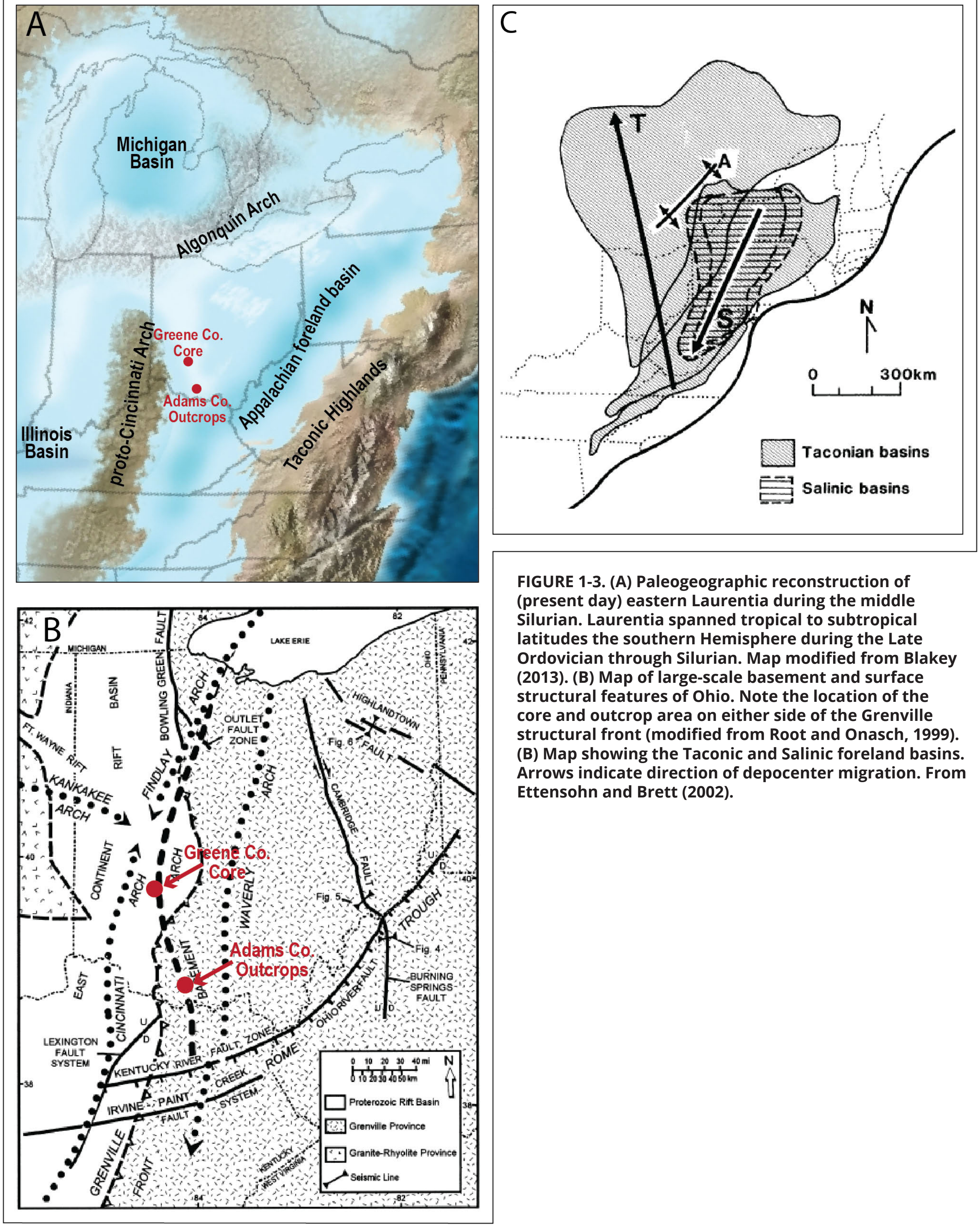


FIGURE 1-3. (A) Paleogeographic reconstruction of (present day) eastern Laurentia during the middle Silurian. Laurentia spanned tropical to subtropical latitudes the southern Hemisphere during the Late Ordovician through Silurian. Map modified from Blakey (2013). (B) Map of large-scale basement and surface structural features of Ohio. Note the location of the core and outcrop area on either side of the Grenville structural front (modified from Root and Onasch, 1999). (B) Map showing the Taconic and Salinic foreland basins. Arrows indicate direction of depocenter migration. From Ettensohn and Brett (2002).

Climate variations were not the only factor influencing sea level and the depositional environment. The Appalachian foreland basin was tectonically active during the Late Ordovician through the Silurian, which caused episodic increases in subsidence and movement of depocenters and arches across the region (Ettensohn and others, 1992; Goodman and others, 1994; Brett and Ray, 2005). The Cincinnati Group was deposited during the main phase of the Taconian orogenic phase of the Taconic Orogeny, during the accretion of the Sherburne Falls arc to the (present day) eastern margin of Laurentia (Ettensohn, 2008). A smaller "Medina tectophase" continued into the Hirnantian and earliest Silurian and created a broad foreland basin that was likely yoked (Ettensohn and Brett, 2002) to the Michigan Basin (fig. 1-3C), into which the Medina Group was deposited. Following the Taconic orogeny significant tectonic rearrangement occurred; uplift along the Findlay and Algonquin arches separated the Michigan and Appalachian Basins, and the depocenter of the basin shifted eastward (Goodman and Brett, 1994; Ettensohn and Brett, 2002). This basin rearrangement was likely due to static load relaxation—once accretion of terrains ceased, the accreted orogenic load flexed the crust downward, essentially tilting the basin back towards the Taconic highlands (fig. 1-3A). The eastward shift in basin depocenter and uplift of regional arches is recorded in the lower part of the Clinton Group. The eastward shift in the basin depocenter, combined with (presumably) lower relief along the Taconic Highlands, trapped clastic sediment in proximal setting and reduced the input of siliciclastics into the basin, respectively. The overall reduction in sediment import and transport distance allowed carbonate deposition to become more prominent in distal regions, such as southern and southwestern Ohio. During the latest Llandovery to early Wenlock, renewed tectonism, termed the Salinic Orogeny, began along the eastern margin of Laurentia, causing renewed subsidence farther into the craton and a broader basin to develop (fig. 1-3C). Crustal movement associated with these tectonic rearrangements were likely focused along basement structures (e.g., Grenville Front) and associated faults (fig. 1-3B; Root and Onasch, 1999). The dynamic tectonics of the region impacted both relative sea level and the availability and distribution of sediment sources, so it was a major controlling factor in the distribution of lithologies throughout the Appalachian Basin.

Common high-frequency cycles that can be traced basin wide are most likely produced by short-term Milankovitch related eustatic sea-level oscillations; probably of glacioeustatic origin. Disentangling regional tectonic effects from global eustatic effects on sea level at a larger scale remains a challenge. Cycles of tectonic loading and relaxation occur on timescales of 1 to 10 myr (Miall, 2010), which overlaps with the supposedly dominant ~4.5 myr Milankovitch forcing that influenced global climate during the Late Ordovician through the Silurian (Sprosen, 2020). Developing precise chronostratigraphic frameworks to constrain the ages of the sequences/cycles can help parse out tectonic from eustatic influence—if sea level changes were coincident across multiple paleocontinents, then eustasy is the likely driving mechanism. If sequences are not expressed in several paleocontinents, then regional tectonism is likely tectonic. Tectonic influence within a basin can be indicated through mapping chronostratigraphically equivalent units across broad geographical areas. Variations in geographic-thickness trends through time (depocenter migration), changes in the geographic distribution of lithofacies, and changes to the geographic location of unconformity surfaces can all point toward tectonic influence (Goodman and Brett, 1994; Brett and Ray, 2005), particularly if they are associated with basement structures known to influence sedimentation patterns over time (for Ohio structures, see Root, 1996; Root and Onasch, 1999; fig. 1-3C). In this workshop and field trip, we will be observing similar-aged strata deposited on opposite sides of the Grenville Front (fig. 1-3C).

The challenge with using three-dimensional mapping to help parse out tectonic impacts on sedimentation patterns is tying the chronostratigraphic precision available at outcrop to the geophysical data common in the subsurface. For the Silurian of the Appalachian Basin, graptolite and conodont biostratigraphy and carbon isotope chemostratigraphy (see Figure 1-1) are commonly used to determine the chronostratigraphic position of lithostratigraphic units. Tying chronostratigraphic and lithostratigraphic information from the surface to geophysical log data in the subsurface requires matching the lithostratigraphic geophysical log patterns from outcrop (gamma ray) and core (gamma-ray and other geophysical parameters) to wells in the nearby subsurface, the majority of which are represented only by geophysical logs. Correlating long distances away from lithostratigraphic control points using geophysical logs requires utilization of allostratigraphic and sequence stratigraphic principles to correlate across facies boundaries. The goals of this workshop and field trip are to:

- Provide an overview of sequence stratigraphy, both in general and as applied to the mixed carbonate/siliciclastic units of the Upper Ordovician lower Silurian in the Appalachian Basin.
- Compare and contrast key sequence stratigraphic patterns, surface, and marker beds in both carbonate and mixed siliciclastic/carbonate depositional environments. Carbonate-dominated

depositional environments are represented by a core from Greene County (southwestern Ohio; fig. 1-3). The facies of mixed siliciclastic/carbonate depositional environments will be observed in outcrop in Adams County, Ohio (fig. 1-3).

- Link the lithological and sequence stratigraphic framework developed for the core and outcrop to gamma-ray patterns in well logs. Correlations using the data from Greene and Adams Counties are shown in a cross-section network (pls. 1-1–1-5).

TECHNIQUES USED IN THIS FIELD TRIP AND CORE WORKSHOP

CARBON ISOTOPE CHEMOSTRATIGRAPHY

Carbon isotope chemostratigraphy of whole-rock carbonate samples is a technique that uses stratigraphic variation in the ratio of the stable carbon isotopes ^{13}C and ^{12}C for correlation purposes. This ratio is standardized to the isotopic signature of Peedee belemnite fossils (PDB standard), or the subsequent Vienna Peedee belemnite (VPDB standard), and deviation from the standard are reported as "$\delta^{13}C_{carb}$" in parts per mil ($^{o}/_{oo}$). The Silurian excursions most utilized for global chronostratigraphic correlation are positive excursions (an increase in ^{13}C relative to ^{12}C; see Figure 1-1) but negative excursions are also significant. One general explanation for the most likely cause of positive carbon isotope excursions, indicated by carbon-cycle modeling, involves increased primary productivity by marine organisms with a coincident increase in burial of the organic matter (Kemp and Arthur, 1999). Photosynthetic reactions preferentially use ^{12}C, which becomes incorporated into the material of organisms. If the organisms are buried rapidly before they can decompose, the ^{12}C-enriched organic matter becomes sequestered in the sediment, causing oceans to become relatively enriched in ^{13}C. The ^{13}C-enriched carbon in the ocean waters then becomes incorporated into the calcite, aragonite, and dolomite of coeval carbonate deposits. Because the residence time of carbon in the ocean is longer than the mixing time of the ocean, most carbon isotope excursions record global phenomena (Weissert and others, 2008)—albeit modified in local basins and across bathymetric profiles—and are therefore a useful tool for global chronostratigraphic correlations.

GEOPHYSICAL WELL LOGS

In basins with extensive oil and gas drilling, the most common subsurface data available are geophysical well logs. Most of the well logs in Ohio have gamma-ray, neutron porosity, and bulk-density curves. Gamma-ray curves measure how radioactive rocks are and can distinguish between radioactive lithologies such as shale and mudstone and less radioactive lithologies such as carbonates and sandstone. Neutron porosity tools measure the concentration of hydrogen in the rock—which is high in water, brine, or oil-filled pore spaces, and low in rocks with gas-filled pore spaces or rocks with low porosity. Clay minerals contain hydrate ions and cause increased neutron porosity measurements, which can be useful for distinguishing low-gamma units with slightly different amounts of clay. Bulk-density curves measure the electron density of rocks and can be used to estimate their physical density. This measurement can help distinguish between sandstone, which usually has a density around 2.65 g/cm^3 and limestone or dolomite, which have densities of 2.71 and 2.88 g/cm^3, respectively. Some more modern well logs have photoelectric factor curves (Pe), which indicate the photoelectric absorption properties of rock. The amount photoelectric absorption is related to the average atomic number of the rocks, which makes it highly useful as a lithology indicator. Even with all of these tools, only basic lithological information can be obtained at resolutions around 1–3 ft (<1 m), which can make correlation with outcropped units defined using subtle sedimentological or paleontological features difficult.

Despite these limitations, well logs are extremely useful for stratigraphic correlations and even have some advantages over geological investigations at outcrop or from core. One advantage is that logs often show complete stratigraphic context, which is rare in most outcrop studies. In regions with extensive oil-and-gas drilling, another advantage of well logs is the high geographic density of data across a broad area, far higher than what is usually available from outcrops or cores. However, for the benefits of well logs to be fully utilized, well log data must be united with chrono- and lithostratigraphic frameworks that are developed at the surface. Sequence stratigraphy offers a way to overcome some of the disadvantages of well logs and facilitate chronostratigraphically meaningful correlations from surface and core to the subsurface.

SEQUENCE STRATIGRAPHY

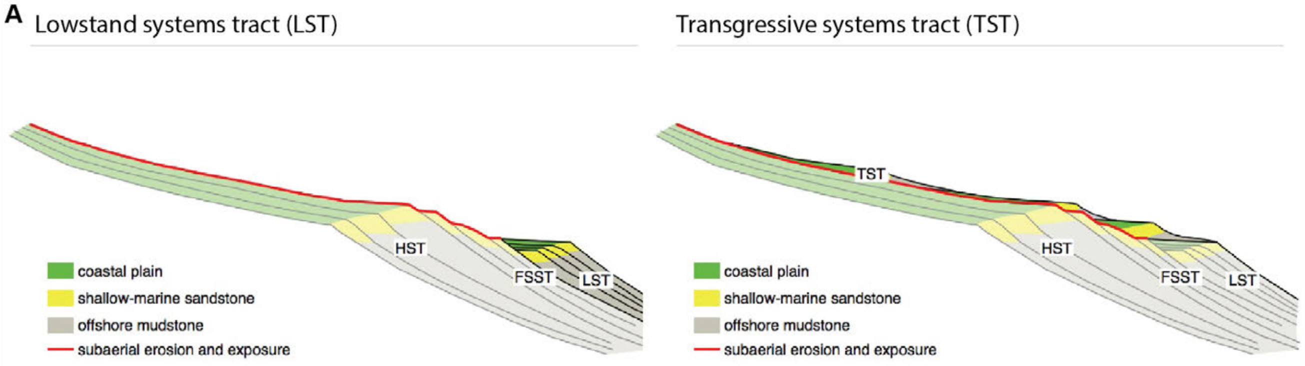
Sequence stratigraphy is an extremely useful framework for precise well log correlations and for basin-scale correlations across different depositional environments because correlations are not confined to the individual lithologies of geological units. Instead, unconformity surfaces caused by relative or eustatic sea level change are used to split up the rock record into “sequences” (Sloss, 1963). Numerous earth processes change regional and eustatic sea level, each occurring over different time scales. Sequences are classified into a hierarchy of orders based on sequence duration (e.g., Vail and others, 1977; Brett and others, 1990; Catuneaunu, 2009), and there are numerous hypotheses as to which earth processes cause sequences of particular durations (Table 1-1). The sequences observed in this workshop and field trip will primarily be third, fourth, and fifth order. Because the Appalachian Basin was tectonically active throughout the Late Ordovician through early Silurian, caution must be applied to interpretations of third-order sequences, which can have both regional tectonic and eustatic causes.

TABLE 1-1. ***Hierarchy of stratigraphic sequences. Information mainly from Miall (2010) and Boulila and others (2011).***

Order	Duration (myr)	Term	Cause
1	200–400	Supersequence	Supercontinent formation cycle
2	10–100	Sloss sequence, Megasequence	Changes in mid-ocean-ridge spreading rate
3	1–10	Sequence	Regional tectonism, Milankovitch forcing
4	0.16–1	Parasequence set/cyclothem	Milankovitch forcing, regional tectonism, sedimentation patterns
5	0.01–0.1	Parasequence	Milankovitch forcing, sedimentation patterns

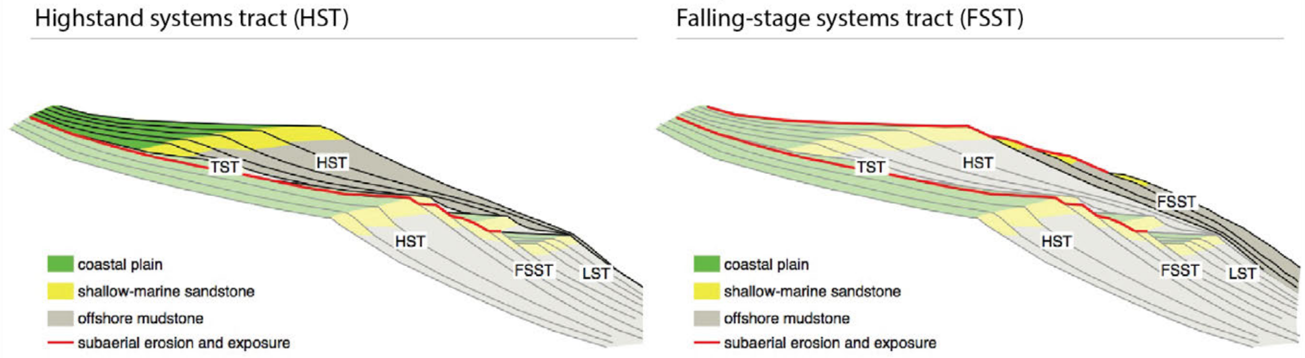
The chronostratigraphic precision of sequence boundaries depends on the rate of sea level change. For example, continental-scale second-order sequences are caused by relatively slow rates of sea level rise and fall, meaning that the unconformity bounding a second-order sequence may be diachronous on a geologically noticeable scale (millions of years). The diachroneity of higher order sequence boundaries (approximately 100 kyr and less) has often been ignored in Paleozoic stratigraphy because it is usually smaller than the general chronostratigraphic precision of Paleozoic time slices. Advances in integrated bio-, chemo-, and event-stratigraphy in the Paleozoic can produce time-slice precision of <100 kyr (Cramer and others, 2010), so future Paleozoic sequence stratigraphic research needs to consider small-scale diachroneity.

Stratigraphic patterns that indicate increasing or decreasing accommodation space (changes in sea level, coupled with subsidence and sedimentation rates) are used to further subdivide each sequence into “systems tracts.” Sequence stratigraphy was first widely applied to clastic sedimentary systems on passive continental margins using seismic profiles (e.g., Vail and others, 1977), so systems tract designations were mainly based on stratal geometry and indications of shoreline progradation or retrogradation (fig. 1-4A), and a conceptual framework was developed that linked systems tracts to base level change (fig. 1-4B). At individual outcrop (or core) scale, clastic-dominated sequences are characterized mostly by changes in grain size (fig. 1-5). Subsequent research highlighted the utility of systems tracts in tectonically active foreland basins with mixed carbonate and siliciclastic deposition (see Brett and others, 1990; Holland, 1993; McLaughlin and others, 2006). The nomenclature used to describe systems tracts in mixed carbonate/clastic environments is the mostly same as the nomenclature in clastic environments, but the lithological characteristics of each systems tract can be different (fig. 1-6).



A stratigraphic sequence begins with the lowstand systems tract. LST strata are deposited when sea level begins to rise, but at a slower rate than sediment input. This leads to a progradational facies stacking pattern. Image © Steven Holland 2019, used with permission.

The transgressive systems tract occurs when the rate of sea level rise outpaces the rate of sediment input. Early strata in a TST show retrogradational stacking, and later strata may show aggradational stacking patterns. Indications of a transgressive ravinement surface may be visible at the base of the TST, and a maximum (sediment) starvation surface (MSS) may occur near the top. Image © Steven Holland 2019, used with permission.



The highstand systems tract occurs when the sedimentation rate outpaces the rise of sea level. This causes a regressive progradational stacking pattern. The geometry of the strata in an idealized HST is similar to the strata in a LST, just higher up in the basin. The HST strata downlap onto the maximum flooding surface (MFS). At outcrop scale it is rare to find a single "surface" representing highest base level, so the term maximum flooding interval (MFI) is sometimes used. Image © Steven Holland 2019, used with permission.

The falling stage is the last systems tract of a sequence. It occurs when eustatic sea level falls at a faster rate than sediment input. This causes rapid loss of accomadation space, and causes the shorline to downstep into the basin. Strata of the FSST are difficult to distinguish from late HST and LST strata in an individual section. Image © Steven Holland 2019, used with permission.

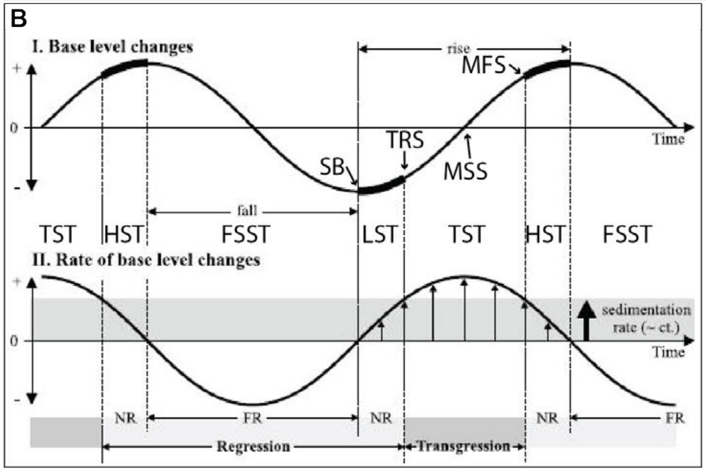


FIGURE 1-4. Sequence stratigraphic diagrams. (A) Systems tract geometry and general facies diagrams. Images from the University of Georgia Stratigraphy Lab, < https://strata.uga.edu/sequence/depositionalSequence.html>, © Steven Holland, 2019. (B) Base-level curve and rate-of-change curve with system tracts. Modified from Catuneanu and others (2009).

Lowstand systems tract (LST) deposits represent the base of a sequence and lie above an erosional sequence boundary or its downramp equivalent conformity, typically at a sharp facies change. Deposition of the lowstand occurs during normal regression when sea level rises but at a slower rate than sediment input (fig. 1-4B). During the LST the shoreline will be near its maximum basinward extent (fig. 1-4A), so in clastic environments grain size will be relatively large (fig. 1-5). In mixed carbonate/clastic environments, lowstand deposits are more likely to be clastic-rich because the shoreline is closer. Depending on paleogeographic position in the basin, the LST may be bounded at the base by an unconformity (sequence boundary). In deeper settings, there may not be a distinct lithological separation between the falling stage systems tract (FSST) and lowstand systems tract at any individual outcrop. In this case, only larger-scale stratal geometry might indicate the transition from downstepping FSST to prograding LST deposits.

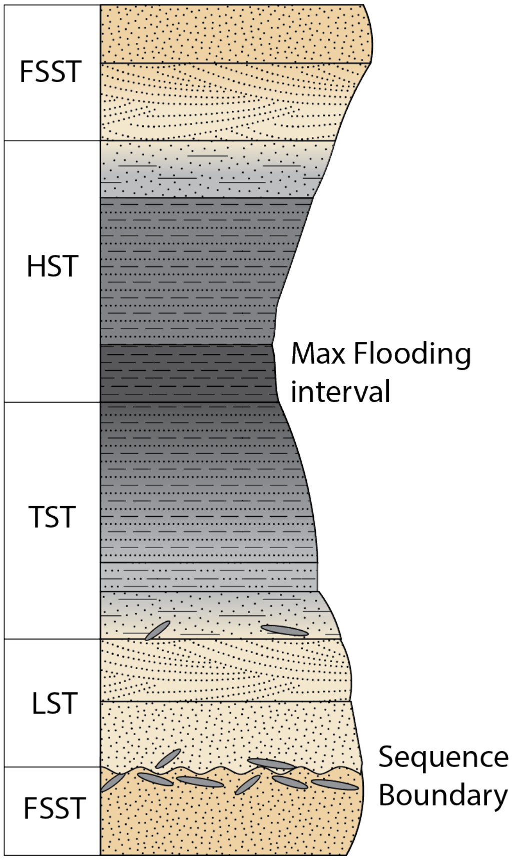


FIGURE 1-5. Generalized lithological column of a depositional sequence in a clastic setting.

Transgressive systems tract (TST) deposits show the most variation between clastic environments and mixed carbonate/clastic environments. The TST occurs when the rate of sea level rise is greater than the rate of siliciclastic sediment input. Note that the TST is the only part of a sequence in which the shoreline moves landward, i.e., transgresses (fig. 1-4B), so deposits of this systems tract commonly record evidence of marine sediments onlapping an erosional surface. In many cases, the actual boundary is a combination of erosion during a falling stage and/or lowstand and erosion by the transgressing high energy wave or tidal shoreface environments. Such transgressive erosive surfaces are referred to as ravinement surfaces and the combined lowstand and transgressive erosion surface is an E/T (erosion-transgression) surface. The ravinement surface is fundamentally diachronous at least at small scale, but assuming that it cuts through the sequence boundary, the unconformity includes a “time barrier,” i.e., all strata above the boundary are everywhere younger than everything below it (Embry and others, 2007). Significantly, when base level rises, sea water may flood coastal areas creating bays, estuaries and coastal wetlands, which serve to trap siliciclastic sediments. Whereas these areas may experience a high rate of aggradation of marginal marine sediment, offshore areas will correspondingly display relative starvation of terrigenous sediment, leading to condensed sections or, where an appropriate balance is achieved, enhanced production of carbonate.

If overall terrigenous sediment supply is low, then TST deposits in siliciclastic-dominated environments will display retrogradational stacking patterns of smaller-scale cycles (sometimes called parasequences), fining-upward successions, capped by condensed sections, and potential mineralization of sediments exposed on the sea floor for long periods of time. If the sediment input is high, nearshore TST deposits may consist of thick, aggradational to slightly retrogradational stacking patterns where grain size remains similar up section.

Lithological characteristics of TSTs in mixed carbonate/clastic environments vary depending on the types of organisms that are present, the rate of in situ carbonate production, and the amount of siliciclastic sediment supply. If overall clastic sediment supply is relatively low, clear water conditions conducive to carbonate production may occur offshore during the TST as land-derived sediment is trapped progressively farther landwards. If carbonate production rates are high (dependent upon climate, types of carbonate producing organisms, water clarity, rates of sea level rise, etc.), then limestone platforms may initially aggrade to keep up with rising sea levels and create thick, clean carbonate units (fig. 1-6). If mounding or reef-building organisms are present their net upward growth may be stimulated both by rising base level and decreasing water turbidity (favoring photosynthesizers). Where physical or biological conditions are not conducive to reef building or general carbonate expansion, TST deposits in carbonate environments are thinner and often characterized by reworking, hardgrounds, and accumulation of glauconite and/or phosphatic material (Glenn and others, 1993; Brett, 1995). Some key surfaces bounding and within the TST are, in ascending order, the transgressive ravinement surface (TRS); a maximum starvation surface (MSS, which not recognized in all models); and maximum flooding surface (MFS). As noted, a transgressive ravinement surface occurs where paleodepth is shallow enough for wave action to erode and winnow sediments as the shoreline moves landward.

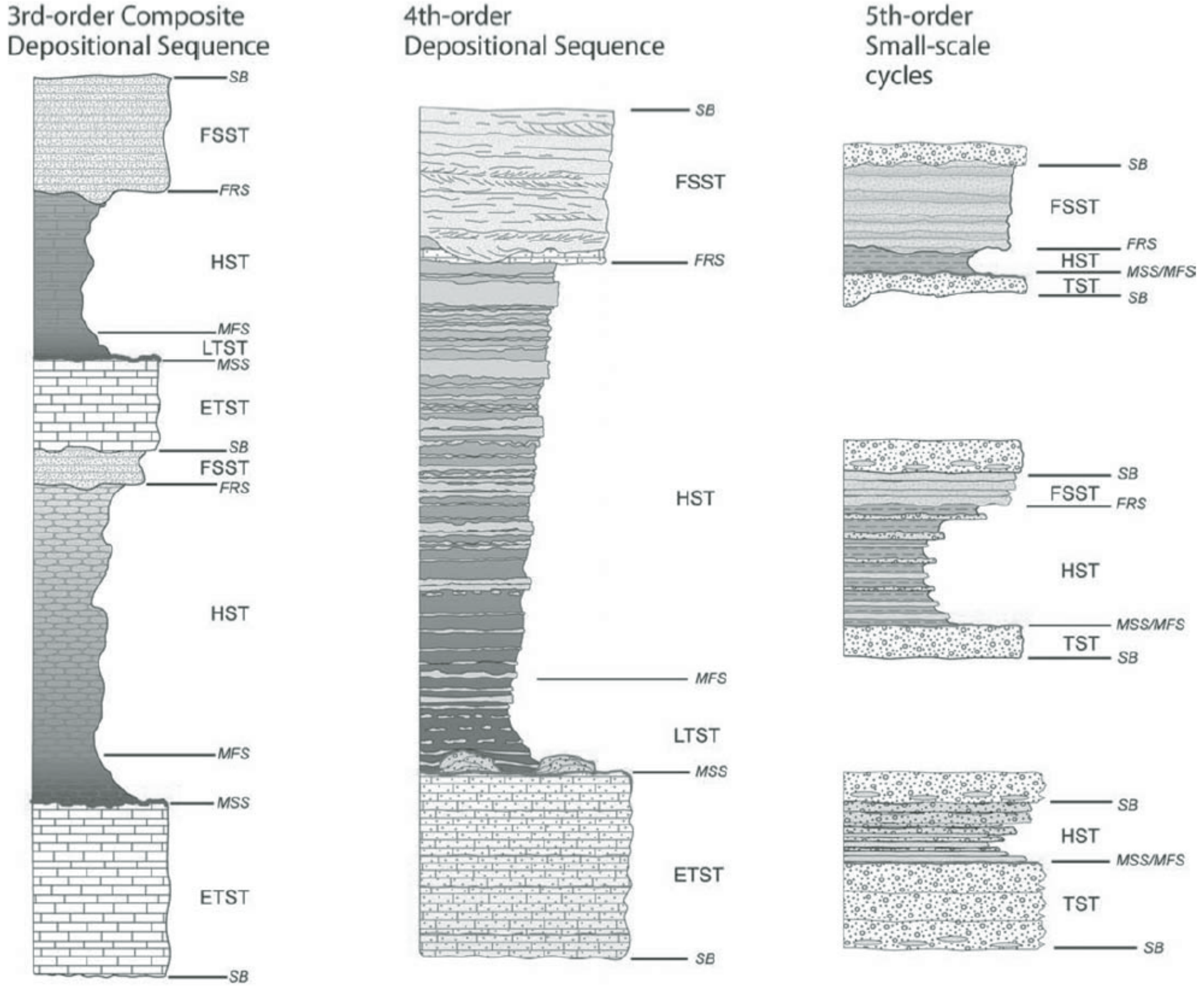


FIGURE 1-6. Generalized lithological columns for third-, fourth-, and fifth-order sequences in mixed carbonate-clastic environments. From Brett and others, (2018, modified from McLaughlin and others, 2008).

Sediments directly overlying the transgressive ravinement surface in both clastic and carbonate environments are often characterized by reworked pebble lag beds and mineral-coated grains. A “maximum starvation surface,” commonly but incorrectly identified as a maximum flooding surface, is present in some cases. This sharp contact is inferred to occur during the maximal rates of sea level rise (fig. 1-4B), when rapid generation of accommodation space traps siliciclastic sediment far onshore and “starves” the rest of the basin of sediment (Baum and Vail, 1988; Brett, 1995). For mixed clastic and carbonate systems, this surface also records a temporary giving up or at least strong reduction of carbonate sediment production, presumably because water depth increases too rapidly and/or the introduction of deeper, cooler water has a detrimental effect on the “carbonate factory.” This surface is often one of the most recognizable in the section in mixed systems, as it is characterized by very “time-rich,” condensed clastic rocks. In carbonate environments with reef-building organisms, the maximum starvation surface is often where the most mounding occurs presumably as the most rapidly growing organisms temporarily keep up with rising base level. In addition, this contact is very commonly marked by a change from pure carbonates to more muddy limestones and/or shales.

The maximum flooding surface caps the retrogradational or aggredational (deepening upward or relative static water depth) later TST, typically slightly above the MSS, and is the base of the highstand systems tract (HST). The maximum flooding surface occurs when relative sea level is at or near its highest (fig. 1-4B) and notably when the shoreline has advanced to its most inboard position. Hence, it separates transgressive from regressive deposits. In purely clastic depositional environments with condensed, but continuous, deposition, the MSS and MFS can be nearly impossible to distinguish and may be coincident, so the term “Maximum Flooding Interval” (MFI) is often used. In these clastic environments, the only way to distinguish a MFS is to observe larger-scale stratal geometry to determine the surface onto which highstand deposits prograde or a change from retrogradational or aggradational to progradational stacking patterns of smaller scale sequences. In “ideal” carbonate and mixed clastic/carbonate environments, the MSS will be the surface on which reef-building organisms mound, and the MFS will be the top of the carbonate mounds.

The highstand systems tract occurs when sedimentation rates begin to outpace sea level rise (fig. 1-4B), causing “normal regression.” During normal regression accommodation space progressively decreases from the shoreline to the deeper basin, causing sediments to prograde farther out into the basin and downlap onto the MFS (fig. 1-4A). This sedimentation pattern is similar in both carbonate and clastic environments. In mixed carbonate-clastic environments, clastic sediments usually reappear during the later TST, when rate of transgression slows to zero, and during the HST, because sediment is no longer being trapped progressively farther on shore. In individual sections the HST is characterized by progradational stacking patterns—coarsening upward parasequences in clastic settings, a transition to shallower-water organisms in carbonate settings, and an introduction of more and commonly coarser siliciclastic material, as well as detrital carbonates in mixed carbonate-clastic settings.

The falling stage systems tract (FSST) begins when sea level begins to fall (fig. 1-4B), causing “forced regression.” During forced regression, the shoreline rapidly moves both out and down slope into the basin, causing strata to “downstep” into the basin. Progressively younger deposits occur as packages at lower elevations and farther seaward (fig. 1-4A). At outcrop scale in clastic settings, the later FSST may be characterized by sudden dislocations to facies indicative of much shallower conditions, abrupt coarsening-upward stacking, and potentially sediment of various sizes due to shoreline erosion (fig. 1-5). Similarly, in carbonate and mixed carbonate/clastic environments the characteristics of the FSST are sudden shallowing, facies dislocations, the introduction of more, and commonly coarser, siliciclastic, as well as detrital carbonate sediments, and potentially erosive rubble (fig. 1-6). The base of the later portion of the FSST may be a sharp, erosive surface at which shallow water, shoreface sediments abruptly overlie more offshore and typically muddier facies. This surface, which can be confused with a sequence boundary, is a regressive surface of marine erosion formed as the high energy shoreface migrates basin ward. Thus, it is the regressive counterpart of a ravinement surface.

The FSST is usually not preserved in relatively shallow parts of a basin, as it is completely removed by the sequence-bounding unconformity. In deeper settings where the FSST is preserved, it is separated from the overlying LST by an unconformity surface or the so-called “correlative conformity,” which correlates to the sequence bounding unconformity. At large scales the transition from FSST to LST is characterized by a shift from downstepping geometry to prograding sediment geometry (compare LST and FSST diagrams in fig. 1-4A). At outcrop scale, the boundary between the FSST and LST will be the sequence bounding unconformity. If an unconformity is not present, then the transition between FSST and LST may not be distinguishable at outcrop scale.

In shallower parts of a basin, the FSST and LST are least likely to be preserved and, in some cases, most or all of the HST is removed by erosion at sequence boundaries (created in upramp areas during and at maximum extent of sea level fall) leaving, sometimes preferentially thickened, aggradational to retrogradational TST deposits. This is the case for the uppermost Ordovician and lower Silurian strata of southwestern and central Ohio, which were on the western flank of the Appalachian Basin (fig. 1-1). In central Ohio, the TST and HST of each sequence are generally preserved, and in some cases in southwestern Ohio, only the TST and/or lowest portion of each sequence is preserved. All other parts of the depositional sequences were removed at sequence bounding erosion surfaces. In eastern Ohio, parts of the LSTs of smaller-order sequences may be preserved in some of the lowermost Silurian strata.

Caution must be maintained when making correlations based on sequence stratigraphic interpretations. Sea level change, and sometimes sedimentation patterns, are cyclical, so they are non-unique features of the stratigraphic record. This leaves the possibility open that sequences can be miscorrelated to one another, especially across areas with numerous unconformities. Unique stratigraphically preserved events, such as the origination or extinction of organisms, time-specific facies, and biostratigraphically constrained carbon isotope excursions, need to be incorporated into correlations as much as possible to ensure that sequences are not miscorrelated.

LATE ORDOVICIAN AND LOWER SILURIAN STRATIGRAPHY OF OHIO

Upper Ordovician stratigraphic terminology in southern Ohio and in the adjacent subsurface is mostly adopted from Ohio outcrop-based nomenclature, which is reasonably uniform. An exception is the region of Adams County in which Kentucky terminology has been locally applied. Thus, the interval subdivided into Arnheim, Waynesville, Liberty, and Whitewater formations (in part) in other parts of the state are locally termed “Bull Fork Formation,” a general facies term for upper Cincinnatian fossiliferous thin bedded shales and limestone, extended from adjacent Kentucky (Weir and others, 1984). However, given that each of the formations can be identified based on widespread discontinuities and condensed marker limestone beds, we suggest that “Bull Fork” is an unnecessary and imprecise term both in southern Ohio and in northern Kentucky and we suggest abandoning the term in both areas. Elsewhere in Kentucky, the Bull Fork, if used at all, is applied to just the Arnheim Formation and all of the remaining upper Cincinnatian strata are referred to as the “Drakes Formation.”

The Cincinnati group is an informal subdivision, and if retained in a formal sense, it should be defined to encompass three subgroup divisions comprising some 600 ft (200 m) of shale, siltstone, and limestone-fossiliferous pack and grainstone formerly divided into Eden, Maysville, and Richmond groups. However, it has been recommended that these terms should be abandoned given that they are used in modified form for chronostratigraphic divisions, viz Edenian, Maysvillian, and Richmondian (USGS Geolex). In the present contribution, we focus only on the upper or Richmondian strata. We suggest that the interval might be termed the Drakes subgroup, as most of what is recognized as Richmondian strata to the north is encompassed within the term Drakes and its members, informally raised to formation rank in Brett and others (2020). The Drakes subgroup correlates to individual formations to the north: Waynesville (Rowland member), Liberty (Bardstown member), Whitewater and Elkhorn combined (Preachersville Member). We further suggest herein that the term Preachersville Member be restricted to the uppermost greenish-gray to maroon shale-rich division and extended into Ohio as the main, shaly member of the Elkhorn Formation. For the present study, we use the formation terms Arnheim, Waynesville, Liberty, Whitewater and Elkhorn formations, divided into formal and informal members which have recently been redefined as allostratigraphic/lithostratigraphic units: Arnheim, with Sunset and Oregonia members, Waynesville with Fort Ancient, Clarksville, and Blanchester members, Liberty and Whitewater, not formally divided at present, and Elkhorn Formation with lower limestone and upper Preachersville Shale Member. These terms are readily extended into the subsurface to the north of the Ordovician outcrop belt and these correlations have been corroborated with carbon isotopic studies (Farnam and others, in prep).

Holland (1993) and Holland and Patzkowski (1997) divided the Cincinnatian strata into a suite of third-order (million year-scale) depositional sequences, C1–C6. Recent detailed study has resulted in a further subdivision and recognition of two additional disconformity bounded sequences in the Richmondian Stage and a series of smaller fourth-order subsequences (Aucoin and Brett, 2016; Brett and others, 2020). These are C1: Kope and equivalent Clays Ferry Formations (Edenian Stage); C2: Fairview Formation; C3: Bellevue and Corryville members of Grant Lake Formation; C4: Mount Auburn member and Arnheim Formation; C5 (sensu stricto): Lower Waynesville; C6: upper Waynesville and Liberty formations; C7: Whitewater Formation; and C8: (formerly C6), Elkhorn Formation. Only the upper (Richmondian) units are discussed herein.

Silurian nomenclature in Ohio is more complex, with three formal and one informal (subsurface) nomenclature schemes used throughout the state. Unit names are mostly correlated into Ohio from surrounding states. Many terms for the units exposed in southwestern Ohio are from Indiana and Kentucky, Silurian units exposed in southern Ohio are primarily from Kentucky, and terms for subsurface Silurian units in eastern Ohio are a mix of drillers' terms (e.g., "Clinton sands," see Pepper and others, 1953) and New York/Ontario units, in some cases incorrectly correlated. Terminology from southern and southwestern Ohio is used for the outcrop and core examined in this trip and workshop, and some terminology from New York is used in Plates 1-1 through 1-5, and while discussing the chronostratigraphic and sequence stratigraphic correlations of Ohio outcrop units (fig. 1-2). The revisions to Silurian nomenclature of southern Ohio proposed in Waid (2018) are followed in this guidebook. The revisions were minor and align the lithostratigraphic nomenclature of southern Ohio with sequence stratigraphic interpretations for the basin (e.g., Brett and others, 1990, 1998; Brett and Ray, 2005; McLaughlin and others, 2008; Sullivan and others, 2016). The Silurian sequence stratigraphic framework for the Appalachian Basin was first developed by Brett and others (1990), based on the classic Silurian exposures of New York and southern Ontario. Their naming convention (S-I, S-II, etc.) for third-order sequences has remained in use by most subsequent researchers. Higher-order subsequences within a third-order sequence are designated with letters (e.g., S-1A). North American sequence naming conventions for the Ordovician generally follow Holland (1993), who named third-order sequences based on North American regional stages (e.g., C1 for the first sequence in the Cincinnatian Stage).

Stratigraphic columns, geophysical log data, and existing carbon isotope ($\delta^{13}C_{carb}$) for the core and outcrop viewed in this workshop are presented in Figures 1-7 and 1-8, respectively. More detailed information on the stratigraphy covered in this trip and workshop are presented below. Descriptions of the subsurface well log characteristics of the Medina and Clinton Group units will also be described; however, the well-log characteristics of Cincinnati Group strata are poorly understood and are beyond the scope of this field guide.

CINCINNATI GROUP—SEQUENCE C5

Lower Waynesville Formation (Fort Ancient and Clarksville Members) southern/southwestern Ohio

The Waynesville Formation consists of 50–100 ft (15–30 m) of sparsely fossiliferous, medium-gray mudstones and shales with some thin-bedded fossiliferous limestones (muddy packstones and grainstones). The basal Fort Ancient member is up to 40 ft (12 m) thick in its type area and shows four unequal divisions, consisting of: a basal-thin, (~3 ft; 1 m) bioturbated silty packstone with abundant fragmentary shells and phosphatic molds of small gastropods; the Southgate Hill Submember, a lower division of sparsely fossiliferous shale with a few minor packstones, a middle division of interbedded shale and thin-bedded brachiopod-rich (predominantly *Cincinnetina meeki* and *Rafinesquina*) packstones;the Bon Well Hill Submember of Aucoin and Brett (2016); and an upper relatively thin (<6 ft; < 2 m) but distinctive sparsely fossiliferous soft olive-gray clay shale noted for well-preserved trilobites, bivalves, nautiloids and other fossils known as the Harpers Run Submember. The Fort Ancient Member thins dramatically to the southeast in the Ohio outcrop belt.

The Clarksville Member is a relatively thin (~18–27 ft; 5–8 m) interval that commences with a cluster of richly fossiliferous pack- to grainstones with a rich fauna dominated by the small orthid brachiopod *Cincinnetina meeki*, but with the appearance of numerous new immigrant taxa including the rugose coral *Grewingkia* and brachiopods including *Eochonetes clarksvillensis*, *Strophomena planumbona*, *Hiscobeccus capax*, and others. Aucoin and Brett (2016) identified this interval as the Clarksville phase of the Richmondian invasion (see Holland and Patzkowsky, 2007; Stigall, 2010). The Clarksville is currently assigned to the upper C5.

Chronostratigraphy of C5

The Waynesville and Liberty formations are assigned to Katian time slice 3. The base of the Waynesville Formation lies at or near the base of the *Amorphognathus ordovicicus* Biozone of the North Atlantic conodont zonation (Bergström et al, 2010). The middle Fort Ancient lower Bon Well Hill Submember shows the peak values of the lower prong of the Waynesville excursion with values of about $1^{o}/_{oo}$. Following a small negative excursion in the Harpers Run to basal Clarksville Member there is a second slightly lower peak in the lower Clarksville Member.

CINCINNATI GROUP—SEQUENCE C6

Upper Waynesville Formation (Blanchester Member) and Liberty Formation

The Blanchester Member of the Waynesville Formation in the southeastern parts of the outcrop belt is about 30 ft (9 m) thick and consists mainly of shale but with some distinctive intervals of limestone, particularly in the basal unit which is characterized by abundant *Cincinnetina*, but associated with three species of invasive brachiopods, which occur only at this level within the member: *Glyptorthis insculpta*, *Retrosirostra carleyi*, and *Catazyga headi*. This bed appears to correlate southward into Kentucky with a major coral and stromatoporoid biostromal bed (Owingsville Bed) which overlies a regionally angular unconformity recognized by Brett and others (2015) and Aucoin and Brett (2016) as the mid-Richmondian unconformity. The upper Blanchester Member is sparsely fossiliferous shale with some distinctive beds of *Rafinesquina* (typically as edgewise coquinas: "Disturbed Beds" of previous authors), *Vinlandostrophia*, and other brachiopods and ramose bryozoans; the Richmondian invading taxa are less common and restricted to a few beds.

The Liberty Formation is comparable in thickness (25–30 ft; 7.5–9 m) and consists of richly fossiliferous packstones and shales with a series of distinctive intervals that are widely traceable and could be proposed as members and submembers. The Liberty shows the peak development of the Richmondian faunas that include abundant rugose and tabulate corals, and diverse brachiopods.

Chronostratigraphy of C6

The Blanchester and Liberty Formations lie within Katian timeslice Ka3 and yield conodonts of the *A. ordovicicus* Zone. An uppermost minor positive excursion occurs low in the Blanchester Member while the lower Liberty is recorded everywhere by a distinctive, short-lived negative excursion as low as - $2^{o}/_{oo}$, termed the "Liberty low" by Aucoin and Brett (2016) see also Brett and others 2020). This is a particularly useful marker that corroborates physically identified Liberty Formation in the subsurface.

CINCINNATI GROUP—SEQUENCE C7

Whitewater Formation

The Whitewater Formation in southern Ohio consists of 40–60 ft (12–18 m) of fossiliferous, thin-bedded, tabular and nodular shaly packstone and shale with the shale proportion increasing as the unit thins to the southeast. To the north it thickens to over 100 ft (30 m) in the central Ohio subsurface and shows intervals of greenish- and dusky-brown maroon shale. The basal boundary of sequence C7 is sharply set off in Adams and Highland Counties where it is marked by a distinctive firmground siltstone bed ("turkey track bed") that rests sharply on underlying sparsely fossiliferous fine grained grain stones of the upper Liberty. The sharp basal contact is overlain by a basal 3–5-ft-thick (1–1.5 m), shaly, micritic limestone zone with the abrupt incursion of Whitewater taxa such as the distinctive coiled nautiloid *Charactoceras* and a number of other rare molluscan species; this interval may record lowstand deposits. An overlying interval with distinctive thin beds of reworked bored and encrusted cobbles as well as beds packed with corroded and bored rugose corals (*Grewingkia*) may represent lag deposits associated with a strongly condensed transgressive interval. Higher beds are a mix of fossiliferous nodular shaly limestones and shales. We tentatively correlate the lower half of the Whitewater Formation of Ohio into dolomitic rugose coral *Tetradium* beds of the lower Saluda Formation (north Madison Member of Brett and others, 2020) and the upper half to the upper Saluda (Hanging Rock Member) in part. The contact between these units is obscure but appears to be marked by a widespread thin black shale and overlying barren micritic beds.

Chronostratigraphy of C7

The Whitewater Formation is assigned to the uppermost Katian timeslice Ka-4. Its base is considered to approximate the *Amplexograptus manitoulinensis–Dicellograptus complanatus* Biozone boundary based upon indirect correlations of the lower minor (~0 $^{o}/_{oo}$) positive carbon isotope excursion identified by Bergström and others (2010) as the Whitewater excursion correlative with the Moe excursion of Estonia (Bergström and others, 2019).

CINCINNATI GROUP—SEQUENCE C8

Elkhorn (upper Drakes Formation) (southern/southwestern Ohio)

The Elkhorn Formation consists of medium-gray siltstones, silty, sparsely fossiliferous silty dolostones overlain by greenish-gray to maroon-red silty shale, and some interbedded fossiliferous limestones. The maroon shales (upper part of Preachersville Member) are interpreted as distal tongues of the Queenston Shale of the Appalachian Basin. These red beds can be seen throughout Ohio and Kentucky. The red beds may also be the result of redox effect explained by McLaughlin and others, (2012) regarding the Silurian red beds of the Appalachian basin. The Silurian red beds were deposited during times of deepened oxic water columns and lower abundance of organic matter that resulted in little to no organic carbon flux to sediments and preserved the primary red color of the iron-rich clay sediments. This hypothesis could also explain the late Ordovician-aged Elkhorn red beds.

The basal and upper bounds of the Elkhorn Formation have been loosely described due to its gradational relationship with the underlying Whitewater Formation and an overlying unconformity that varies in intensity across the region. Observations by Cummings (1908) and Shideler *in* Marak (1994) as well as recent field studies revealed a zone of limestones contain the brachiopod *Rhynchotrema dentata* in abundance that can be recognized from Richmond, Indiana, to Dayton, Ohio. This zone has yet to be recognized in southern Ohio. The abrupt basal contact of the *R. dentata* zone limestones, or locally, in southern Indiana an interval of desiccation-cracked micrites (upper tongue of Saluda lithology) provides an objective base for the Elkhorn Formation (Brett and others, 2020). The upper boundary is bit more complex since the upper Elkhorn is separated from the overlying Whippoorwill formation by the Cherokee unconformity. This unconformity differs across the basin and can erode the upper Elkhorn Formation to varying levels. A second unconformity also exists above the overlying Whippoorwill formation and can combine with the lower unconformity in some Kentucky localities, which results in the Brassfield directly overlying the Elkhorn Formation.

Chronostratigraphy of C8

The Elkhorn Shale preserves very few biostratigraphically useful fossils, but Grahn and Bergström (1985) assigned the Preachersville to the Ashgill Stage (presently termed upper Katian Stage; Late Ordovician) based on the presence of the chitinozoan *Ancyrochitina merga*. The Preachersville Member shows steadily rising values of the Elkhorn (or Paroveja) excursion (Bergström and others, 2010, 2019) with peak values near +2 ($^{o}/_{oo}$) associated with the lower part of the maroon shale in a core from the Fairborn quarry near Dayton. Uppermost green shales, which locally carry a typical Richmondian fossil assemblage (Shideler, *in* Marak, 1994), show slightly descending value below the sharp though cryptic contact with the Centerville Member. The latter shows a return to positive values with a peak similar to or slightly higher than the Elkhorn Peak (Farnam and others, 2019). Our data corroborate the evidence of Bergström and others (2011) that the Elkhorn (Paroveja) and HICE are separate excursions. Assuming the maroon Preachersville shales record the peak and very initial falling limb of the Elkhorn excursion, the Preachersville is predicted to correlate to strata bearing upper *D. complanatus* to lower *Pacificograptus pacificus* Biozone fauna of the late Katian; however, the absence of graptolites means that this zonation cannot be tested at present. Our results further suggest that the supposed lower Hirnantian (HICE) elevated values noted by Bergström and others (2011) in the upper Queenston red shale of Ontario may instead be part of the Elkhorn excursion.

MEDINA GROUP—SEQUENCE H1(?)

Whippoorwill formation (southwestern/southern Ohio, central Ohio subsurface)

The Whippoorwill formation of Waid (2018) is composed of the Centerville and overlying Belfast members (formerly assigned as members of the Brassfield Formation). It is separated from the underlying Elkhorn Formation (equivalent to the Queenston Shale to the northeast) by the large-scale but subtle Cherokee unconformity, which probably represents emergence and erosion during a global lowstand associated with maximum ice extent in Gondwana regions during the late Ordovician glaciation. In southern and central Ohio, the Centerville Member is a bluish-gray silty shale interbedded with gray, slightly calcareous siltstone beds. In some locations, there are occasional laminae and thin interbeds of very light-gray, fine-grained quartz sandstone, which are interpreted as distal stringers of the Whirlpool Sandstone (a prominent sandstone traditionally used to mark the base of the Silurian in New York and Ontario, and in the subsurface of northeastern Ohio). The Belfast Member is composed of two distinct units. The lower unit, “Belfast A,” is a bioturbated, occasionally glauconitic packstone of skeletal fragments. The upper unit, “Belfast B,” consists of thin, silty, somewhat nodular to wavy carbonates interbedded with gray silty mudrock. The Belfast Member is characterized by the presence of firmgrounds and hardgrounds, indicated by *Thalassinoides* burrows and *Trypanites* borings, which require firm to lithified sediment, respectively, to be preserved. Glauconite accumulations indicate slow deposition in offshore marine settings.

H1(?) in well logs

The Whippoorwill formation in well logs is subtle and difficult to identify. Oftentimes it can be distinguished only by precisely correlating the upper and lower bounding units (Brassfield Formation and Elkhorn/Queenston, respectively), and noting that an additional unit lies between. The silty and slightly calcareous Centerville Member is generally expressed as a descending gamma-ray trend from the underlying Elkhorn in southern Ohio (figs. 1-8 and 1-9), and where more expanded may show a gamma-ray (and bulk density, if the curve is present) low at the base where sandy stringers correlative to the Whirlpool Sandstone are present (fig. 1-9). The overlying Belfast Member is generally easier to identify than the transitional Centerville. Where both submembers of the Belfast are present, the Belfast A carbonate bed is identified as being lower gamma (figs. 1-8, 1-9) and higher bulk density (see examples on Plates 1-2 and 1-3) that the underlying Centerville or Elkhorn/Queenston (where Centerville is absent). Throughout most of the study area, the more argillaceous Belfast B beds are usually indicated by slightly elevated gamma-ray values compared with the underlying Belfast A and overlying “lower massive Brassfield” (fig. 1-9), but in southwestern Ohio the Belfast generally shows progressively lowering gamma-ray values from bottom to top (fig. 1-8). Deeper into the basin the Centerville becomes more sandy and correlates to the Whirlpool Sandstone, which is characterized by low gamma-ray and low bulk-density values. The lower, more carbonate-dominated part of the Belfast (Belfast A) correlates to the Manitoulin Formation, a muddy carbonate, and the upper, shaly part of the Belfast (Belfast B) becomes thicker and shalier deeper into the basin and correlates with the Power Glen Shale of New York/Ontario (pls. 1-2 and 1-3).

Chronostratigraphy of H1(?)

Subsurface correlations from Adams County to southeastern Ohio using geophysical well logs (Waid, 2018) and studies of cores from central to northern Ohio (Farnam and Brett, 2021) indicate that the Centerville merges to the northeast with the Whirlpool Sandstone and the Belfast with the overlying Manitoulin Dolostone and possibly lower Power Glen formations. If these correlations are correct, then the Centerville represents the distal edge of third-order LST/ early TST deposits, and the Belfast A and B represent a higher order (fourth or fifth?) TST/early HST pair superimposed on the late TST/HST of the third-order sequence. The Whirlpool and lower Manitoulin formations in southern Ontario have yielded a 2.5 $^{o}/_{oo}$ positive excursion (Bergström and others, 2011). Such a strong positive excursion is uncharacteristic of the lower Silurian Rhuddanian Stage but consistent with a mid-Hirnantian age associated with the upper prong of the Hirnantian isotopic carbon excursion (HICE); i.e., after the stronger early Hirnantian phase of the HICE.

Recent work has demonstrated an excursion of similar magnitude in the Centerville Member of southern Ohio, including a drill core from near Dayton and outcrops in Adams County, corroborating a Whirlpool/lower Manitoulin correlation. The overlying Belfast Member shows a drop to low values comparable to the upper Manitoulin on Manitoulin Island and the Bruce Peninsula of Ontario, suggestive of a latest Hirnantian to earliest Rhuddanian age.

If the Centerville-lower Manitoulin $\delta^{13}C_{carb}$ values indeed represent the peak and falling limb of the later part of the HICE excursion, then these units should fall correlate to *M. persculptus* graptolite Biozone strata, and the Cherokee unconformity should then encompass the upper part of the latest Katian *P. pacificus* Zone and the lower Hirnantian *M. extraordinarius* Zone and should perhaps represent a hiatus of less than a million years.

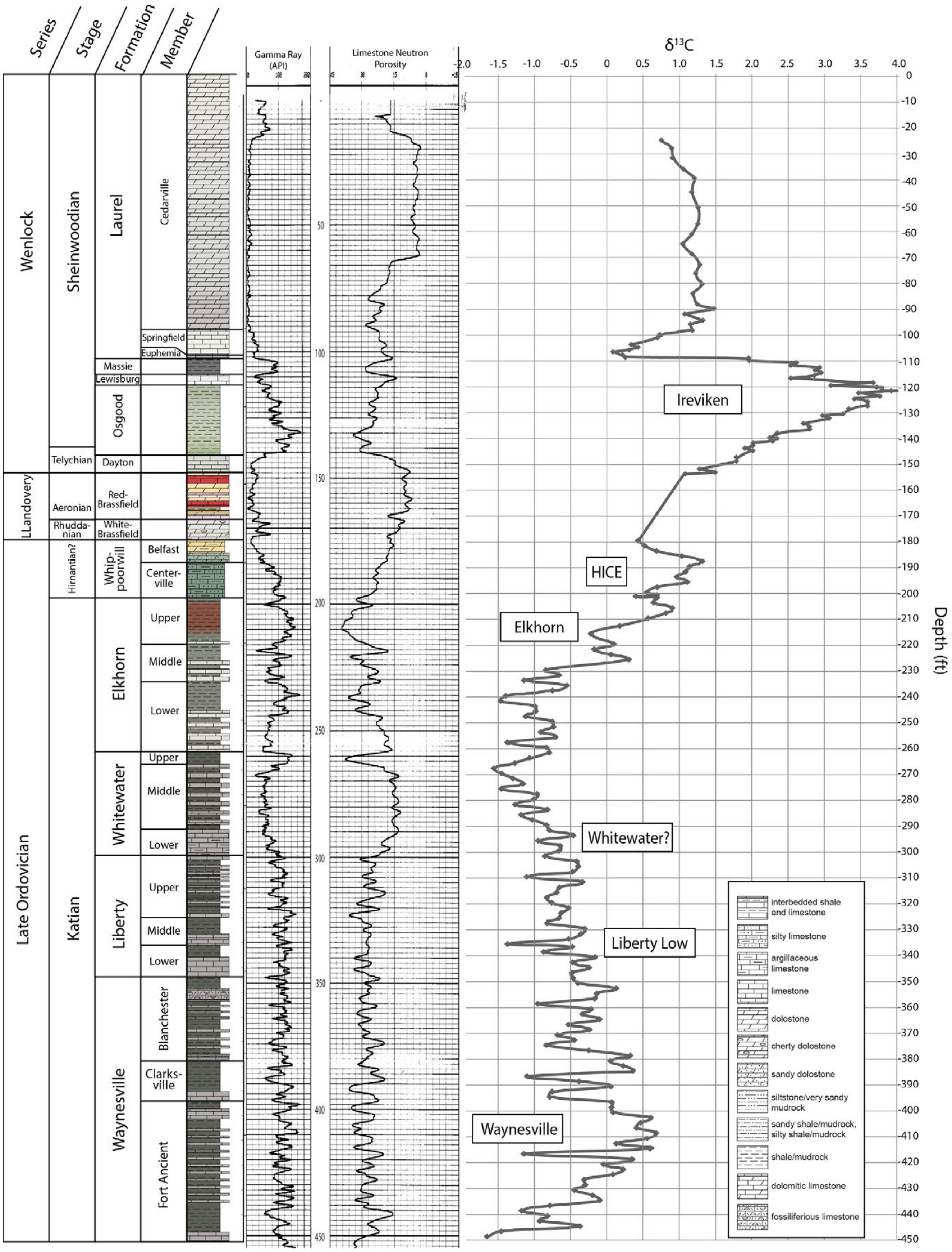


FIGURE 1-7. Stratigraphy of OGS Core 3245, Greene County, Ohio. Left to right: lithologic column, well log with gamma ray and neutron curves, and δ13C carbon isotope curve (Dayton and above modified from Cramer, 2009).

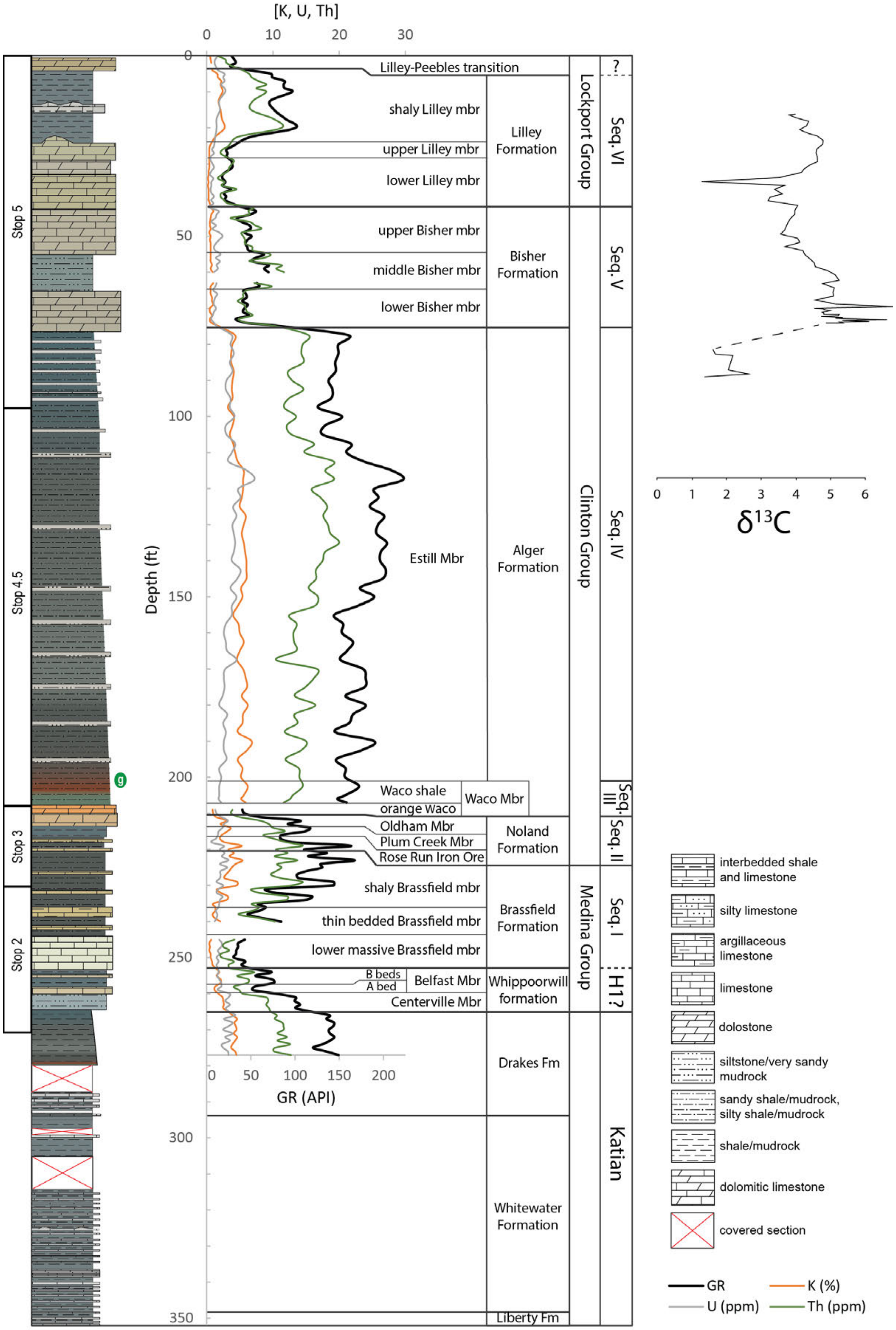


FIGURE 1-8. Stratigraphy of Adams County, Ohio sections. Left to right: composite lithologic column, spectral gamma-ray curve (from handheld GR Spectrometer; Waid, 2018), and δ13C carbon isotope curve (modified from Cramer, 2009). Carbon isotope profile is limited, but it does show the Ireviken Excursion in the Bisher and Lilley Formations.

MEDINA GROUP—SEQUENCE S-I

Brassfield Formation

The unit known as the “Brassfield Formation,” “Brassfield Dolomite,” or “Brassfield Limestone,” is found in western Tennessee, Kentucky, Ohio, and Indiana. Local informal members are commonly used because the lithology of the Brassfield varies considerably over such a large geographic area. Additionally, the unit, as presently recognized, spans different chronostratigraphic intervals in different regions—the so-called “red” or “golden” Brassfield” on the western side of the Cincinnati Arch is entirely younger than the Brassfield on the eastern side of the Arch (Ettensohn and others, 2013) and is probably equivalent to the Oldham Member of Kentucky, which is separated from the true Brassfield by a major sequence boundary (Brett and Ray, 2005; McLaughlin and others, 2008). Therefore, the “red facies” is not appropriately termed Brassfield and the name is only used here provisionally, because of historical precedence. The Brassfield proper contains one formal and four informal members at its type area in central Kentucky (Ettensohn and others, 2013) and all of these members are also present in southern Ohio. (Note: we are treating the Belfast as a member of the Whippoorwill formation and not as a member of the Brassfield Formation, as originally designated.)

Lower massive, thin bedded, and upper shaly Brassfield members (southern Ohio, central Ohio subsurface)

These informal members of the Brassfield are units from the type area in Kentucky (Gordon and Ettensohn, 1984). The lower massive member of the Brassfield sharply overlies the Belfast Member (of Whippoorwill Formation of Waid, 2018) and locally rests directly on upper Katian shales, where the Whippoorwill formation is entirely cut out. It is considerably more massive and resistant to weathering than the underlying Belfast B and lower, Ordovician units and weathers to a strongly overhanging ledge. The unit is a generally fossil-rich, massive packstone to grainstone with evidence of hardgrounds.

Occasional golf-ball- to fist-sized nodules and thin, patchy beds of pale-gray to white chert are present. The contact between the lower massive Brassfield and overlying thin-bedded Brassfield is gradational in the Brassfield type area of central Kentucky and is usually placed at the lowest occurrence of consistently thin (3–6 in) beds (for example, see Ettensohn and others, 2013). The contact between the lower massive and thin-bedded Brassfield members is gradational in Ohio as well, where the thin bedded Brassfield consists of thin dolo-bio-wacke- to packstones interbedded with slightly calcareous, medium-gray shales. The thin-bedded Brassfield becomes progressively shalier upsection, and grades into the overlying upper shaly Brassfield. The lower massive Brassfield represents the TST of S-1, the thin-bedded Brassfield represents the late TST, and the deposits of the shaly Brassfield are the earliest part of the HST of S-1. The lower massive member may correlate to the upper Devils Hole Member, especially the sandy and locally cherty, phosphatic, bryozoan-rich packstone of the Artpark Beds (Brett and others, 1995). The thin-bedded Brassfield may be approximately equivalent to the lowermost Grimsby Formation (lower Grimsby Shale) in New York State.

White Brassfield (southwestern Ohio)

The “white Brassfield” is an informal unit that is widespread in southwestern Ohio. It is a grainstone with irregular thin to medium beds and prominent stylolites at some of the bedding contacts. The white Brassfield likely represents the TST of S-I, and therefore correlates to the lower massive Brassfield of southern Ohio. The underlying Belfast B is progressively truncated underneath the lower massive and white Brassfield from southern to southwestern Ohio.

S-I in well logs

The Brassfield Formation in Adams County generally exhibits a trend of increased gamma-ray values upsection. The lower massive Brassfield is the thickest, cleanest carbonate of the formation, so it has the lowest gamma-ray values. In well logs with bulk-density and photoelectric curves, the lower massive often has higher bulk-density and Pe values than the underlying Whippoorwill Formation or overlying thin-bedded Brassfield member. As the thin-bedded Brassfield and shaly Brassfield members become progressively muddier upsection, the gamma-ray values increase and reach their maximum values in the shaly Brassfield (fig. 1-9). In more clastic-rich settings (pls. 1-2 and 1-3), the thin-bedded Brassfield is muddier and has higher gamma values than in Adams County. In some wells the thin-bedded and shaly Brassfield have nearly identical gamma values but can be distinguished by the higher bulk-density and photoelectric values of the more carbonate-rich thin bedded Brassfield. In eastern Ohio (pls. 1-4 and 1-5), where the Medina Group becomes much more clastic dominated and begins to resemble more the Medina Group of New York, the lower massive Brassfield is the only remaining carbonate.

In southwestern Ohio, the white Brassfield shows gamma values typical of carbonate rocks—low gamma values (fig. 1-8) with concurrent high bulk density. The muddier (and therefore higher gamma) upper units of the Brassfield Formation were either never deposited or were eroded during the S-I/S-II sequence boundary in southwestern Ohio.

In eastern Ohio, S-I becomes much sandier, and is better described using New York Medina Group terminology or a mix of Ohio and New York terms (pls. 1-4 and 1-5). The sandstone units can be distinguished from carbonate units by bulk density and photoelectric curves, if available. Sandstones are generally much less dense than carbonates, so they have both lower gamma-ray and lower bulk-density values, in contrast to carbonates which have lower gamma-ray and higher bulk-density values. The photelectric factor curve will also be lower in sandstone and higher in carbonates. The Grimsby Formation consists of three informal members. The lowest is the “lower shale,” which can have some discontinuous sandstone interbeds, and is characterized by generally high, uniform gamma-ray values in some wells, and a sawtooth pattern of gamma ray on wells with sandstone interbeds (see lateral variation in unit on Plate 1-5). The next unit is a “middle sandstone” which has variable thickness and a variable number shale interbeds across the study region (pls. 4 and 5) and is characterized by low bulk-density, low photoelectric, and low gamma-ray values with occasional gamma-ray spikes if where shale interbeds are present. The “upper shale” of the Grimsby Formation is lithologically variable—it can range from a relatively thick, high-gamma shale to a sandstone that is more argillaceous that the underlying middle Grimsby sandstone or the overlying Thorold Sandstone. The Thorold Sandstone has variable thicknesses, and is identified by low bulk-density, gamma-ray, and photoelectric values compared with the underlying upper Grimsby shale and overlying Cambria Shale. The Cambria Shale is the uppermost unit of S-I in the study area (pls. 1-4 and 1-5) and is a moderate to high gamma-ray-value shale.

Chronostratigraphy of S-I

The age of the Brassfield Formation (and the white Brassfield in southwestern Ohio) is poorly constrained by direct methods. Conodonts recovered from the unit all are indicative of the *Distomodus kentuckyensis* Biozone (e.g., Cooper, 1975; Kleffner in McLaughlin and others, 2008), which spans the Hirnantian through middle Aeronian (lower Silurian) stages. No useful carbon isotope excursions have been found in any of the units. Berry and Boucot (1970) assigned the Brassfield to the late Rhuddanian through middle Aeronian stages, based on brachiopods. This age assignment is not contradicted by correlations to surrounding regions. The minimum age of S-I is well constrained in western New York. Waid and Over (2015) recovered elements of the lower to middle Aeronian conodont *Pranognathus tenuis* from the Densmore Creek Phosphate Bed (LoDuca and Brett, 1994). The Densmore Creek Phosphate Bed is the basal unit of S-II, so S-I can be no younger than middle Aeronian.

CLINTON GROUP—SEQUENCE S-II

Noland Formation (southern Ohio, central Ohio subsurface)

The Noland Formation (*sensu* Waid, 2018) consists of (in ascending order) the Rose Run iron ore (commonly called the upper massive Brassfield; note that it is not the same unit as the late Cambrian “Rose Run sandstone” of drillers’ terminology), Plum Creek Member, Oldham Member, and Lulbegrud Member.

The Rose Run iron ore can be distinguished from the lower carbonates of the Brassfield Formation by a locally phosphatic lag bed that overlies its sharp basal contact and its higher hematite content. It is usually a reddish, hematitic packstone interbedded with minor gray shale. In its type area in Kentucky, the lowermost bed, often termed the “bead bed,” contains a distinctive cogwheel-shaped crinoid *Floricolumnus* (Thomka and Brett, 2017). These columnals are typically worn and may have been reworked from the underlying upper shaly Brassfield where they can be more abundant and occasionally articulated. The presence of *Floricolomnus* columnals does not constitute a precise stratigraphic marker because they occur in stratigraphically lower positions north of Kentucky (McDowell, 1983), and stratigraphically higher positions farther to the north in the subsurface of north-central Ohio (authors’ observation in core from Marion County, Ohio, where they occur in the overlying Plum Creek) but in the context of adjacent stratal units they are useful for determining general stratigraphic position in the field.

The Plum Creek Member consists of greenish-gray, silty, and calcareous shales with interbedded thin dolostones. The interbedded carbonate beds are distinctly less ferruginous than the underlying upper massive Brassfield or the overlying Oldham Member. In general, the Oldham Member consists of several ferruginous and dolomitic fossiliferous wacke- to packstones with occasional argillaceous partings, typically with three 3-ft- (1-m-) scale cycles. A shaly middle part of the Oldham is present in some sections. The Lulbegrud Shale overlies the Oldham Member, and in its type area consists of sparsely fossiliferous, greenish-gray, clay-rich shales with some discontinuous dolomitic zones (Ettensohn and others, 2013).

The Rose Run iron ore and Plum Creek Member represent a small-scale T-R cycle superimposed the third-order TST of S-II (Brett and Ray, 2005; McLaughlin and others, 2008; termed S-IIA here); these units are correlated with the Maplewood and Reynales Formations of New York. The Oldham and Lulbegrud Members are another T-R cycle (termed S-IIB) within S-II. The widespread Oldham was likely deposited during the late TST of S-II, and the shale dominated Lulbegrud marks the beginning of the HST of S-II. It is tentatively correlated with the Sodus Shale of New York and northern Ohio.

"Red Brassfield" (southwestern Ohio)

The "red Brassfield" of southwestern Ohio is generally a crinoidal and coral packstone, rudstone and grainstone, with irregular lenses of green to slightly reddish shale. In outcrop it can contain small grayish-pink micritic mounds or bioherms with scattered fistuliporoid bryozoans, small corals, and numerous attached crinoid holdfasts. In some locations, such as Oakes Quarry Park in Greene County, Ohio, coral biostromes containing colonial rugosans, *Favosites*, *Halysites* and heliolitids, as well as stromatoporoids are abundant near the top of the unit. The "red Brassfield" does not actually correlate to the Brassfield of Kentucky or southern Ohio (McLaughlin and others, 2008), and likely correlates to the Oldham Member of the Noland Formation, and the Reynales Limestone of New York.

In some limited locations (e.g., Oakes Quarry Park), there are additional strata below the "red Brassfield" and above the white Brassfield. The white Brassfield is overlain sharply by about ~2 ft of fine-grained limestone with large, orange crinoid columnals, possibly *Floricolumnus*, and greenish siltstones, topped by about 6 in of green and reddish shale. This, in turn, is overlain by 3 to 7 in of gritty, brick-red ironstone or hematitic siltstone. These beds may be the lateral equivalent of the *Floricolumnus*-rich upper shaly member of the Brassfield to the south in south central Ohio and into Kentucky. These beds are cut into by the sharp, planar to channelized base of a distinctive, yellowish brown, coarse-grained grainstone bed that is packed with white calcified gastropods and nautiloid cephalopods. This is an important marker, which can be traced through three other nearby quarries (see Stops 1 and 2 in Waid and Brett, 2019). Its significance is uncertain but the ferruginous nature of the bed and large orange weathering crinoid columnals suggest that it may be a remnant of the Rose Run iron ore bed and that its base is the Sequence I-IIA boundary. Its sharply erosional top including undercut hardgrounds then represents the Sequence IIA-IIB boundary.

S-II in well logs

The units of S-II are generally more lithologically uniform across the study area than those in S-I. The Noland Formation is mainly characterized by alternating low and high gamma-ray values in Adams County (fig. 1-9), corresponding to the alternating carbonate and shaly units. The Rose Run Iron Ore has lower gamma values than the underlying shaly Brassfield and overlying Plum Creek, and sometimes has one or two shaly beds in the middle that produce slightly elevated gamma spikes in the middle of the unit. The Plum Creek has higher gamma values than the Rose Run Iron Ore and the overlying Oldham Member, which has low gamma values typical of a carbonate. The Lulbegrud Member is not present in Adams County, but deeper into the basin where it is present (pls. 1-2–1-5) it is characterized by high, usually uniform gamma-ray values. In areas where the Noland Formation overlies sandstone Medina Group units, the base can be marked by the higher density of the Rose Run Iron Ore (pls. 1-2–1-5). The Oldham Member is often a hematitic carbonate, in some places at least part of the unit can become mostly hematite (i.e., an "ironstone"), which is expressed as extremely high values (>3 g/cm^3) on bulk-density curves (see Oldham in well 34167284410000 on Plate 1-4 for a good example) which go off scale and wrap around the curve track. These well log patterns useful for identifying the Noland Formation units in southern Ohio remain consistent throughout most of eastern Ohio (pls. 1-4 and 1-5).

In southwestern Ohio the red Brassfield is expressed as a low-gamma, high-density carbonate, which may be separated by the underlying white Brassfield by a slightly higher gamma zone and shift in Neutron Porosity values (fig. 1-8). Distinguishing the red Brassfield from the overlying Waco Member is difficult because both units have low gamma values. The contact is picked at some change in either the bulk-density or neutron curves that may indicate a bedding plane and/or a slight lithological change, but this pick is usually tentative at best.

Chronostratigraphy S-II

The age of the Noland Formation is poorly constrained by conodont biostratigraphy. Conodonts indicative of the *Distomodus kentuckyensis* Biozone were recovered from the Rose Run iron ore and Plum Creek by Cooper (1975), which merely indicates a Hirnantian through lower to middle Aeronian stratigraphic position. Limited conodont data from the Oldham also indicate a *Distomodus kentuckyensis* biozone fauna (Rexroad, 1967; Nicoll and Rexroad, 1968), and Brett and Ray (2005) and Ettensohn and others (2013) correlate it to the Reynales Limestone of New York. Acritarchs from the upper Oldham suggest a late Aeronian-early Telychian age (J. Verniers, personal comm. 2013) and the presence of the stricklandiid brachiopod *Microcardinalia* (Berry and Boucot, 1970) likewise suggests a late Aeronian to early Telychian age, which is consistent with the correlation to Reynales (Sequence IIB transgressive limestone).

Biostratigraphic data from the Lulbegrud are also limited; Huddle (1967) and McDowell (1983) assigned the unit to the upper part of Zone I through Zone II (approximately *Pterospathodus celloni* zone) of Walliser (1964), indicating a Telychian stratigraphic position. However, Huddle (1967) did not specify the conodont species he used to determine his zonation, and neither Huddle (1967) nor McDowell (1983) illustrated any of the specimens used to assign this zonation. In general, most of the evidence indicates that the Aeronian/ Telychian boundary likely occurs somewhere from the top of the Oldham to the middle of the Lulbegrud.

In western New York, the ages of the Neagha, Reynales, and Sodus Shale (approximate equivalents to the Noland Fm) are slightly better constrained by conodont data. Waid and Over (2015) recovered *Pranognathus tenuis* Zone conodonts from the Densmore Creek Phosphate Bed and Budd Road Phosphate Bed, indicating a lower to middle Aeronian position for the Neagha Shale. Conodonts of the *Distomodus kentuckyensis* Zone through *Pt. celloni* Super Zone have been recovered from the Reynales and Sodus Shale (Kleffner, reported in LoDuca and Brett, 1994; Verniers and others, 2012), indicating that the Aeronian/ Telychian boundary occurs within or just above the Reynales.

CLINTON GROUP—SEQUENCE S-III

Alger Formation-Waco Member (southern Ohio, central Ohio subsurface)

The Alger Formation (sensu Waid, 2018) consists of (in ascending order) the Waco and Estill Members. The Waco Member comprises S-III, and the Estill (sensu stricto) S-IV (Brett and Ray, 2005; Sullivan and others, 2014a, 2016). In southern Ohio and northern Kentucky, the Waco is further subdivided into three informal submembers: the white Waco limestone, orange Waco limestone, and Waco shale (fig. 1-3). The white Waco is a light-gray, glauconitic dolomudstone to wackestone bearing occasional fossils including a variety of tabulate and rugose corals. The orange Waco overlies the white Waco and is a heavily bioturbated, ferruginous dolomudstone. The Waco Shale is a dark-gray, somewhat silty sparsely fossiliferous unit in Ohio though locally in Kentucky this unit carries a diverse assemblage of bryozoans, brachiopods, and corals. The Waco Shale is overlain by the Estill Member, which is lithologically very similar. The cryptic boundary between the two shales is marked by a band of dark maroon shale with abundant glauconite granules at the top (Sullivan and others, 2014a). In the central Ohio subsurface (Pickaway County, core 3241), only the orange Waco and Waco shale are present.

The white and orange Waco represent the TST of S-III, and the Waco shale represents the HST. The white Waco has a spotty distribution in southern Ohio and in the subsurface of central Ohio and will not be seen on this trip. The spotty distribution of the white Waco and the appearance of a thin (approximately 10-ft-thick) shale between the orange and white Waco in the subsurface of southeastern Ohio (Waid, 2018) indicates that the Waco submembers represent parts of two higher-order T-R cycles superimposed on S-III. Sea level rise was probably greater during the second T-R cycle, leading to the more widespread deposition of the orange Waco and the “upper” Waco shale.

S-III in well logs

Where overlying a shale (either the Plum Creek or the Lulbegrud Shale), the base Waco Member of the Alger Shale is pronounced in well logs as a sharp drop in gamma values. When lying above the Oldham or red Brassfield, it is usually distinguished by a very small gamma spike at the base, which likely represents an argillaceous stringer from the cut-out Lulbegrud Member. Because the upper boundary of the Waco

Member throughout most of the study area is a shale/shale contact with the Estill Member, it is very difficult to identify in well logs. All identifications of the boundary where the overlying unit is the Estill Member in this report are considered tentative but are placed at a slight deflection in gamma-ray values. In some areas, the lower part of the Estill grades into the carbonate Dayton Formation (pl. 1-2) making the upper boundary of the Waco shale easy to identify. Where the Dayton has cut through the Waco shale and overlies the Waco carbonates (orange and/or white Waco), the contact is difficult to distinguish because both units have similar gamma-ray and bulk-density values. The contact is picked at slight changes in the gamma, bulk-density, or neutron porosity curves, but the picks are considered tentative.

Chronostratigraphy of S-III

The occurrence of *Pterospathodus eopennatus* Superzone conodonts and the Valgu isotope excursion (fig. 1-2) within the orange Waco indicates a Telychian stratigraphic position for the unit. The orange Waco likely correlates to the Wolcott Furnace hematite in New York based on sequence stratigraphic patterns and similar conodont faunas and the white Waco may represent the Wolcott Formation proper (Brett and Ray, 2005; Sullivan and others, 2014b).

CLINTON GROUP—SEQUENCE S-IV

Dayton Formation (southwestern Ohio, central Ohio subsurface, eastern Ohio subsurface?)

The Dayton Formation is a widespread unit in southwestern and central Ohio. It was previously miscorrelated with the somewhat similar Waco carbonates (Foerste, 1935; Brett and Ray, 2005). In part, this was a result of the tendency for either one or the other unit to be absent in most outcrop sections where the sub-Dayton unconformity has removed Waco in most northwestern sections, whereas the Dayton is cryptically developed as a glauconitic shale zone or absent to the southeast. It is very lithologically consistent even over a large area to the northwest, where it is generally a light-gray to tannish-gray dolowackestone to dolopackstone with few macrofossils. Its most distinctive feature is the presence of very glauconitic zones throughout the unit. It is most glauconitic in eastern Ohio, where one zone has enough glauconite nodules to be described as a “glauconite sand.” The Dayton represents the TST of S-IV, and correlates to the lower part of the Estill Member that outcrops in southern Ohio and in the subsurface of central Ohio based on conodont faunas (Kleffner, 1987; Cramer, 2009) and subsurface correlations (fig. 1-2, pls. 1-1 and 1-2).

Osgood Formation (southwestern Ohio)

The Osgood Formation is a lithologically variable unit that generally consists of rhythmically alternating bluish-gray shale, thin, calcareous, bioturbated siltstone beds, and dolomitic wacke- to packstone. The relative proportion of these three lithologies varies considerably. The base of the Osgood in southwestern Ohio is usually marked by a prominent dolostone/limestone bed (e.g., at Fairborn Cement Quarry, John Bryan State Park, and Glen Helen Reserve). This basal carbonate unit and overlying alternating carbonate and mudrock beds represent a higher-order transgressive-regressive deposit superimposed on the HST of S-IV.

Alger Formation-Estill Member (southern Ohio, eastern Ohio subsurface)

In contrast to southern Ohio, the Estill Member in central Ohio does not overlie the Waco shale. Instead, the lower part of the Estill grades into the Dayton Formation in southwestern and central Ohio. This leads to the awkward correlation of the Dayton Formation in between the Waco and Estill members of the Alger Formation. The Estill Member consists of alternating layers of green, gray, and maroon shale with occasional thin, silty dolostone beds in the lower part. Siltstone beds become more frequent toward the top of the formation in a coarsening-upward sequence. Where the Estill overlies the Dayton Formation, it represents the HST deposits of S-IV.

S-IV in well logs

In southwestern Ohio S-IV is represented by the Dayton Formation and Osgood Formation. The Dayton is a dense, clean carbonate and has corresponding low gamma-ray (fig. 1-8). Toward the basin, the Dayton becomes progressively more muddy, and gamma-ray values increase until it grades into the basal part of the Estill Member (pl. 1-2). The Osgood Formation is mix of interbedded shale, siltstone, and limestones, so it has relatively high, but variable gamma-ray values in a saw-tooth like pattern (fig. 1-8, pls. 1-1 and 1-2).

In southern Ohio, S-IV is represented by the Estill Member of the Alger Shale. The Estill Member is the thickest, most uniform shale of the Clinton Group, and is characterized by high gamma-ray values. It does have some variations in gamma-ray and bulk-density patterns which may enable the unit to be split up into four informal submembers, here correlated as the "Williamson equivalent," "Rockway equivalent," and the "Osgood equivalent," which an unnamed interval between the Osgood and Rockway equivalents in some areas (see Plates 1-2 and 1-5 for best illustration of the relationship between these tentatively correlated submembers). The "Williamson equivalent" part of the Estill generally has the highest gamma-ray values. The "Rockway equivalent" part of the Estill has lower gamma-ray values and higher bulk-density values, indicated increased carbonate content. The "Osgood equivalent" part of the Estill usually has relatively high gamma-ray values as well as some bulk-density spikes, indicating increased carbonate content.

Chronostratigraphy of S-IV

The correlation of the Estill, Dayton, and Osgood with the typical sequence S-IV Williamson and Rockway formations in New York has been somewhat problematic. Conodonts from the Second Creek Phosphate Bed, of the Williamson Shale in New York, which was identified as a basal transgressive lag of S-IV (Brett and others, 1990, and correlated with the Dayton (Brett and Ray, 2005) are indicative of the *Pterospathodus amorphognathoides angulatus* Zone (Sullivan and others, 2014b).Conodonts from the Dayton Formation, lower part of the Estill member, and upper part of the Williamson Shale belong to the younger *Pterospathodus amorphognathoides amorphognathoides* Zonal Group (Kleffner, 1987; Loydell and others, 2007 McLaughlin and others, 2008; Kleffner and others, 2012; Brett and others, 2014), and conodonts from the Rockway are from the lower *Pseudooneotodus bicornis* Zone (Kleffner, 1991; Jeppsson, 1997). The Osgood and middle to upper part of the Estill contain, respectively, conodonts of the upper *Kockelella ranuliformis* Zone, and uppermost *Pterospathodus amorphognathoides amorphognathoides* Zonal Group through *Kockelella ranuliformis* (?) Zone (fig. 1-2; McLaughlin and others, 2008; Kleffner and others, 2012).

On strictly litho- and sequence-stratigraphic grounds, the Osgood Shale and Estill Member appear to be directly correlated. However, several conodont zones are missing between the Dayton Formation and Osgood in southwestern Ohio (Kleffner and others, 2012), whereas the Dayton and lower part of the Estill are within the same conodont zone. This indicates that there is a significant cryptic disconformity between the Dayton and Osgood. Furthermore, the ascending limb of the Ireviken carbon isotope excursion (fig. 1-2) is present in the upper Osgood in many locations (fig. 1-7) and is sometimes present in the uppermost few feet of the Estill (see McLaughlin and others, 2008; Cramer, 2009; McLaughlin and others, 2012), indicating that the Osgood is an expanded section of the uppermost Estill.

CLINTON GROUP—SEQUENCE V

Bisher Formation (southern Ohio, central Ohio subsurface)

At its type area in southern Ohio, the Bisher Formation overlies the Estill Member at a sharp, erosive surface. The Bisher Formation is divided into three informal members: the lower, middle, and upper Bisher (McLaughlin and others, 2008). The lower Bisher is typically a crinoidal grainstone or dolograinstone with coquinas of the brachiopod *Cryptothyrella* (*Meristina*?) *cylindrica*. Macrofauna of these lower beds includes coquinas of *Atrypa* and *Cryptothyrella* (*Meristina*) *cylindrica* closely resembling those of the basal Lewisburg limestone found in western Ohio (Brett and others, 2012). The Lewisburg Formation (as defined in Brett and others, 2012) overlies the Osgood Shale, and is a dolomitic crinoidal packstone with varying amounts of argillaceous material in the middle of the unit. We infer that it correlates, at least in part, with the lower Bisher "*Cryptothyrella* Beds," and that both units represent the lower TST of sequence S-V.

The informal middle member of the Bisher Formation is medium-dark-gray, dolomitic shale. It is poorly developed in Adams County, but a shaly zone up to about 1 m thick is present in some localities. However, 25 mi (40 km) to the north at Hillsboro the interval is a distinct shale-dolosiltite up to 7 ft (2 m) thick that passes upward in thicker bedded argillaceous dolostone with local soft-sediment deformation. At Leesburg, nearly 10 ft (3 m) of shale intervene between the *Cryptothyrella* limestone and the overlying Lilley Formation.

The upper member of the Bisher comprises dolomitic and somewhat silty calcarenites that display varying types of cross bedding, ranging from symmetrical ripples and hummocky bedding to low angle cross stratification. Ball-and-pillow deformation is common, and the unit may exhibit small pale gray chert nodules. This interval closely resembles and has been correlated with, the upper Rochester Formation, Gates Member and the overlying DeCew Formation near Rochester, New York.

S-V in well logs

In southern Ohio S-V is represented by the Bisher Formation, which has a mix of low and high gamma-ray values corresponding to carbonate units and shale units, respectively, within the formation. In Adams County the Bisher has three informal submembers (fig. 1-9), which show a low-high-low gamma-ray pattern, corresponding to the lower Bisher, middle "shaly" Bisher, and upper Bisher. Across the study area, however, the position and amount of shale content in the Bisher is variable, so the tripartite division of informal members cannot be correlated everywhere. Some places the shale is absent, so it has relatively low gamma-ray values throughout the unit (e.g., well 3416320924000 on Plate 1-3), and at other places the shale occurs at the top (e.g., well 3413120038000 on Plate 1-3).

In southwestern Ohio, S-V is represented by only a thin sliver of the Lewisburg Formation, which is a carbonate with low gamma-ray values.

Chronostratigraphy of S-V

Conodonts indicative of the *Kockelella ranuliformis* Superzone (fig. 1-2) were recovered from the lower Bisher (Kleffner, 1987) and Irondequoit Limestone (Kleffner, 1991), corroborating that correlation. The middle and upper Bisher and Rochester Shale contain conodonts indicative of the *Ozarkodina sagitta rhenana* Zone (fig. 1-2; Kleffner, 1987; Kleffner, 1991). The lower part of the Ireviken carbon isotope excursion is present in the lower Bisher and Irondequoit Limestone, and the middle part of the excursion is present in the Rochester and middle/upper Bisher (Cramer and others, 2006; McLaughlin and others, 2008; Cramer, 2009).

Brett and Ray (2005) related this middle Bisher shale to the Rochester Shale of New York and the Massie Formation (Brett and others, 2012) a gray shale that overlies the Lewisburg Limestone in Green, Clinton, and Preble Counties. The Bisher shale and the Massie Formation share many macrofossil species in common and with the fauna of the Rochester Shale of New York. But the correlation of middle Bisher and Massie remains controversial, as carbon isotope data and conodont microfossils suggest a younger stratigraphic position (see Cramer and Kleffner in McLaughlin and others, 2008; Oborny and others, 2020).

LOCKPORT GROUP—SEQUENCE S-VI

Lilley Formation (southern Ohio, central Ohio subsurface?)

Where best exposed along OH-32 at Measley Ridge, west of Peebles, the Lilley Formation comprises four informal units. In ascending order, these are the lower, middle, upper middle and shaly members, all described below.

Lower member of Lilley: This is a massive- to thick-bedded crinoidal dolograinstone, about 5–9 ft (1.5–3 m) thick at Measley Ridge, which rests sharply upon the shaly fossiliferous thin-bedded crinoidal limestone beds of the upper Bisher Formation. This unit displays large-scale cross stratification at this location. It is composed of bluish-gray, herringbone cross-bedded, crinoidal dolograinstone (calcarenite).

The contact with the underlying unit is lithologically subtle, but in the right light the sharp and undulating contact is very apparent. Locally it is marked by a thin rusty crust. This massive basal unit of the Lilley Formation is heavily covered by a dark brownish-gray weathering rind. The upper contact of this unit with the middle Lilley is also sharp and undulating.

Skeletal material, primarily crinoids in this unit, are heavily abraded and fragmented, although in some cases localized stringers of relatively well-preserved material are present. Diversity is relatively low and dominated by crinoidal debris (BA 3), and bioturbation is sparse (ichnofacies index [ii.] 1–3). The facies data together suggest that this unit formed under relatively high carbonate sedimentation rates in a high-energy, shoal depositional environment. Pervasive herringbone cross bedding within a carbonate, such as that characteristic of the basal Lilley, is rare within the Lower Silurian strata of the Cincinnati Arch and Appalachian Basin. However, the Gasport Dolostone, as exposed in sections near Niagara Falls, not only displays herringbone cross-bedded, crinoidal calcarenite facies, but also rests directly on the DeCew Dolostone (noted above for its distinctive seismites) with a sharp contact marked locally by a thin ferric crust. The lower Lilley is tentatively correlated to the Gothic Hill Member of the Gasport Dolostone of western New York (Brett and others 1995; Brett and Ray, 2005).

Middle member of Lilley: This member is composed of approximately 3 ft (1 m) of interbedded, tabular, thin-bedded skeletal dolopack-grainstone and gray dolomitic shales with thin wavy-bedded, fine-grained dolopack- and dolograinstones. These carbonates are distinct for containing a relatively well-preserved and diverse fauna (benthic assemblage 4, or BA 4, of Boucot, 1975) and an abundance of limonitic skeletal grains that give fresh exposures a medium-gray and orange speckled appearance. Bioturbation is relatively sparse (ii. 1–3). In a nearby section (Peebles abandoned quarry, 1.4 mi (2.3 km) to the north-northeast) this interval contains small bioherms. This unit is truncated by an undulating surface at the base of the overlying unit. Together the facies data suggest relatively high sedimentation rates in an open-marine, episodically high-energy, mid-ramp depositional environment. This unit is tentatively correlated to the Pekin Member of the Gasport Formation of western New York.

Upper Lilley Limestone: The upper-middle portion of the Lilley Formation, is composed of 6 ft (2 m) of light yellowish-gray, coarse-grained, massive, bedded dolograinstone-rudstone. Fossil composition is moderately diverse and is dominated by crinoids, rhombiferan cystoids, corals and stromatoporoids (BA 3–4). Preservation of skeletal grains is variable, and bioturbation is not clearly. Locally, the upper 4 ft (1.2 m) intertongues with irregular, micritic, biohermal masses that in most cases extend up above the top of the unit by up to 3.5 ft (1 m). The upper part of the unit is locally composed of up to 2 ft (60 cm) of tabular, medium-bedded, amalgamated dolocalcisiltites. Together, the facies data suggest relatively slow deposition in an episodically high-energy, mid-ramp depositional environment. This unit likely correlates to the Niagara Falls Member of the Goat Island Formation of western New York.

Shaly Lilley: the upper portion of the Lilley Formation (“shaly Lilley”), is composed of up to 16 ft (5 m) of silty, dolomitic, medium-gray, sparsely fossiliferous shale and rare, thin dolowackestones and dolocalcisiltites. The sparse fauna is composed primarily of crinoids (*Eucalytocrinites*) and small brachiopods and solitary corals (BA 4–5). A thin discontinuous interval of fine-grained dolograinstone-dolocalcisiltite occurs near the middle of the unit and locally displays small, non-skeletal, shaly micritic bioherms up to 3 ft (1 m) tall. This unit and the immediately overlying shale yield stromatoporoids up to 1 ft (30 cm) across as well as rare favositids and cladoporids. Bioturbation is sparse (ii. 1–2). Together the facies data suggest relatively high siliciclastic sedimentation rates in an outer-ramp setting. This division is traceable throughout south-central Ohio from the city of Leesburg to Adams County and locally into northern Kentucky.

Although Cramer (2009) correlated this interval with the Massie Shale of western Ohio, the macrofaunas are quite different and this correlation is controversial (see S-V). However, in the subsurface correlations of this report we follow Oborny and others (2020) and correlate the Lilley with the Lewisburg Formation and Massie Shale of southwestern Ohio (but see caveats in that paper on possible correlation of the Massie and middle Bisher shale; see Plate 1, herein). The shaly Lilley is also tentatively correlated to the Vinemont Member of the Goat Island Formation of western New York.

Lilley-Peebles transition interval

The “Lilley-Peebles transition” interval is composed of approximately 4 ft (1.2 m) of nodular, fossiliferous, silty, argillaceous dolocalcarenites. The contact with the underlying shale ranges from sharp to gradational; in places this contact appears to show broad, shallow channels approximately 6 ft (2 m) deep.

The macrofauna is moderately diverse and dominated by thickets of small branching *Coenites* (cladoporid) colonial corals and small bulbous stromatoporoids (BA 3–4). Bioturbation is locally high with multiple ichnogenera cross-cutting one another, including: *Paleophycus*, large *Chondrites* and *Planolites* (ii. 3–5). The upper contact is sharp and planar where exposed. Together, the facies data suggest moderate sedimentation rates in an open-marine, inner- to mid-ramp depositional environment.

S-VI in well logs

In southwestern Ohio, S-VI is (controversially) represented by the upper part of the Lewisburg Formation and the Massie Shale. The Lewisburg has low gamma-ray values, and the Massie has distinctively high gamma-ray values (fig. 1-8). These units correlate to the Lilley Formation in southern Ohio, which has the same gamma ray pattern (fig. 1-9; pl. 1-1).

Chronostratigraphy of S-VI

All of the lower units have yielded a low diversity conodont assemblage typified by *Ozarkodina sagitta rhenana*, typical of the *O.s. rhenana* Zone but extending into the overlying *K. walliseri* Zone. The latter species has not been positively identified here, but an indeterminate form, referred to as K. sp., may represent a local variant of *K. walliseri*. We tentatively assign the Lilley to the *K. walliseri* Zone pending further study of *Kockella sp*. conodonts. This contrasts to the situation to the northwest in Greene, Clinton, and Preble Counties, Ohio, and in eastern Indiana. In those regions, strata probably correlative to the Lewisburg Formation and Massie Formation yield definite *K. walliseri* and no *O. s. rhenana*.

LOCKPORT GROUP—SEQUENCE S-VII

Note: The focus of this guidebook is on sequences S-VI and lower, but since these higher units are visible at the last stop, we will provide some information about them below.

Peebles Dolomite (southern Ohio)

The Peebles Formation is a dark brownish-gray- to yellowish-gray-weathering, light-gray, fossiliferous, vuggy, sugary, crystalline dolostone. The Peebles in this area is typically over 60 ft (18 m) thick and relatively uniform lithologically. Rexroad and others (1965) reported that the Peebles is lower in silica and alumina than any other Silurian unit in southern Ohio. One of the most notable features of this unit is the pervasive moldic porosity—skeletal grains are preserved as external molds that show moderate fragmentation. The macrofauna is relatively diverse; Foerste (1931) listed 31 species dominated by corals and brachiopods (BA 3–4). External molds of abundant pentamerid brachiopods (BA 3) are prominent features of some horizons near the base. The lower 5 ft shows well-developed bedding with broad, shallow channels and the overlying 5 ft weathers massive. In nearby cores this interval has a distinctively variegated appearance that may represent extensive bioturbation (ii. 4–5). If this pattern is the result of bioturbation, the record of the burrows themselves has been largely removed by dolomitization. Together the facies data suggest relatively slow carbonate sedimentation in an open-marine, inner-ramp depositional environment. The great abundance of pentamerid brachiopods, identified as *Cannanella* (Kovach, 1974), near the base of the Peebles Formation, noted by several authors, is unusual and unique in the Silurian of southern Ohio, and is here designated an epibole. The top of the Peebles in the nearby Plum Run Stone Company quarry is highly irregular, erosional, and overlain by a paleosol (Court, 1990; Court and Kahle, 1993), which separates it from the overlying peritidal, micrite facies of the Greenfield Formation. Foerste (1935) correlated the Peebles with the Guelph of Ontario, based on the occurrence of the large bivalve *Megalomus*. Boucot and Johnson (1966) suggested that the Peebles is older than Guelph in age, based on the occurrence of *Plicocoelina occidentaus* (a Guelph species) in the overlying Greenfield Formation.

LOCKPORT GROUP—SEQUENCE S-VIII

Note: The focus of this guidebook is on sequences S-VI and lower, but since these higher units are visible at the last stop, we will provide some information about them below.

Peebles Dolomite (southern Ohio)

The Peebles Formation is a dark brownish-gray to yellowish-gray-weathering, light gray, fossiliferous, vuggy, sugary, crystalline dolostone. The Peebles in this area is typically over 60 ft thick and relatively lithologically uniform. Rexroad and others (1965) reported that the Peebles is lower in silica and alumina than any other Silurian unit in southern Ohio. One of the most notable features of this unit is the pervasive moldic porosity—skeletal grains are preserved as external molds that show moderate fragmentation. The macrofauna is relatively diverse; Foerste (1931) listed 31 species dominated by corals and brachiopods (BA 3–4). External molds of abundant pentamerid brachiopods (BA 3) are prominent features of some horizons near the base. The lower 5 ft shows well-developed bedding with broad, shallow channels and the overlying 5 ft weathers massive. In nearby cores this interval has a distinctively variegated appearance that may represent extensive bioturbation (ii. 4–5). If this pattern is the result of bioturbation, the record of the burrows themselves has been largely removed by dolomitization. Together the facies data suggest relatively slow carbonate sedimentation in an open-marine, inner-ramp depositional environment. The great abundance of pentamerid brachiopods, identified as *Cannanella* (Kovach, 1974), near the base of the Peebles Formation, noted by several authors, is unusual and unique in the Silurian of southern Ohio, and is here designated an epibole. The top of the Peebles in the nearby Plum Run Stone Company quarry is highly irregular, erosional and overlain by a paleosol (Court, 1990; Court and Kahle, 1993), which separates it from the overlying peritidal, micrite facies of the Greenfield Formation. Foerste (1935) correlated the Peebles with the Guelph of Ontario, based on the occurrence of the large bivalve *Megalomus*. Boucot and Johnson (1966) suggested that the Peebles is older than Guelph in age, based on the occurrence of *Plicocoelina occidentaus* (a Guelph species) in the overlying Greenfield Formation.

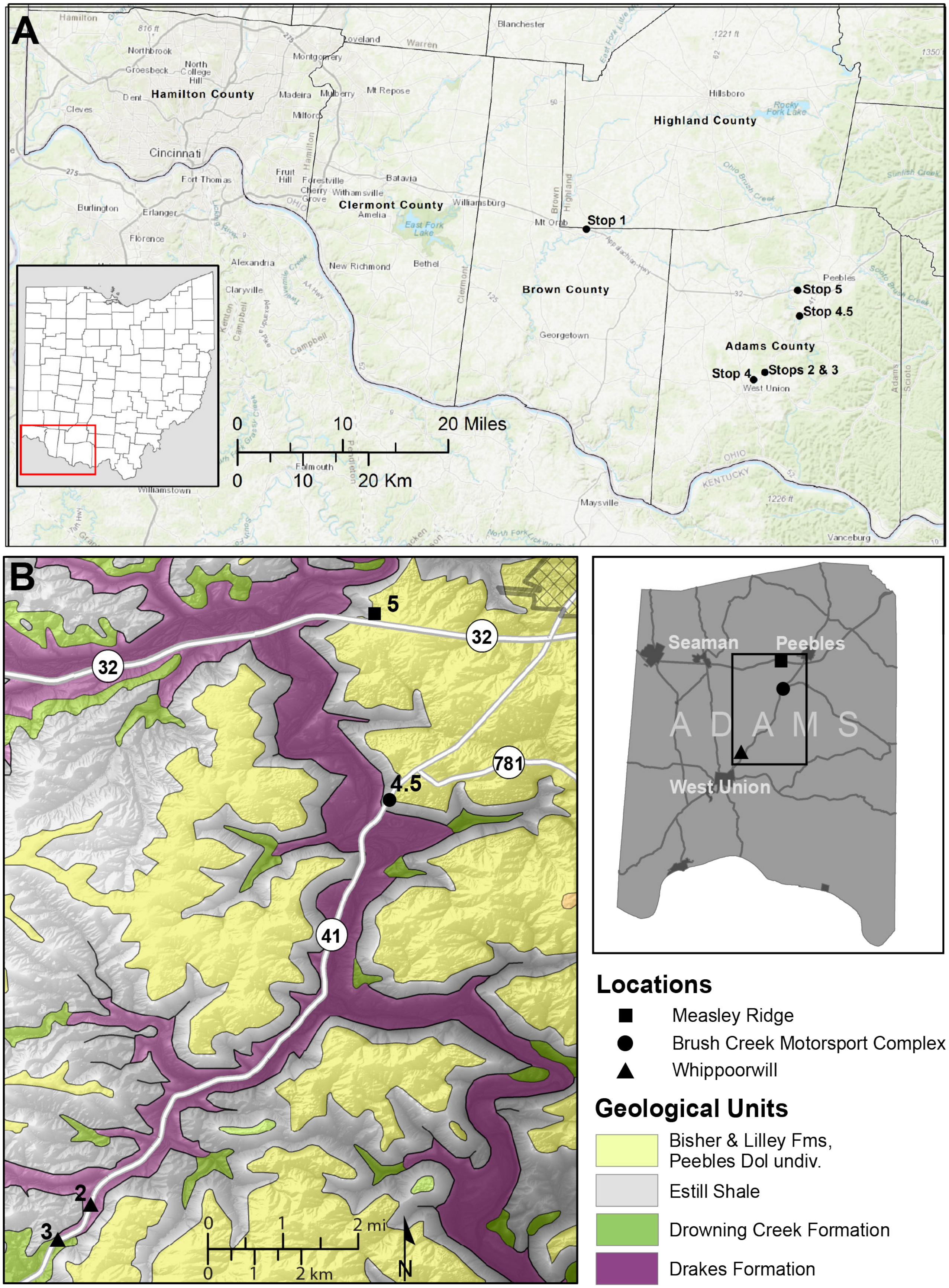


FIGURE 1-9. (A) Overview map of field trip stops. (B) Outcrop stops overlaid on topographic shaded-relief geological map. The geological units are those mapped by the Ohio Geological Survey. The Drowning Creek Formation (mapping unit) includes the Whippoorwill formation, Brassfield Formation, and Noland Formation of Waid (2018) and Waid and Brett (2019).

FIELD TRIP STOPS

STOP 1: ODOT REST AREA ON OH-32 BETWEEN MOUNT ORAB AND SARDINIA, OH (39.018756° N, 83.825013° W)

At this rest stop we will look at some of the uppermost Ordovician and lowermost Silurian units in the Greene County Core (southwestern Ohio). The core lithology log, well log, and isotope curve is shown in Figure 1-7.

The units viewed in this first stop will span the same general chronostratigraphic interval of the units that will be viewed in outcrop at Stops 2 and 3. The Centerville and Belfast Members of the Whippoorwill formation, the white Brassfield, the red Brassfield, possibly the Waco Member, and the Dayton Formation will be viewed.

Some lithostratigraphic characteristics to think about while viewing the core:

- Look for diagenetic structures and features: stylolite nests, cherty zones, nodular intervals, mineralized zones, etc.
- Trace and body fossils

Some sequence stratigraphic characteristics to think about while viewing core:

- Surfaces such as wavy erosive contacts and sharp facies dislocations
- Condensed intervals: strong concentrations of shells, mineralization, intensely bioturbated zones
- General deepening/shallowing trends

Comparing litho/sequence stratigraphic findings with the well log:

- Match carbonate/shale contacts with gamma-ray spikes and troughs. Is there a difference between the core depth and log depth? If so, determine the difference, and remember to account for this “depth shift” when comparing the log to the core.
- Are there any shallowing or deepening lithological characteristics that also occur in the log?

STOP 2: OH-41 EXPOSURE NORTH OF LICK FORK CHURCH (38.827498° N, 83.505647° W)

The Katian (Upper Ordovician) Preachersville Member of the Drakes Formation is the oldest unit exposed at this outcrop (fig. 1-10). It is a dark-gray, clay-rich shale interbedded with fossiliferous wacke- to packstones. Red to maroon silty shale layers represent distal tongues of the chronostratigraphically equivalent Queenston Formation of the subsurface in eastern Ohio.

FIGURE 1-10. Photo showing labeled Ordovician and lowermost Silurian strata exposed along OH-41 north of Lick Fork Church.

The Centerville Member of the Whippoorwill formation lies above the Preachersville Member and below the massive beds of the Belfast Member. It is a bluish shale interbedded with dark-gray, sparsely fossiliferous limy siltstone beds. Shale is the dominant lithology in the lower part of the Centerville, with progressively more silty limestone interbeds towards the top of the member in a coarsening upward pattern.

The Belfast Member overlies the Centerville along an erosional surface. Two distinct units can be differentiated within the Belfast. The lower unit is massive, displaying bioturbation and hardgrounds within its dominantly packstone-grainstone lithology. The upper unit of the Belfast consists of thinner carbonate units topped by hardgrounds and interbedded with more argillaceous sediments and glauconitic zones. The hardgrounds of the Belfast Member indicate that depositional hiatuses allowed carbonate beds to at least partially lithify before any other significant sedimentation took place. Indicators of hardgrounds include *Thalassinoides* burrows and *Trypanites* borings, which require lithified sediment to be preserved, and glauconite, which requires very slow deposition to accumulate. Carbon isotope chemostratigraphy and subsurface correlations indicate that the Whippoorwill formation correlates to the Whirlpool Sandstone and Power Glen Shale of New York.

The lowest informal member of the redefined Brassfield (Waid, 2018), the lower massive Brassfield (also termed the cherty Brassfield), lies above the Belfast Member of the Whippoorwill formation. At this outcrop it consists of roughly 8 ft of medium-bedded, coarse- to medium-grained skeletal grainstones interbedded with nodular, occasionally glauconitic fine-grained grainstones. The skeletal grains are primarily comprised of fragmented and abraded crinoids, corals, and brachiopods. Occasional *Thalassinoides* burrows and glauconite indicate relatively slow deposition in an open-marine inner- to mid-ramp environment. Obstacle marks (fig. 1-11) on some beds indicate the occurrence of storm events.

Mostly covered at this outcrop, the informal thin-bedded Brassfield member overlies the lower massive Brassfield. The thin-bedded Brassfield is composed of carbonate beds of similar lithology to the lower massive Brassfield, but interbedded with olive-gray mudrock. The lower massive Brassfield and thin-bedded Brassfield likely correlate, at least in part, to the Devils Hole Sandstone and the lower part of the Grimsby Formation of New York.

FIGURE 1-11. Photo showing a sedimentary structure known as an obstacle mark (Karcz, 1968; Potter and Pettijohn, 1977). This sole marking on a thin packstone bed from the Brassfield is indicative of strictly unidirectional flow over an obstacle, in this case the brachiopod, *Leptaena.* When the water flows over the obstacle, sediment is deposited in the lee. Suspended sediment settles when the unidirectional flow event ends, creating a mold of the obstacle shadow. This obstacle shadow is indicative of a mid-ramp storm event.

STOP 3: OH-41 EXPOSURE SOUTH OF LICK FORK CHURCH (38.821372° N, 83.511839° W)

Moving up in the Silurian section, this exposure contains the upper portion of the thin-bedded Brassfield Formation, and the upper shaly and upper massive Brassfield, the Noland Formation, and the Waco Member of the Alger Shale (fig. 1-12). The thin-bedded Brassfield is mostly covered up by talus at the road cut but can be seen along the banks of Lick Fork Creek on the opposite side of the road (private property; cover photo). The upper shaly beds of the Brassfield (fig. 1-13C) are mostly gray in color, and occasionally contain some hematitic, silty dolostone beds. The upper shaly beds form the talus slope at this outcrop but are somewhat exposed at steeper parts of the road cut. The thin-bedded and upper shaly members of the Brassfield are likely upper Rhuddanian to Aeronian in age (Sullivan and others, 2016), and correlate to part of the Grimsby Formation.

FIGURE 1-12. Photo showing the westward view of outcrop (Stop 3) along OH-41. The labelled shaly Brassfield, Noland Formation, and Waco Memberof the Alger Formation are exposed. Photograph courtesy of Kyle Hartshorn.

The Rose Run Iron Ore (formerly upper massive Brassfield) has several horizons preserving large crinoid columnals, referred to regionally as "beads" (fig. 1-13A). The lowest of these crinoid-bearing beds is a useful marker for the base of the upper massive Brassfield throughout the Kentucky type area, but in northern Kentucky/southern Ohio the crinoids appear at a lower stratigraphic level (McDowell, 1983). In southern Ohio, the Rose Run Iron Ore can be distinguished from the interbedded limestones of the shaly Brassfield because it is more orange to red in color and hematitic. The abundance of skeletal crinoid material and occasional weakly developed wave ripples are indicative of an inner-ramp shoal environment. The upper massive Brassfield represents the lower part of S-II, and correlates to the lowermost units of the Clinton Group of New York, probably the Densmore Creek Phosphate Bed (Sullivan and others, 2016).

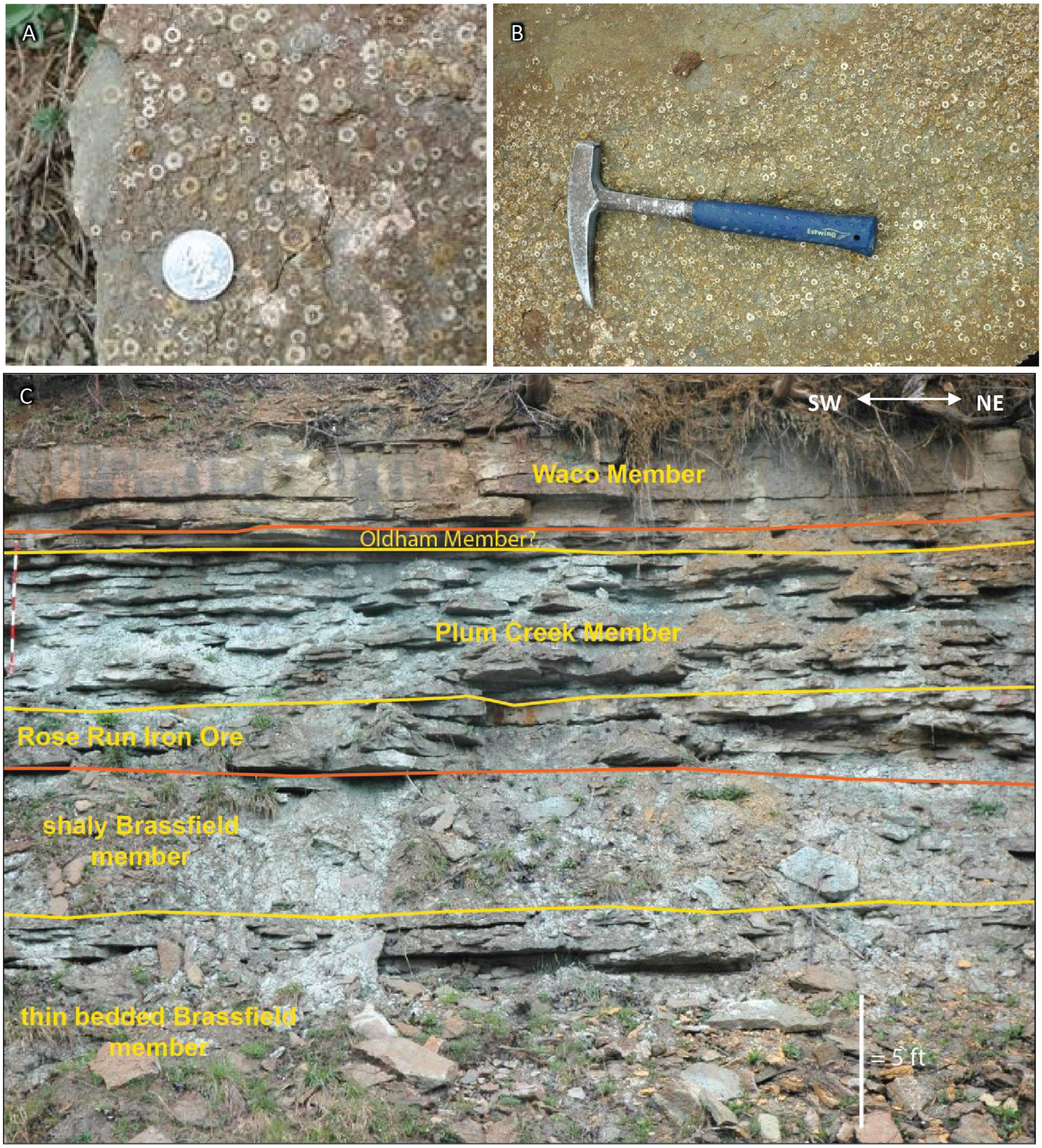


FIGURE 1-13. (A) Close-up image of the Brassfield "bead bed" with a U.S. quarter for scale. (B) Wider image of the Brassfield bead bed with a 13-inch rock hammer for scale. This bed lies locally within the upper massive bed of the Brassfield but can appear in stratigraphically lower positions. (C) Outcrop photograph. Six-inch interval staph in upper left corner for scale. The thin bedded and upper shaly Brassfield are mostly covered up by talus at this exposure.

The Plum Creek Shale lies above the Rose Run Iron Ore and is a shaly unit interbedded with carbonates similar to the shaly Brassfield. Carbon isotope data and revised sequence stratigraphic interpretations outlined in Brett and Ray (2005) and Sullivan and others (2016) indicate that the Plum Creek is Aeronian in age, and likely correlates to the Neahga and Maplewood Shales of western New York. The Plum Creek rapidly thins to the west as the influence of the Cincinnati Arch led to subaerial exposure and erosion.

A relatively thin, tan-to-buff colored dolomitic unit lies on top of the Plum Creek Shale (fig. 1-13C). It is more resistant than the underlying shale of the Plum Creek, and slightly less resistant than the overlying Waco Member. It is unclear whether this dolomitic unit is part of the Plum Creek or a remnant of the

Oldham Limestone of Kentucky. The Lulbegrud Shale is not present in the outcrops visited on this field trip, having been cut out under the S-II/S-III sequence boundary. Together, the upper massive Brassfield, Plum Creek, Oldham, and Lulbegrud comprise sequence II, correlate to the "lower" Clinton Group of New York and represent much of the Aeronian Stage (fig. 1-2).

Sitting atop the Oldham(?) Limestone at the top of the outcrop is a buff-colored dolomitic previously unit mapped as the Dayton Member of the Drowning Creek Formation by Slucher (2006), but which has been recently revised (Sullivan and others, 2014a, 2016) to the Waco Member (also termed the Waco Limestone) of the Alger Shale Formation of northern Kentucky (fig. 1-13C). This unit was long thought to be chronostratigraphically equivalent to the Dayton Formation of western Ohio, but recent conodont and stable carbon isotope data indicate that the Waco Member is distinctly older than the Dayton Formation (Sullivan and others, 2014a). The true Dayton Formation grades lithologically to the south and east into the lower and middle portions of the Estill Member of the Alger Shale Formation (also termed the Estill Shale), part of which will be seen at the next stop.

The Waco represents part of S-III (fig. 1-2). There are two Waco submembers exposed in southern Ohio. The lower is termed the "white Waco," and the upper is termed the "orange Waco." The white Waco is not present in all outcrops and will not be seen on this trip. Where present, it is a light-gray, coral- bearing calcareous dolostone. The orange Waco, seen at this stop, is a tan, heavily bioturbated dolostone with scarce fossils. The sporadic distribution of the white Waco underneath the orange Waco indicates that it was likely preserved from pre-orange-Waco erosion in paleotopographic lows.

STOP 4: LUNCH STOP AND CORE VIEWING AT ADAMS LAKE STATE PARK (38.813399° N, 83.527003° W)

After lunch we will continue studying the Greene County core. This time we will focus on the Dayton, Osgood, Lewisburg, Massie, and the lowermost Lockport Group. Consider the same features outlined at the previous core stop. Pay special attention to the lithological changes in the Osgood (i.e., does it deepen or shallow upward) and how that compares with the gamma-ray signature.

STOP 4.5: OPTIONAL STOP AT BRUSH CREEK MOTORSPORT COMPLEX (38.904607° N, 83.448677° W)

This optional stop provides a view of the Estill Member of the Alger Shale Formation. The lower part of the unit is exposed within the Motorsport Complex property, and the upper part of the unit is exposed in a roadcut on the east side of OH-41 N.

STOP 5: MEASLEY RIDGE ROADCUT ALONG OH-32 WEST OF OH-41 (38.937402° N, 83.453183° W)

This road cut is likely the most comprehensive exposure of Silurian strata found within state, showing the Estill Member of the Alger Formation through the Peebles Dolomite. The Estill Member is the lowest and most easily eroded unit exposed at the Measley Ridge roadcut (fig. 1-14) and is visible along small gullies leading up to the more competent Bisher Formation (fig. 1-15A). The base of the Estill is not exposed at this stop, but it is gradational with the underlying Waco and marked by a thin glauconitic band. The contact can be seen on the hillside northeast of Brush Creek Motorsports Complex (7 mi south of Peebles on OH-41; Optional Stop 4.5). Thin dolostone beds at the base of the Estill in southern Ohio correlate to the Dayton Formation of western Ohio (Cramer, 2009; Sullivan and others, 2016). The rest of the Estill contains alternating intervals of maroon to greenish-gray, clay-rich shales interbedded with thin, gray-to-tan dolomitic siltstones. The siltstone beds become more frequent toward the top of the formation in a coarsening-upward sequence. Iron oxide nodules, likely goethite pseudomorphs of pyrite, ranging from pea to golf ball size become prevalent at the top of the Estill (fig. 1-15B).

FIGURE 1-14. Photo of the south-facing view of Measley Ridge roadcut showing the contact between the Estill Member of the Alger Shale Formation (below) and the Bisher Formation. Some gullies along this cut allow for good views of the upper Estill. Photograph courtesy of Kyle Hartshorn.

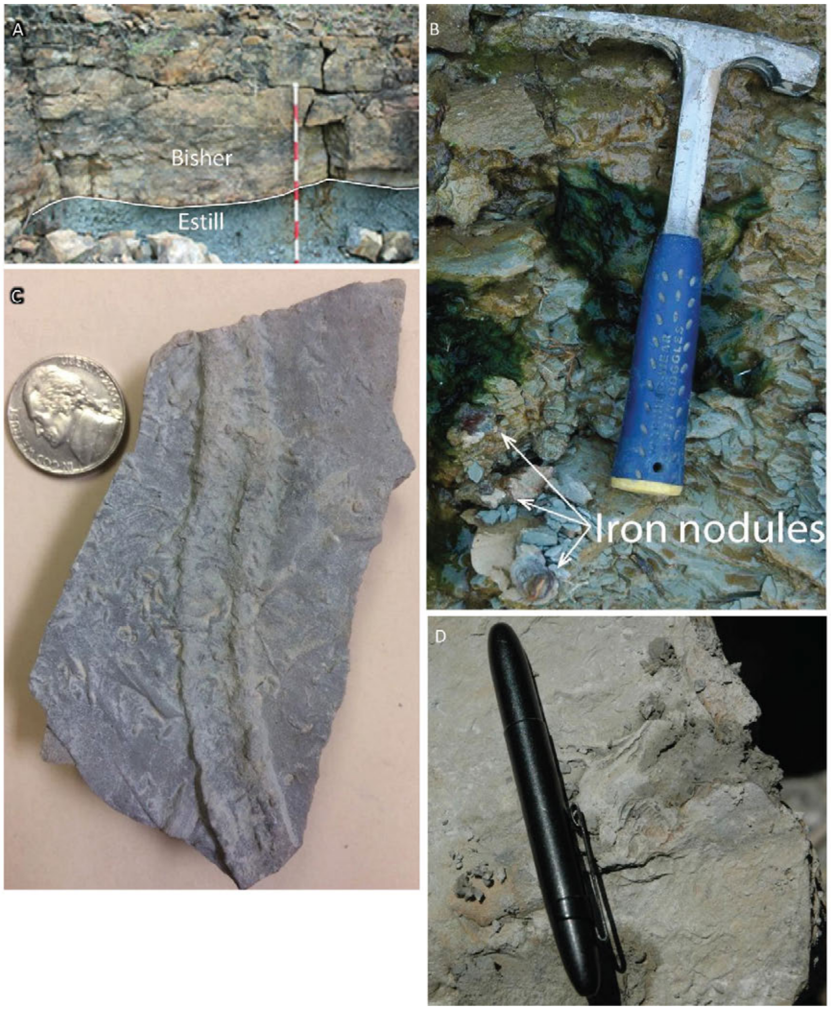


FIGURE 1-15. (A) Photo of the unconformable contact between Estill Shale (below) and the lower Bisher Dolomite. Six-inch interval staff for scale. (B) photo of *in situ* iron nodules near the top of the Estill Shale. (C) photo of *Arthrophycus* ichnosp. and *Planolites* ichnosp. trace fossils on the base of a siltstone bed within the Estill Shale. U.S. nickel for scale. (D) photo of a trilobite impression to the right of pen. From the base of a siltstone bed within the Estill Shale.

Abundant *Planolites*, *Cruziana*, and *Chondrites* trace fossils (fig. 1-15C) as well as obstacle marks and gutter casts can be found on the bottom of the dolomitic siltstone layers. Occasional trilobite skeletal impressions can also be found in the silty layers (fig. 1-15D). The presence of *Chondrites* and *Cruziana* trace fossils indicate that the Estill was primarily deposited under oxic conditions. The interbedded siltstone layers preserving gutter casts and obstacle marks indicate occasional rapid increases in depositional energy, probably due to density flows caused by storm action in nearby, shallower environments. The general clay-rich composition and regional extent of the Estill may make it a suitable cap rock for the Medina Group ("Medina" and "Clinton" sands) reservoirs of southeastern Ohio.

The Estill represents sequence IV, extends east into the Appalachian Basin, and correlates, at least in part, to the Dayton and Osgood formations in western Ohio, and to the Williamson Shale and Rockway Dolomite in the northern Appalachian Basin (fig. 1-2). In subsurface investigations, the Estill is often either combined with, or erroneously correlated as, the stratigraphically higher Rochester Shale (S-V).

The Bisher Formation overlies the Estill (fig. 1-15A). It is much more resistant than the Estill, and along with the overlying Lockport Group carbonates forms prominent cliffs in southern and southwestern Ohio. The contact with the underlying Estill is wavy, and iron oxide nodules are abundant in the uppermost Estill along the contact bedding plane (figs. 1-15B, 1-16A). In general, the Bisher is composed of sand-sized dolomitic grains and is buff to orange in color. It is split into three informal members: the lower, middle, and upper Bisher. The lower and upper Bisher are tan to orange in color in weathered color, composed of sand-sized dolomitic grains and exhibit prominent trough crossbedding (fig. 1-16B). The middle Bisher is a grayish-tan argillaceous dolocalcarenite to a dolomitic shale with less prominent crossbedding than the lower or upper Bisher. Bases of a few dolosiltites/fine calcarenites show excellently preserved *Rusophycus* traces probably attributable to the large trilobite *Trimerus*. There are also minor stringers of crinoidal debris and brachiopods. The middle Bisher is almost absent at this locality, but some argillaceous beds can be seen in the middle of the unit. The trough and swaly crossbedded dolocalcarenites of the lower and upper Bisher likely indicate high sedimentation rates with storm influence at depths near fair weather wave base, and the argillaceous dolostone and shales of the middle Bisher likely indicate deeper-water conditions. The Bisher represents Silurian sequence V, and correlates to the Irondequoit Limestone, Rochester Shale, and Decew Dolostone in the northern Appalachian Basin (fig. 1-2).

FIGURE 1-16. (A) Photo of iron oxide nodules formed within burrows on the base of the Bisher Dolomite. (B) Photo showing cross bedding in the upper Bisher Dolomite. There are numerous types of cross bedding throughout the Bisher. Note the trough cross bedding below the pen and the symmetrical cross bedding on the layer on which the pen is resting.

The Lilley Formation overlies the Bisher Formation (figs. 1-17, 1-18A) and is the lowest unit in the Lockport Group. The Lilley is made up of four informal members: the lower Lilley, middle thin-bedded Lilley, upper Lilley, and uppermost shaly Lilley. The lower Lilley is known for its blueish-gray weathering, herringbone crossbedded, skeletal dolomitic pack- to grain-stones (fig. 1-18B). The herringbone crossbeds indicate that the Lilley was deposited under slightly deeper conditions than the lower or upper Bisher, likely just above storm-weather wave base in a tidally influenced shoal. The middle Lilley is a thin (<3 ft) interval of thin-bedded argillaceous dolostone and dolomitic shale correlated with the Pekin Member of Gasport in New York. Nearby quarries show small mounds or bioherms at this level but they are absent at Measley Ridge. The upper Lilley is a dolograinstone with reef mound and reef-flank facies. Biohermal masses at the top of the upper Lilley extend upward into the shaly Lilley (fig. 1-18A). Bioherms are around 5 ft thick and occur only in 6 to 7 ft diameter patches at this outcrop. Deeper in the basin, the bioherms can show several hundred feet of relief, and are often termed the "Niagaran Pinnacle Reefs" in Silurian literature. Stromatoporoid-rich cores can be seen in some of the bioherms exposed in this section (fig. 1-18C). The shaly Lilley is almost entirely a dark gray dolomitic shale that drapes over and surrounds the reef mounds of the upper Lilley. The influx of clastic sediment during the deposition of the shaly Lilley prevented further growth of the bioherms. The Lilley represents S-VI and may correlate to the upper Lewisburg Formation and Massie Shale in Greene County, and to all or part of the Gasport and Goat Island Dolostones in the subsurface of eastern Ohio (fig. 1-2).

The highest units at this location are the Lilley-Peebles Transition (LPT) and the Peebles Dolomite (fig. 1-17A). The LPT is a distinct zone where there is a facies transition from the Lilley to the Peebles (Swinford, 1985). In places it is sharply set off from the underlying shale by a slightly undulatory surface, and at its top by a sharp contact with the Peebles. Its transitional character is expressed as a decreasingly argillaceous and silty dolocalcarenite, locally with cladoporid corals, which is sharply overlain by the clean, crystalline Peebles Dolomite. The chronostratigraphic position of the LPT is considered to be the falling stage of sequence VI.

FIGURE 1-17. Photo of the northward view of the Measley Ridge outcrop showing the subtle contact between the Bisher Formation and the overlying Lilley Formation. Note subtle bioherm structures at the top of the upper Lilley. Photograph courtesy of Kyle Hartshorn.

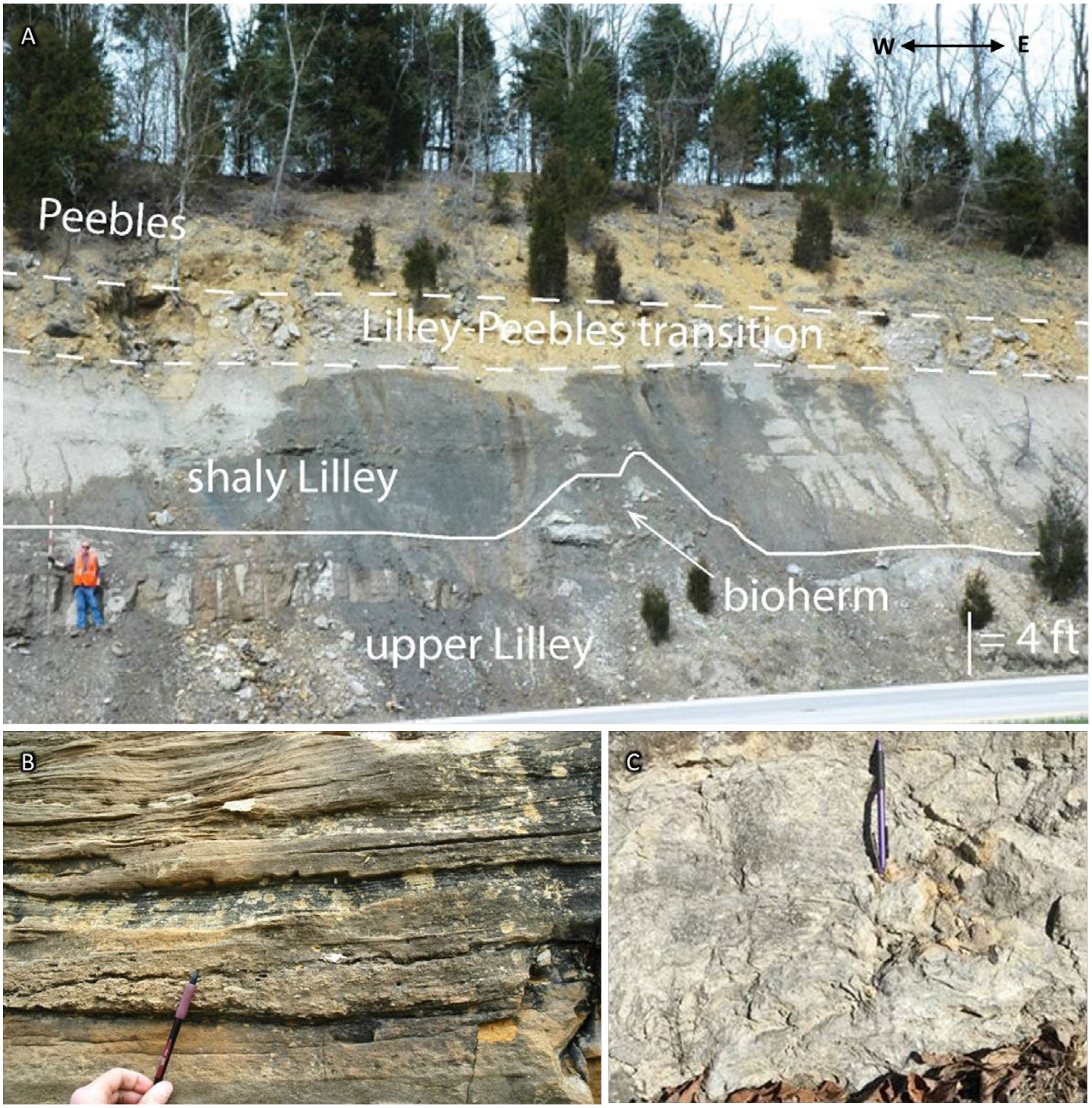


FIGURE 1-18. A: Photo showing the uppermost units exposed at the Measley Ridge roadcut on OH-32 (38.936536°, -83.448249°). Note the relief in the contact between the upper and shaly Lilley Formation due to the bioherm. Bioherms at this location are small and were suffocated by siliciclastic input during the deposition of the shaly Lilley. B: Close-up photo showing subtle cross bedding in the lower Lilley Formation. The head of the pencil is pointing to a brachiopod hash bed, interpreted to represent storm deposition. C: Photo showing the Stromatoperoid core of a bioherm in the upper Lilley Formation.

SUBSURFACE CORRELATIONS

Once detailed lithostratigraphy within a sequence stratigraphic framework can be confidently applied to geophysical logs, precise subsurface correlations can be made, guided by sequence stratigraphic predictions. Plates 1-1–1-5 show correlations of Medina Group and Clinton Group strata in southern and southeastern Ohio. Plates 1-1–1-4 show form intersecting cross section lines, and Plate 1-5 shows how the coarser, more-clastic-rich “New York” Medina Group units correlate with the fine clastic and carbonate Medina Group units of southern Ohio.

The units correlated on the cross sections are mostly the southern Ohio Silurian units (fig. 1-2), even in regions where other unit names are used (e.g., wells in southwestern Ohio). Similarly, the lithology fill patterns used in the cross section are based on the unit lithologies in outcrop in southern Ohio. Due to software limitations, lithology patterns cannot be changed across facies boundaries. For example, the Whippoorwill formation transitions laterally from argillaceous carbonates into high-gamma shale of the Power Glen Formation (pls. 1-2 and 1-3), but the “muddy carbonate” lithology fill pattern continues. Despite this, the lithology fill patterns are useful for distinguishing thin units from each other on the cross sections, so they were retained. In eastern and southeastern Ohio, Medina Group formation names (Whirlpool, Power Glen, Grimsby, etc.; fig. 1-2) from New York are used, as well as some New York Clinton Group names (Williamson-equiv.?, Rockway Dolostone).

Plate 1-1 shows a stratigraphic cross section from the core in Greene County to a composite of the exposed sections in Adams County. Overall, there is a trend towards higher gamma values in all units from Greene County to Adams County, indicating increasing mud content, which in turn reflects increased water depth in Adams County and/or closer proximity to sediment sources. The overall thickness of sequences H1(?) through S-III do not change much from Greene County to Adams County. This indicates that aside from some slight water depth differences leading to differential mud deposition, water depth was fairly similar between the two locations during the “Medinan” phase of the Taconic foreland basin evolution (sequences H1(?) and S-I) and during the time between the end of the Taconic Orogeny and initiation of the Salinic Orogeny (sequences S-II and S-III). Notable differences in sequence thicknesses begin during the Salinic Orogeny, with S-IV, S-V, and S-VI strata being markedly thicker in Adams County than in Greene County. This may indicate that the Grenville Front acted as a sort of “hinge” where Salinic subsidence occurred to a greater extent to the east over Grenville basement in contrast to the more limited subsidence to the west, which is underlain by Granite-Rhyolite province basement and Proterozoic sedimentary (rift and/or foreland) basins.

Plates 1-2 and 1-3 extend from the core and outcrop areas (Greene and Adams Counties, respectively) mostly dipping down (depending on the basin shape at the time of unit deposition) into deeper, more proximal parts of the Appalachian Basin. Plate 1-2, and to a lesser extent Plate 1-3, show the relationship between the units comprising the Medina Group in southern and southwestern Ohio (Whippoorwill formation, Brassfield Formation, white Brassfield) with the coarser clastic Medina Group units named for type sections in New York and Ontario, Canada. The Centerville Member and Belfast Member correlate to the Whirlpool Sandstone and Power Glen Shale, respectively. The silty carbonates of the Centerville grade into the sand of the Whirlpool, and the carbonate Belfast grades into the Power Glen Shale, which is dominated by shale with some occasional carbonate interbeds. The transgressive lower massive Brassfield correlates to the Artpark phosphatic carbonates just above the lowstand deposits of the Devils Hole Sandstone, and the thin-bedded and upper shaly Brassfield correlate to the “lower shale” member of the Grimsby Formation, and represent the TST and possibly early HST of S-I. The rest of the New York Medina Group units appear to be stratigraphically higher than the Brassfield and are tentatively assigned separate, stratigraphically higher subsequences (pl. 1-3). This interpretation means that in southern and southwestern Ohio, roughly half of the Medina Group was either not deposited at all or was removed during the S-I/S-II sequence boundary. Sequences S-II and S-III are mostly similar in both cross sections—they are thicker in the east, deeper into the basin, and thinner towards the west on the distal basin ramp. Sequences S-IV and S-V show more differences than the lower sequences in Plate 2 and Plate3. In the southern cross section (pl. 1-3), S-IV is completely shale/mudrock and has a uniform thickness across the section, whereas in the northern cross section (pl. 1-2) the sequence has a prominent carbonate at its base (Dayton Formation) across much of the cross section and shows distinct westward thinning. This pushes the boundary of the Dayton Formation, as defined in Brett and others (2012), farther eastward into central Ohio. The pronounced westward thinning of S-IV apparent in Plate 1-2 does not occur in Plate 1-3, which indicates that subsidence related to the initiation of the Salinic Orogeny was more pronounced in southern Ohio than in southwestern Ohio. The same difference in thickness patterns between Plates 1-2 and 1-3 is visible in S-V strata (regardless of whether the Lewisburg and Massie are considered S-V)—in southern and southeastern Ohio S-V strata have similar thicknesses along the cross section (pl. 1-3), in contrast to the more northern cross section (pl. 1-2), where S-V strata show pronounced westward thinning.

Plates 1-4 unites the eastern ends of Plates 1-2 and 1-3, and when combined with Plate 1-5, illustrates a long cross section line along depositional strike from southeastern Ohio to central Ohio. These two cross sections are useful for illustrating the facies changes that occur in the Medina Group from southeastern Ohio, where the coarse Medina Group sandstone units are more limited, to where sandstones become the dominant lithology in central eastern Ohio. In Plate 1-4, the lowermost Medina Group, H1(?), is similar to that of New York, being represented by the Whirlpool Sandstone and Power Glen Shale. The S-I units are slightly different—in southeastern Ohio the LST/ETST Devils Hole Sandstone is not present, but a greatly thinned carbonate unit equivalent to the lower massive Brassfield (ETST) occupies the base. The thin-bedded Brassfield and shaly Brassfield are equivalent to the lower Grimsby Shale. The thin-bedded Brassfield can be distinguished from the overlying shaly Brassfield because it has slightly lower gamma values and/or minor carbonate interbeds. In Plate 1-4 the remainder of the Medina Group appears to be composed of standard New York units (middle Grimsby sandstone, upper Grimsby shale, Thorold Sandstone, and Cambria Shale). In Plate 1-5, extending farther north, the Devils Hole Sandstone appears, and the facies correlated to the thin bedded Brassfield in Plate 1-4 disappears.

Plates 1-4 and 1-5 show an interesting unit at the base of the Clinton Group (S-II) that does not appear to be present at any area in the northern or western Appalachian Basin containing outcroppings of this chronostratigraphic interval. There is a relatively thin but traceable sandstone that appears under the Rose Run Iron Ore. It is tentatively interpreted as LST deposits at the base of S-II and termed the "lower Clinton sand." Further mapping of this unit is required to determine if its geometry continues to point towards our interpretation as a lowstand sand deposit of S-II, or if it is just an additional sand unit at the top of S-I, perhaps equivalent to the Kodak Sandstone of New York. The remainder of the Clinton Group units along Plates 1-4 and 1-5 are consistent with previous sequence stratigraphic interpretations, with the exception of the placement of the "Rockway" as a unit within the middle of the Estill Shale. Under previous interpretations (e.g., Brett and others, 1998), the Rockway is considered to represent the FSST at the top of S-IV, whereas its placement in these cross sections is stratigraphically lower, and interpreted to represent the TST of a higher-order cycle (S-IVB) in the middle of S-IV. This interpretation is based both on conodont and chemostratigraphic evidence of the older chronostratigraphic position of the Rockway (see discussion of Rockway above), as well as correlations from central eastern and northeastern Ohio into New York (C. Waid, personal observation). Correlation of S-V strata (Bisher Formation) is challenging, because of extensive lateral facies changes. In some wells it is a thin carbonate, in others it is a thick carbonate, and in still others it can be a mix of higher-gamma, mud-rich lithology with carbonates. In general, the top of the Bisher is picked at the base of the very clean carbonates of the Lockport Group.

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ROAD LOG

Depart Radisson Hotel Cincinnati Riverfront

1. Exit south end of Radisson Hotel parking lot. Turn left on W. 5th St. to head eastward.
2. Follow W. 5th street until it turns left into Garrard St. — **0.8 mi**
3. Use right lane to turn onto W 4th St. — **0.1 mi**
4. Follow W. 4th St. to traffic circle. At traffic circle take third exit for W. 3rd St. — **0.4 mi**
5. Follow W. 3rd street to Washington Ave. Use right lane to turn left onto Washington Ave. — **0.7 mi**
6. Turn right onto Dave Cowens Dr. — **0.1 mi**
7. Turn right to merge onto I-471 S. Follow I-471 S towards I-275 E. — **0.1 mi**
8. Use left two lanes to take exit 1A to merge onto I-275 E. towards Columbus — **16 mi**
    a. Entering Ohio
9. Exit onto OH-32 E. toward Batavia — **11.6 mi**
10. Exit right into rest area — **25.8 mi**

Stop 1 will be on the right (39.018756° N, 83.825013° W)

Depart Stop 1: ODOT Rest Area on OH-32 between Mount Orab and Sardinia, OH

1. Turn right from rest area parking lot onto OH-32 E.
2. Turn right onto OH-247 S./Main Street. — **15.6 mi**
3. Turn left onto Rigdon Rd. then turn left onto Logans Lane. — **7.8 mi**
4. Turn right onto OH-41 S. — **2.5 mi**
5. Outcrop will be on right. — **0.5 mi**

Stop 2 will be on the right (38.827498° N, 83.505647° W)

Depart Stop 2: OH- 41 exposure north of Lick Fork Church

1. Continue south on OH-41 S.
2. Outcrop will be on right. — **0.5 mi**

Stop 3 will be on the right (38.821372° N, 83.511839° W)

Depart Stop 3: OH- 41 exposure south of Lick Fork Church

1. Continue south on OH-41 S.
2. Turn right onto Park Rd. 1. — **0.8 mi**
3. Pavilion will be on right. — **0.4 mi**

Stop 4 will be on the right (38.813399° N, 83.527003° W)

Depart Stop 4: Lunch Stop and Core Viewing at Adams Lake State Park

1. Head east on Park Rd. toward OH-41 N.
2. Turn left onto OH-41 N. — **0.4 mi**
3. Turn right (if there is space) into dirt driveway next to roadcut. — **7.8 mi**

Optional Stop 4.5 will be on the right (38.904607° N, 83.448677° W)

Depart Optional Stop 4.5: Brush Creek Motorsport Complex

1. Continue north on OH-41 N.
2. Turn left onto OH-32 W. — **2.7 mi**
3. Pull off at safe location on right side of highway. — **~2.0 mi**

Stop 5 will be on the right (38.937402° N, 83.453183° W)

Depart Stop 5: Measley Ridge Roadcut along OH State Rt. 32 west of OH State Rt. 41

1. Head west on OH-32 W. toward Lawshe Rd. — **47.5 mi**
2. Continue straight to stay on OH-32 W. — **0.3 mi**
3. Turn right to merge onto I-275 S. towards US-52/Kentucky — **11.9 mi**
4. Use the right two lanes to take exit 74B for I-471 N. towards Newport/Cincinnati — **0.4 mi**
5. Merge onto I-471 N. — **4.7 mi**
   a. Entering Ohio
6. Take exit 6A for US-50 S. towards I-71 S./I-75/Third St. — **450 ft**
7. Keep left, follow signs for US-50 W./I-71 S./I-75/Third St. and merge onto US-50 W. — **0.5 mi**
8. Use the right two lanes to take the Third St. exit toward Downtown/Riverfront — **0.2 mi**
9. Continue onto E. 3rd St. — **0.5 mi**
10. Use the right two lanes to continue on W. 3rd St. **— 350 ft**
11. Use the right two lanes to turn right at the first cross street onto Elm St. — **0.2 mi**

Conclude field trip upon return to Radisson Hotel Cincinnati Riverfront (39.1008° N, 84.5163° W)

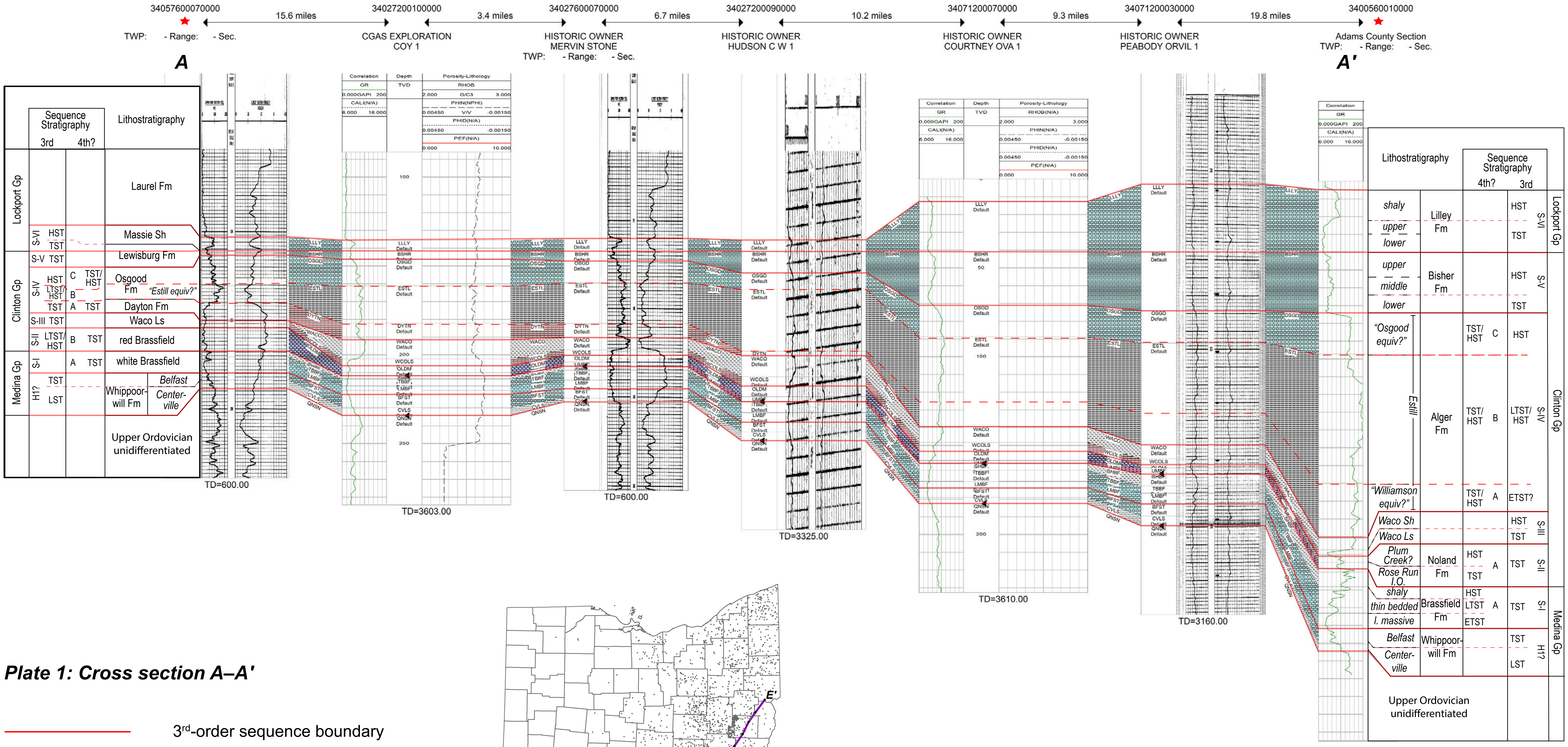
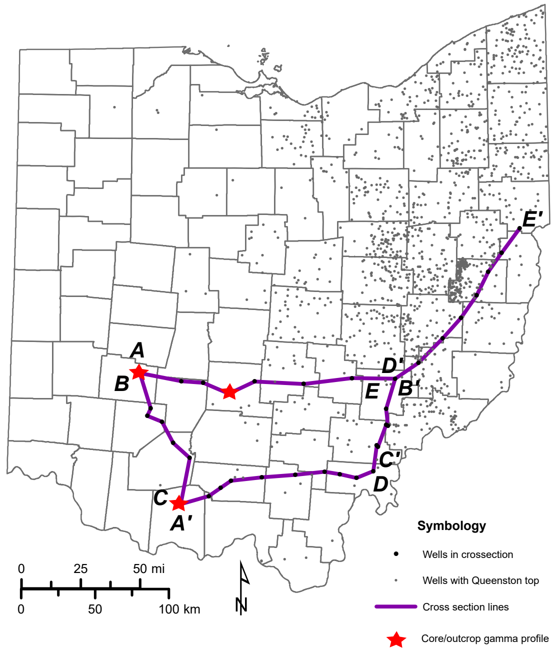


Plate 1: Cross section A–A'

3rd-order sequence boundary

4th?-order sequence boundary

Systems tract boundary



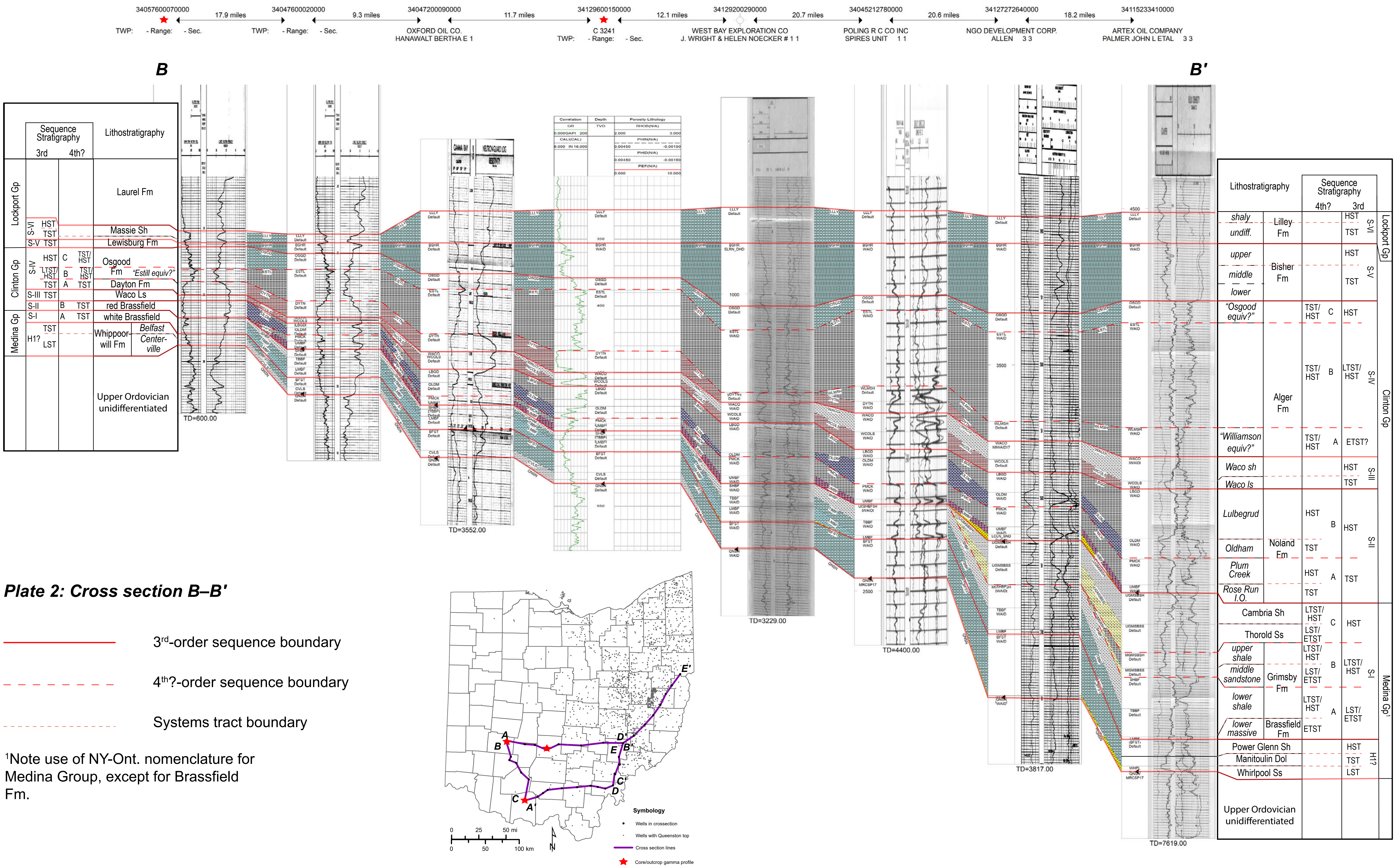


Plate 2: Cross section B–B'

3rd-order sequence boundary

4th?-order sequence boundary

Systems tract boundary

¹Note use of NY-Ont. nomenclature for Medina Group, except for Brassfield Fm.

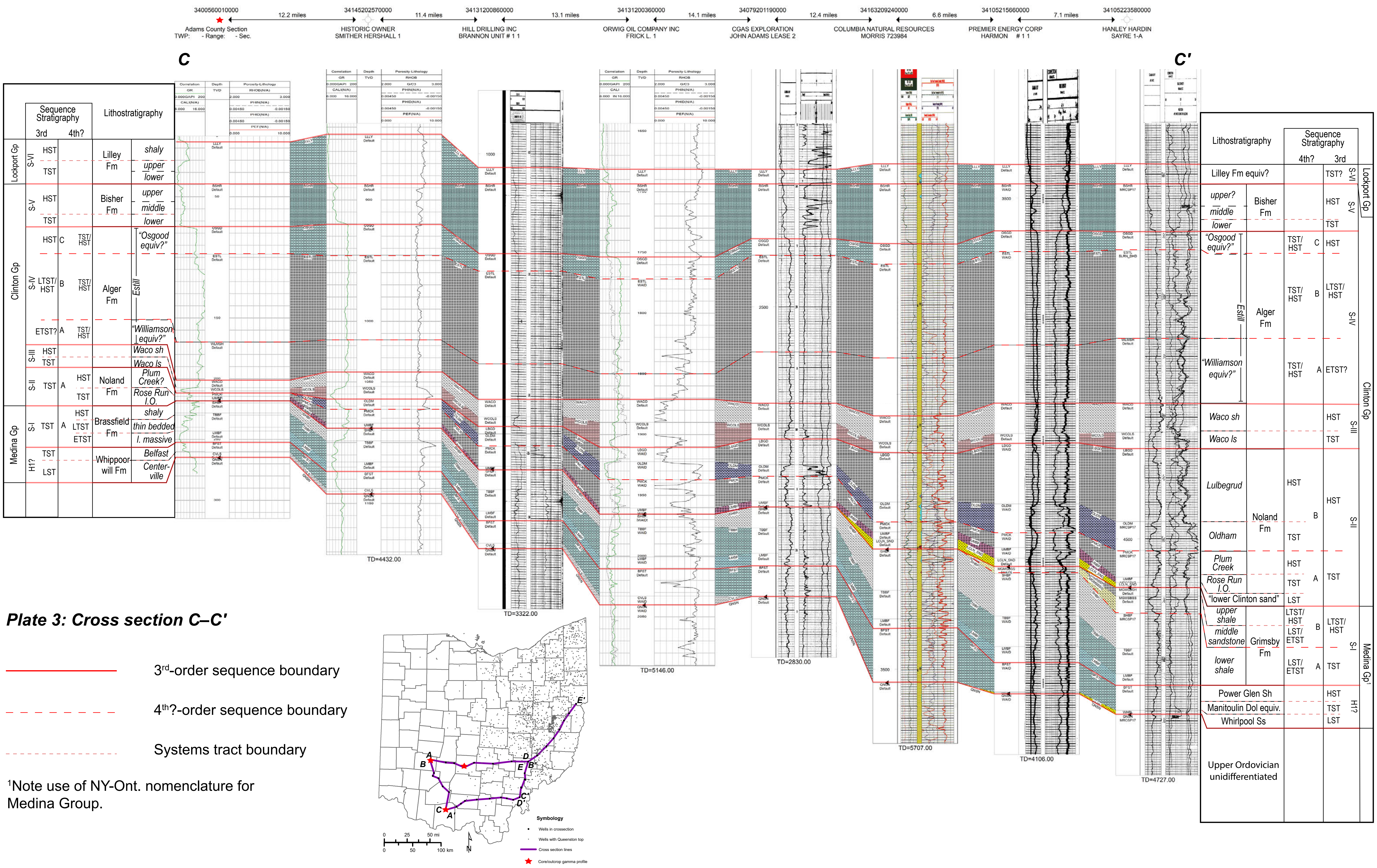


Plate 3: Cross section C–C'

3rd-order sequence boundary

4th?-order sequence boundary

Systems tract boundary

[1] Note use of NY-Ont. nomenclature for Medina Group.

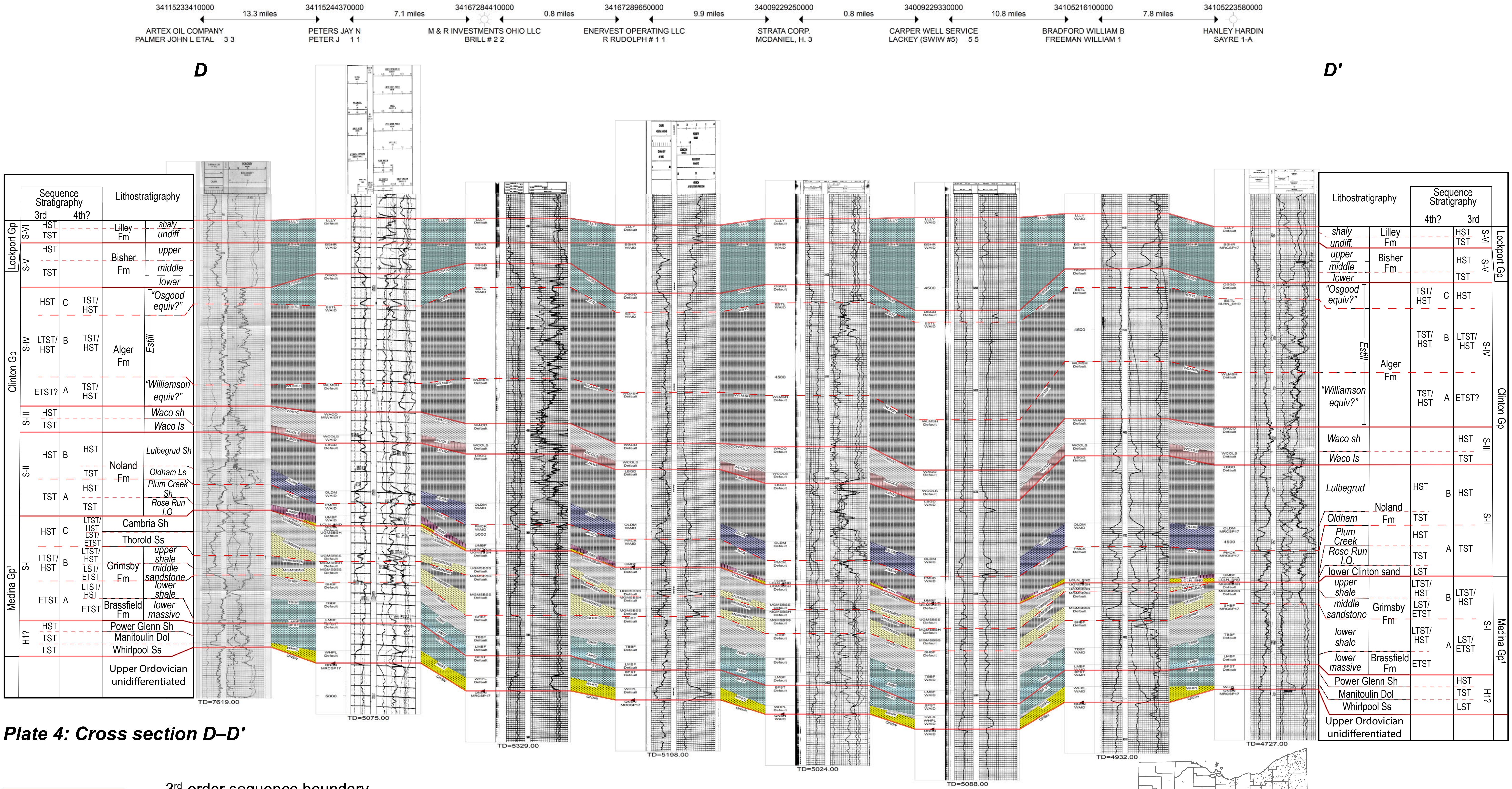


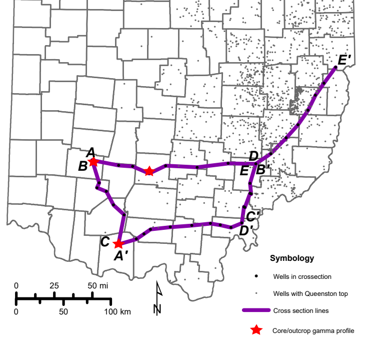
Plate 4: Cross section D–D'

3rd-order sequence boundary

4th?-order sequence boundary

Systems tract boundary

[1] Note use of NY-Ont. and OH nomenclature for Medina Group.



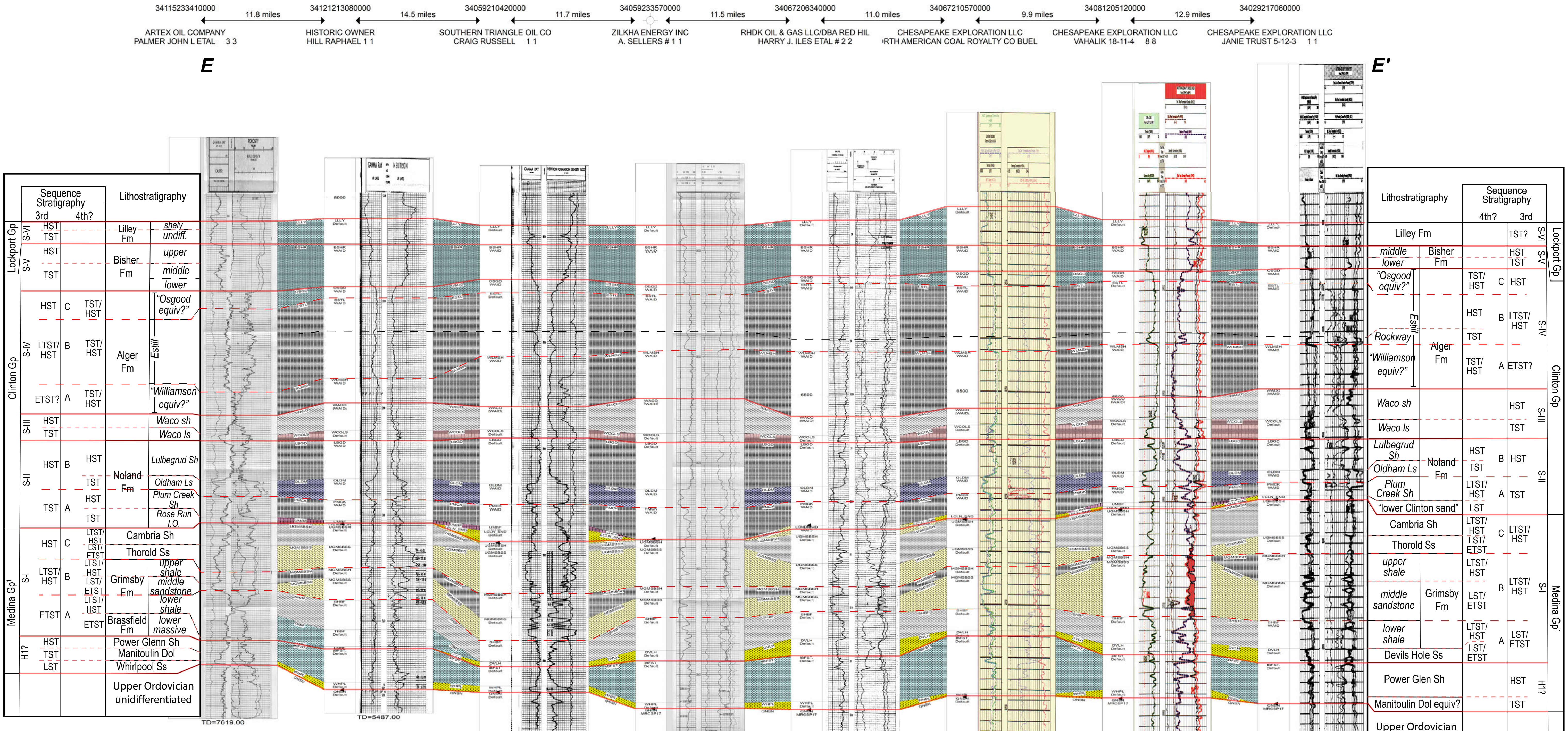
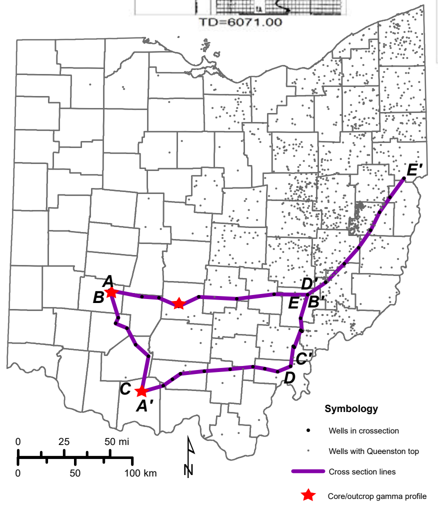


Plate 5: Cross section E–E'



━━━━	3rd-order sequence boundary
─ ─ ─ ─	4th?-order sequence boundary
- - - - - -	Systems tract boundary

[1] Note use of NY-Ont. nomenclature for Medina Group.

CHAPTER 2

Exploring the type Cincinnatian Series (Upper Ordovician) and its world-famous fossils at Hueston Woods State Park

OHIO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES

American Institute of Professional Geologists
60th Anniversary Conference 2023

Geologic Field Trip

Exploring the type Cincinnatian Series (Upper Ordovician) and its world-famous fossils at Hueston Woods State Park

Field trip leader: Mark E. Peter*,[1]

Ohio Geological Survey

*** Field trip guide author.**

[1] Ohio Department of Natural Resources, Division of Geological Survey

Field trip cover photo: Photo of Late Ordovician fossils on display at Hueston Woods State Park nature center in College Corner, Ohio. Fossils include the trilobites *Flexicalymene retrorsa* (left center) and *Isotelus maximus* (right center) and stream-worn rugose "horn" corals, a tabulate coral, brachiopods, and bryozoans (at bottom).

INTRODUCTION

TRIP OVERVIEW

This one-day trip will provide an opportunity to view museum exhibits of fossils from the type Cincinnatian Series (Upper Ordovician) and to view and collect these fossils in stratigraphic context at Hueston Woods State Park. This guide was originally written to accompany a field trip associated with the 2023 AIPG 60th Anniversary National Conference hosted in Covington, Kentucky. The trip is designed to last approximately 9 hours, including transportation between the conference hotel and the various field trip stops.

The first field trip stop will be a visit to the Karl E. Limper Geology Museum in Oxford, Ohio on the campus of Miami University. There, participants will have an opportunity to view exhibits of both common and rare Upper Ordovician fossils from the type Cincinnatian Series, including many from nearby localities.

The remaining stops (fig. 2-1) are within the boundaries of Hueston Woods State Park. Stop 2 is a visit to an excavated hillside exposure at the Acton Lake Spillway. This stop will provide an opportunity to view outcroppings of the Waynesville Formation and to briefly collect fossils. Stop 3 is a restroom break and picnic lunch at tables by the Hueston Woods State Park nature center. Stop 4 is a visit to natural stream exposures of the Liberty Formation (and possibly the Whitewater Formation) along East Fork, Four Mile Creek. Here, participants will be able to walk upstream to inspect outcrops and to collect fossils. Stop 5 is a return to the nature center for a final restroom break before returning to the conference hotel.

Important note: Although collecting of fossils and other natural objects is usually prohibited in Ohio's state parks, fossils at Hueston Woods have been determined to be a plentiful and renewable resource and personal collecting for non-commercial purposes is currently allowed within portions of the park that are not located within the nature preserve. Please verify that these rules still apply before collecting any fossils.

Likewise, please verify museum hours of operation and access prior to visiting the Karl E. Limper Geology Museum. It is also recommended to consult the website of Miami University for information about parking on campus for the date and hours of any planned visit.

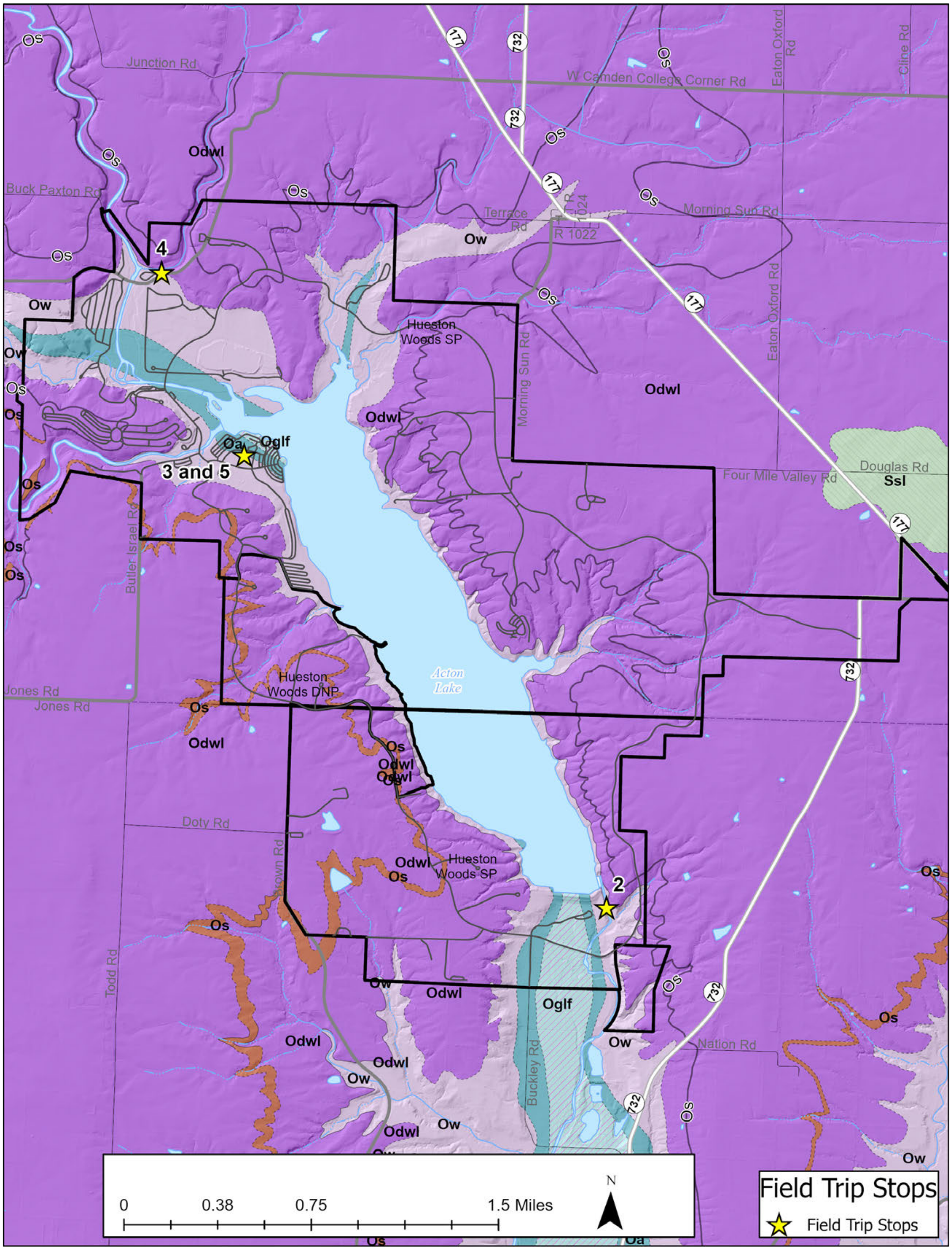


FIGURE 2-1. (A) Overview map showing field trip Stops 2–5. Stop 1 at the Limper Geology Museum in Oxford, Ohio is outside of the overview map area. The map has a bedrock geology base and shows roads, county lines, nature preserve, and Hueston Woods State Park boundary (bold black lines). Relevant bedrock map symbols: Ow=Ordovician System, Waynesville Formation; Odwl= Ordovician System, Drakes, Whitewater, and Liberty Formations, undivided.

THE TYPE-CINCINNATIAN

The Upper Ordovician sedimentary rocks exposed near Cincinnati, Ohio, are some best studied in North America and the world. Several hundreds, if not thousands, of academic papers have been published and scores of professionals over the last one hundred and fifty years have devoted much of their careers to work on the paleontology, sedimentology, and stratigraphy of these rocks. Major museums in Europe and around the world exhibit fossils from Cincinnati. Natives of this region often take for granted the abundance of well-preserved fossils and may be surprised to see locally common brachiopod shell fossils prominently displayed in distinguished museums. But the fact is that the rocks around Cincinnati contain some of the world's most well-preserved fossil assemblages of Late Ordovician age. Because these rocks were so well known to North American geologists, the Late Ordovician in North America was named the Cincinnatian Epoch, and the Upper Ordovician rocks that bear record of that time the Cincinnatian Series (Davis, 1998; Nickles, 1902).

Cincinnati has also produced a disproportionate number of North American paleontologists, beginning with the "Cincinnati School of Paleontology," comprised of informally trained paleontologists and "amateur" (avocational) geologists in the time following the American Civil War and into the early twentieth century (Meyer and Davis, 2009). All of these were affiliated with the Cincinnati Society of Natural History. Some remained avocational paleontologists, but others became distinguished professional geologists and paleontologists, including Charles Schuchert (Yale University), John Nickles (U.S.G.S.), Ray Bassler (U.S.N.M., Smithsonian Institution), and E.O. Ulrich (U.S.G.S.)(Meyer and Davis, 2009).

The tradition of collaboration between avocational and professional paleontologists continues in Cincinnati today. One of the oldest—possibly *the* oldest—continuously active associations of avocational paleontologists is the (Cincinnati) Dry Dredgers, which has been meeting on the campus of the University of Cincinnati since 1942. The association has been advised by local academicians, beginning with Professor Kenneth E. Caster at the University of Cincinnati. Members of the Dry Dredgers have authored and contributed to many peer-reviewed publications relating to Cincinnatian stratigraphy and paleontology. Two members, William White and Stephen Felton, have received the Harrell L. Strimple Award, an honor bestowed by the Paleontological Society for significant contributions by avocational paleontologists (Miller, 2017).

PALEOGEOGRAPHY AND DEPOSITIONAL SETTING

During the Late Ordovician, the land that is now Ohio, including Cincinnati and the area surrounding Hueston Woods State Park, was submerged beneath a shallow epicontinental epeiric (inland) sea. The Ordovician was a time of high sea levels (Vail, 1977), often attributed to high rates of seafloor spreading, and the global climate was initially under greenhouse conditions (briefly transitioning in the latest Ordovician to icehouse)(Brenchley and others, 1994). These factors have been implicated for the flooding of much of the interior of the paleocontinent Laurentia, which included what is the core of present-day North America.

The Late Ordovician rocks of the region were deposited between about 451–446 million years before present, which corresponds to a global mid-late Katian Age (Brett and others, 2020). No rocks in the type-Cincinnatian have been numerically dated, but K-bentonites (volcanic ash beds) in the Utica Shale of New York State suggest an age of approximately 451 million years for the lowermost Cincinnatian rocks (Brett and others, 2020).

Owing to the movement of tectonic plates over the last ~450 million years, the Cincinnati region is now far from where it was during the Late Ordovician; the region was at that time in a tropical to subtropical latitude, approximately 20–23 degrees south of the paleoequator. What is now "North America" was also rotated about 45 degrees clockwise (when viewed from above) with respect to celestial north (fig. 2-2; Brett and others, 2020).

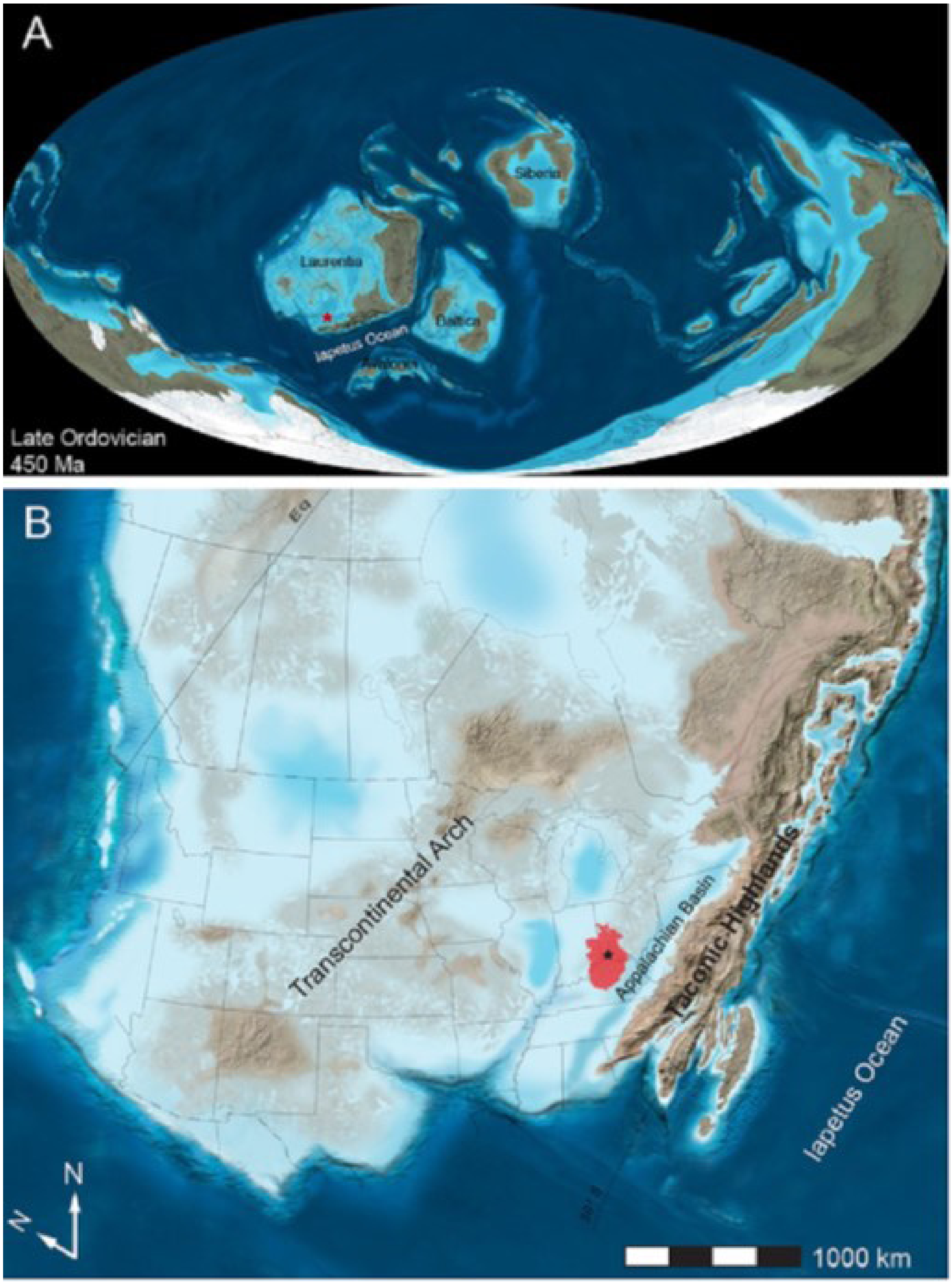


FIGURE 2-2. Late Ordovician paleogeographic reconstructions. (A) Location of the Cincinnati area within the paleocontinent of Laurentia marked with a red star. (B) Regional Ordovician outcrop area in red; present-day Cincinnati marked with black star. Note rotation with respect to paleoequator. "N" indicates present-day north and *"N"* is paleo-north. Reproduced from Stigall (2023) as modified from Blakey (2013) and Colorado Geosystems, Inc. (2016).

The latitude would have been comparable to that of the present-day Bahamas Islands, except in the southern hemisphere rather than the northern hemisphere. This latitude was in a zone conducive to the production of calcium carbonate by a variety of macroscopic and microscopic life, which allowed for the build-up of a carbonate platform (the Lexington Platform), which extended from areas that would become central Kentucky northward into Ohio and Indiana, deepening to the north (Meyer and Davis, 2009).

The seas were fully marine and included abundant brachiopods and corals as well as crinoids. Echinoderms, because of their water vascular systems, can be somewhat intolerant of hyposaline or hypersaline waters; this is particularly true for crinoids, which seem to be restricted to stenohaline environments (Russell, 2013).

The Cincinnatian rocks are a mix of impure autochthonous carbonates and allochthonous, fine-grained siliciclastics derived from the Taconic Highlands, located on the southern margin of the paleocontinent at least 400 kilometers (km) to the paleosouth of the Cincinnati region (fig. 2-2; Brett and others, 2020). Cincinnatian rocks have been fondly described by local geologists as "muddy limestones" and "limy mudstones." Prior to the evolution of terrestrial plants, more sediments were probably being shed from landmasses, so the water column was likely often somewhat turbid (Vogel and Brett, 2009). The total thickness of sedimentary deposits of limestones and shales that are exposed in the Cincinnati region is less than 300 m, compared to sedimentary packages of 1,000 m closer to the source area (Meyer and Davis, 2009).

The areas of Cincinnati and Hueston Woods State Park were located on a long, shallow ramp that deepened very gradually to the paleonorth (Brett and others, 2015). A deep trough, the Sebree Trough, was located to the north of this area, but this had largely filled in by Richmondian time when the bedrock at the surface of Hueston Woods was being deposited. No modern environment has the precise conditions of the Cincinnati Sea, but the Persian Gulf, which has a carbonate ramp with siliciclastic input, is sometimes cited as the closest modern analogue (Meyer and Davis, 2009; Brett and others, 2020).

The Cincinnatian strata were heavily influenced by frequent tropical storms or hurricanes, and a great many of the beds represent storm deposits (Tobin, 1982). Storms tracked from the direction of the equator southward into the Cincinnati sea. Previously, limestone beds were often interpreted as winnowed storm deposits (tempestites), whereas shales were interpreted as background sedimentation; Dattilo and others (2008) proposed an "episodic sediment starvation model" in which limestones represent the background sedimentation (overprinted and reworked by high-energy events), and "shales" (mudstone beds) represent high-energy event deposits that are preserved (Appendix 2-1).

The water depth varied over the span of time the Cincinnatian rocks were deposited, but the sea was never very deep (from supratidal near Richmond, Kentucky, to about 30, or at most 50 m deep, farther north near Hamilton, Ohio) (Brett and others, 2015) and was apparently within the euphotic zone (the depth within which photosynthesis can occur). Evidence for water depth comes from lithologic evidence and from the presence of microendoliths (traces of light-sensitive endolithic cyanonbacteria, and red and green algae) (Vogel and Brett, 2009). Other fossil evidence includes the presence of calcareous algae and corals, two of the prime carbonate producers on modern carbonate platforms. Green calcareous dasyclad algae are represented by several species and have been found in all Cincinnatian formations, indicating shallow depths within the photic zone. Calcareous algae fossils are rare and most commonly found at the top of the shoaling upwards cycles (Meyer and Davis, 2009). Not all present-day corals live within the euphotic zone or harbor photosynthetic endosymbionts, but there is some evidence that early Paleozoic tabulate corals may have, because their fossil calcium carbonate skeletons showed isotopic $\delta^{18}O$ to $\delta^{13}C$ ratios that were comparable to those of modern schleractinian corals that harbor zooxanthellae symbionts (Zapalski, 2014).

The Late Ordovician records the final stages of the Great Ordovician Biodiversification Event (GOBE), which occurred primarily during the Darriwilian global stage, when phyla established during the Cambrian became increasingly diverse at lower taxonomic levels (a "filling out" of the tree of life) with high rates of origination and high levels of morphological disparity (e.g., Stigall and others, 2019). Much of the increase in diversity was among benthic suspension-feeding organisms (Harper and others, 2014). However, the end-Ordovician extinction was one the "big five" mass extinction events (Raup and Sepkowski, 1982).

The extinction occurred in two phases, with the first phase associated with a significant regression caused by a global drop in sea levels (as much as 80–100 m) during the Hirnantian, the final Ordovician global stage. This severe drop in sea levels was owing to a short-lived (0.5–1 million years) glaciation on the supercontinent Gondwana, which straddled the polar region in the southern hemisphere (Brenchley and others, 1994). The second phase of the extinction involved sea level rise and pervasive anoxia. Losses were especially high in many benthic groups, including brachiopods (Brenchley and others, 2006; Harper and others, 2014).

Exposures of the Cincinnatian rocks, both natural and human-made, are numerous, owing in part to relatively thin-bedded (versus massive-bedded) limestones packaged with alternating layers of clay and shale. Frost wedging from seasonal freeze and thaw cycles will tend to replenish any semi-vertical outcropping of rock with newly exposed material. In addition to natural banks in stream exposures, the hilly geomorphology of the landscape has created the need to grade roads, resulting in many roadcut exposures in modern times. The numerous and accessible exposures make the Cincinnati area a near-ideal laboratory for both stratigraphers and paleontologists.

THE CINCINNATI ARCH AND ITS WELL-PRESERVED FOSSILS

Hueston Woods lies above a geological structure called the Cincinnati Arch (fig. 2-3), which spans hundreds of miles. This subsurface structure is an anticline, or up-folding, of Earth's crust. The arch is revealed by maps published by the Ohio Department of Natural Resources, Division of Geological Survey, such as the bedrock geologic map of Ohio (Slucher and others, 2006).

Now trending roughly north and south, the Cincinnati Arch extends through parts of central Kentucky, eastern Indiana, and western Ohio. East and west of the arch, rock layers dip gently into the subsurface. Erosion has exposed older rocks at the arch center. Beginning just north of Cincinnati, the arch divides into two branches: the Findlay Arch, which trends roughly north–northeast and south–southwest and passes through Findlay, Ohio; and the Kankakee Arch, which trends northwest–southeast as it extends through Indiana and northern Illinois and into Wisconsin. Together, these structural arches separate the Appalachian, Michigan, and Illinois basins (Potter, 2007; fig. 2-4).

Continental collisions during the Paleozoic Era caused several orogenies, or mountain-building events, in the region of the Appalachian Mountains. Each event, beginning with the Taconic Orogeny during the Ordovician Period, contributed to uplift of the arch rocks.

On either side of the arch, Ordovician-age rocks were buried by thick packages of younger rocks. Along the arch center, Ordovician rocks and fossils remained close to the surface. Never subjected to the destructive heat and pressure of deep burial, and far enough from the orogenic center to escape intensive folding and contact metamorphism, fossils on the Cincinnati Arch remained well preserved (Meyer and Davis, 2009).

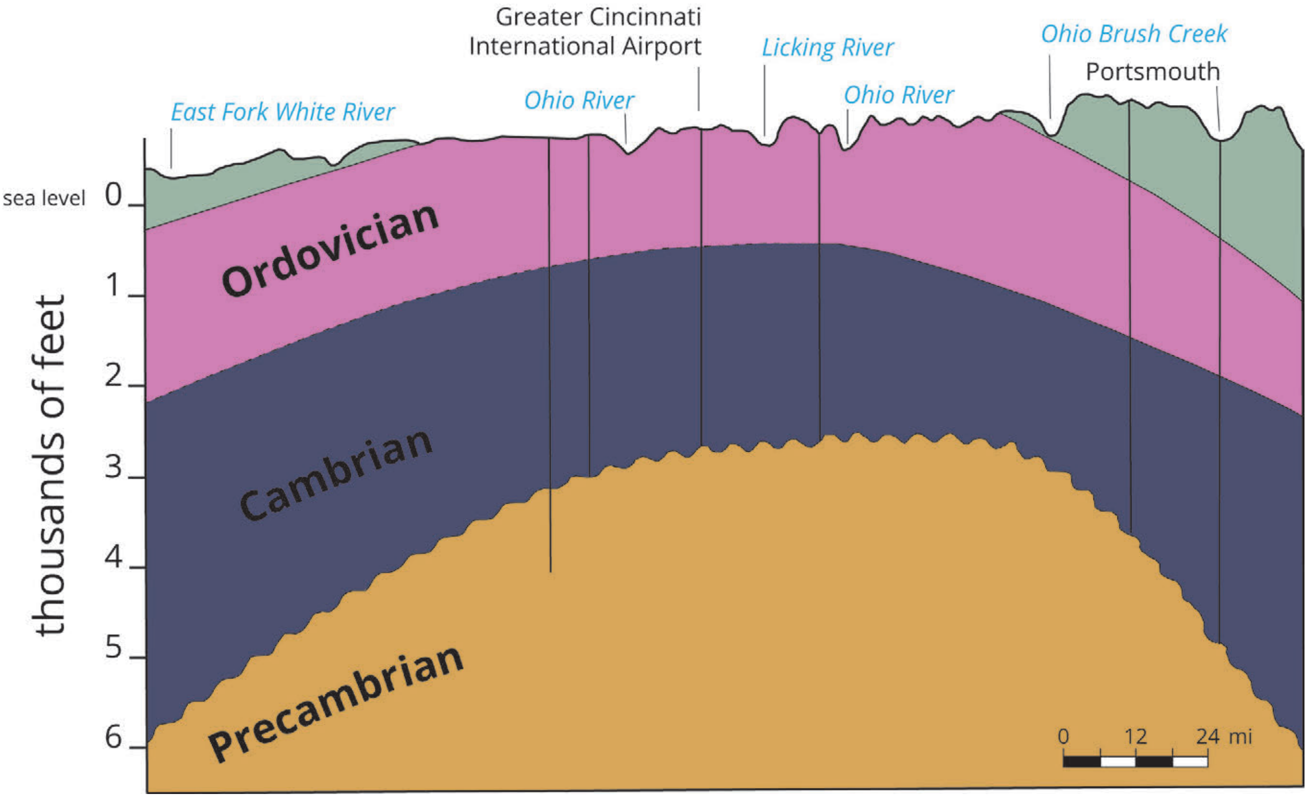


FIGURE 2-3. Cross section through the Cincinnati Arch, from southcentral Indiana to near Portsmouth, Ohio. Green shading represents rocks and sediments younger than Late Ordovician. Thick black lines are deep wells. Note different units of distance on map axes and high degree of vertical exaggeration. Modified from Potter (2007).

FIGURE 2-4. Major structural features of the U.S. midcontinent, including the Cincinnati, Findlay, and Kankakee Arches. Reproduced from Brett and others (2012).

CINCINNATIAN LITHOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY

The stratigraphy of the Cincinnati area is complex, in part because the entire series is a succession of mostly shales and limestones, and in part because the succession of rocks has been endlessly studied, divided and subdivided, and analyzed in great detail for more than 150 years. Formations sometimes ended at the Ohio, Kentucky, and Indiana state boundaries because of different approaches to mapping taken by state surveys of each state (Brett and others, 2020).

Rocks of the Cincinnatian Series of North America exposed near the land surface along the Cincinnati Arch fall within the Katian (and possibly Hirnantian)(Waid, 2018) global stages and are divided into three provincial stages: Edenian, Maysvillian, and Richmondian, in ascending stratigraphic order (Brett and others, 2020). The rocks well exposed at Hueston Woods State Park fall within this upper stage, the Richmondian.

Formations easily viewed within Hueston Woods State Park include, in stratigraphic order, the Waynesville, Liberty, and Whitewater; the lithostratigraphy of these formations are briefly described below under the sections covering the field trip stops. These formations together comprised part of a single, third-order stratigraphic sequence, the C5 sequence of Holland and Patzkowsky (1996); however, sequence divisions that had been employed since the late 1990s were revised by Brett and others (2020) (fig. 2-5); these authors identified multiple third-order and subordinate fourth-order sequences within the Waynesville, Liberty, and Whitewater formations. For a summary of the recent high-resolution sequence stratigraphy of the Cincinnatian rocks, the reader is referred to that study; see also Waid and others (2023) pages 1–54 of this guidebook.

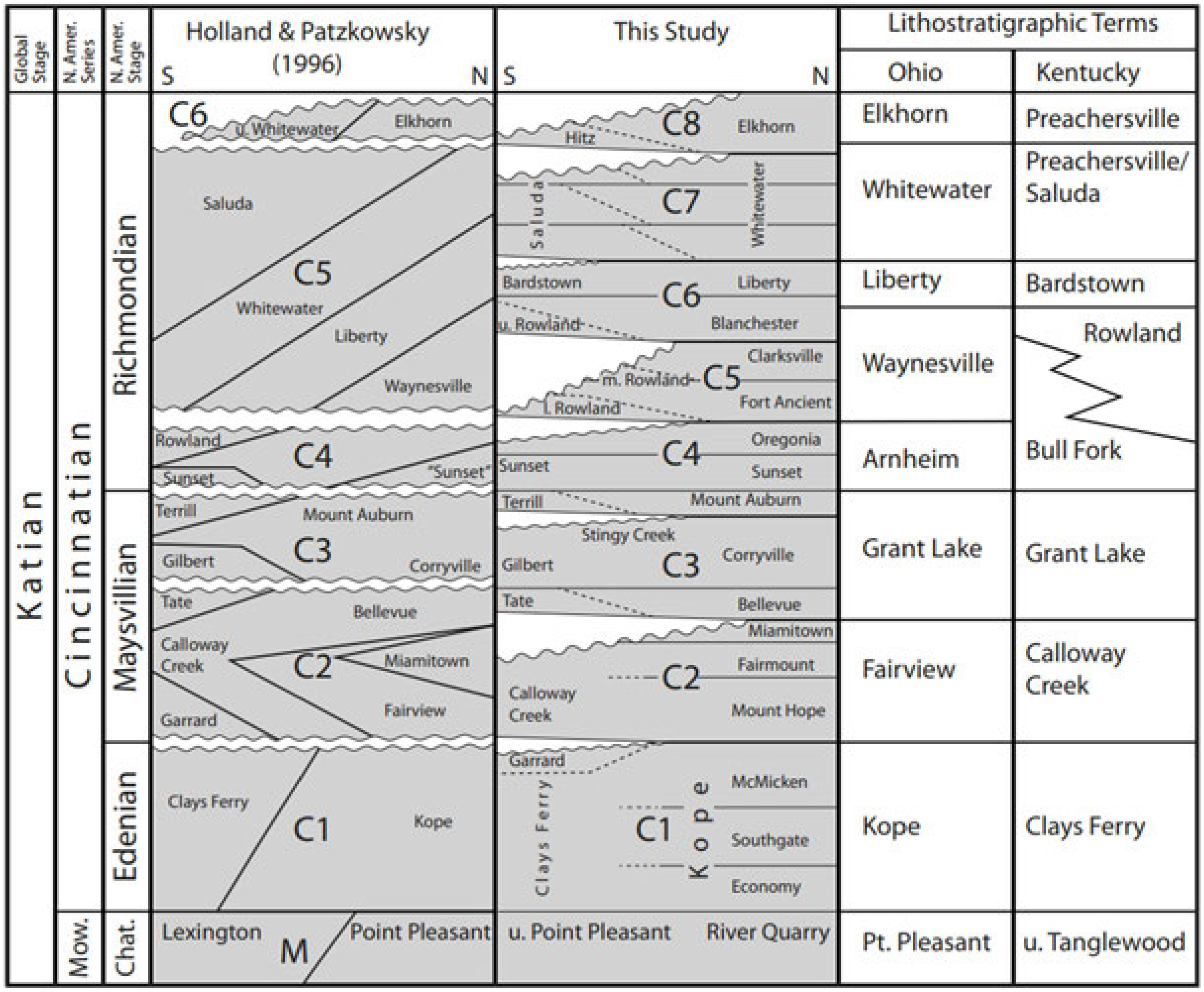


FIGURE 2-5. Comparative sequence stratigraphy of Holland and Patzkowsky (1996) and Brett and others (2020) and corresponding lithostratigraphy. Solid lines in left column indicate putative markedly diachronous facies changes; dashed lines in middle column indicate minor facies transitions; wavy lines indicate unconformities (reproduced from Brett and others, 2020).

THE RICHMONDIAN INVASION

The "Richmondian Invasion" is a name paleontologists give to the sudden appearance of new fossil species in the Ohio region during Late Ordovician time. This mass influx of species from other regions was distributed across many animal groups, including corals, mollusks, arthropods (trilobites), and brachiopods, among others (Stigall, 2010). Rocks layers exposed at Hueston Woods show evidence of this change in fauna from older rock layers underlying the park (Appendix 2-2).

Rocks of Richmondian age (named for Richmond, Indiana) include the youngest Ordovician rocks in Ohio. During early Richmondian time, elevated sea levels and possibly global warming removed geographic barriers between ocean basins. This opened new corridors for the dispersal of larvae drifting in ocean currents as plankton. Species from other regions entered the area, including warm-water animals from closer to the equator; notable was the return of corals. Many of the invaders came from the paleoequatorial region to the north (parts of the present-day western U.S. and Canada); the invasive fauna was originally referred to as an invasion of the "Arctic Fauna" (Stigall, 2010; Foerste, 1917; fig. 2-6).

Occurring in multiple phases, the Richmondian Invasion had significant ecological consequences. Some native species occupying specialized niches were replaced by these invaders while others successfully coexisted alongside them. Paleontologists know that overall biological diversity reached new heights during this time because of fossils revealed in rock layers at Hueston Woods and elsewhere in the region (Stigall, 2010). For a summary of research on the Richmondian Invasion, see Stigall (2023).

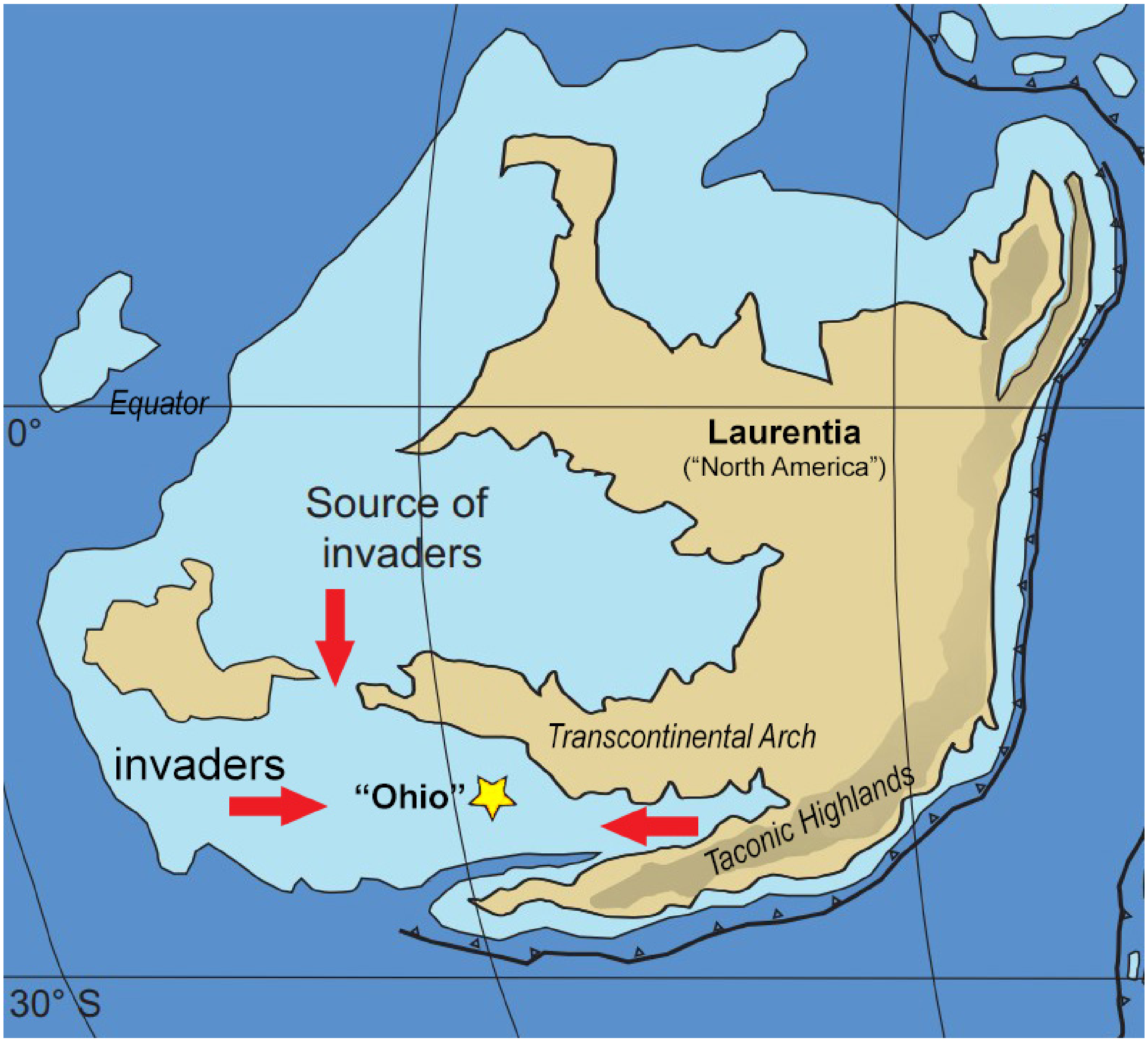


FIGURE 2-6. The Richmondian Invasion. Map shows a reconstruction of the ancient continent Laurentia during the Late Ordovician. Invasive species from multiple source regions (red arrows) entered the Ohio area (yellow star) during early Richmondian time. Modified from Stigall (2010).

FIELD TRIP STOPS

STOP 1: KARL E. LIMPER GEOLOGY MUSEUM (SHIDELER HALL, RM. 126, OXFORD, OH 45056) (39.5077° N, 84.7313° W)

This stop is a visit to a small geological museum on the first floor of Shideler Hall on the Miami University campus in Oxford, Ohio. The Karl E. Limper Geology Museum (fig. 2-7) is an excellent place to view examples of locally derived Ordovician fossils on public display. Most of the Cincinnatian fossils are arranged taxonomically. For trilobite enthusiasts, there is an exhibit of common as well as some very rare local species. A large diorama at one end of the main museum hall provides a living reconstruction of Ordovician sea life. Other highlights include large bryozoan colonies (fig. 2-8) and a rare, nearly complete *Jugiaster speciosus* sea star fossil from a find near Hueston Woods State Park. In addition to the many fine examples on display, the museum is a repository for Cincinnatian fossils with holdings of approximately 150,000 specimens (Hauer, 2022).

FIGURE 2-7. The main hall of the Karl E. Limper Geology Museum in Shideler Hall at Miami University, Oxford, Ohio. The museum features an assortment of geological specimens, with a heavy concentration of invertebrate fossils from the local Upper Ordovician rocks. The large trilobite in the foreground is *Isotelus maximus,* an example of Ohio's official State Invertebrate Fossil. A large diorama of Late Ordovician sea life adorns the rear wall.

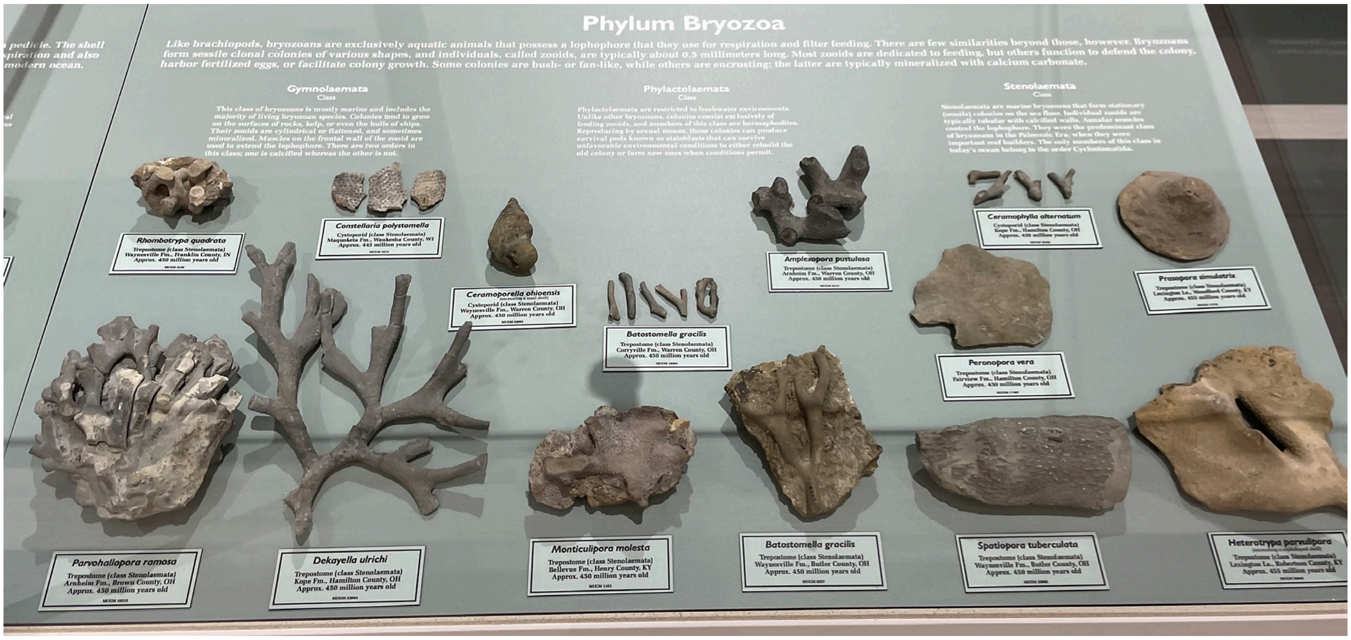


FIGURE 2-8. A Limper Geology Museum exhibit of Late Ordovician bryozoans, mostly from the Ordovician rocks of southwestern Ohio. The large trepostome bryozoan colony, reconstructed from fragments (bottom row, second from left), is an especially impressive specimen. Most branching bryozoans are found as short, broken fragments like the small grouping of specimens in the center of this exhibit.

Across the hall lobby from the entrance to the museum is a larger-than-life sculpture, “Southwestern Ohio’s Ancient Sealife,” (fig. 2-9), created by artist James M. Herrmann, a local schoolteacher and an alumnus of the Miami University geology department. The sculpture, cast in bronze using a “lost wax” technique, measures approximately 4 ft by 8 ft. The bas-relief sculpture was designed to be touched, making it accessible to visually impaired individuals. The depiction of the Late Ordovician sea features reconstructions of the animals in life, scaled to approximately four times their actual size. The sculpture, unveiled in 2021, was commissioned to celebrate the centennial of Miami University’s Department of Geology and Environmental Earth Science (formerly the Department of Geology), founded by paleontologist William H. Shideler in 1920. (Hauer, 2022).

FIGURE 2-9. Bronze sculpture, *Southwestern Ohio’s Ancient Sealife,* by local artist Jim Herrmann in Shideler Hall on the Miami University campus in Oxford, Ohio. Unveiled in 2021, the sculpture commemorates the first 100 years of the Department of Geology and Environmental Earth Science (with field trip leader Mark Peter for scale). Photo by Dr. Kendall Hauer.

STOP 2: ACTON LAKE SPILLWAY 39.5561 ° N, 84.7336° W

(Park in lot at the end of Buckley Road and walk to site; figs. 2-10 and 2-11)

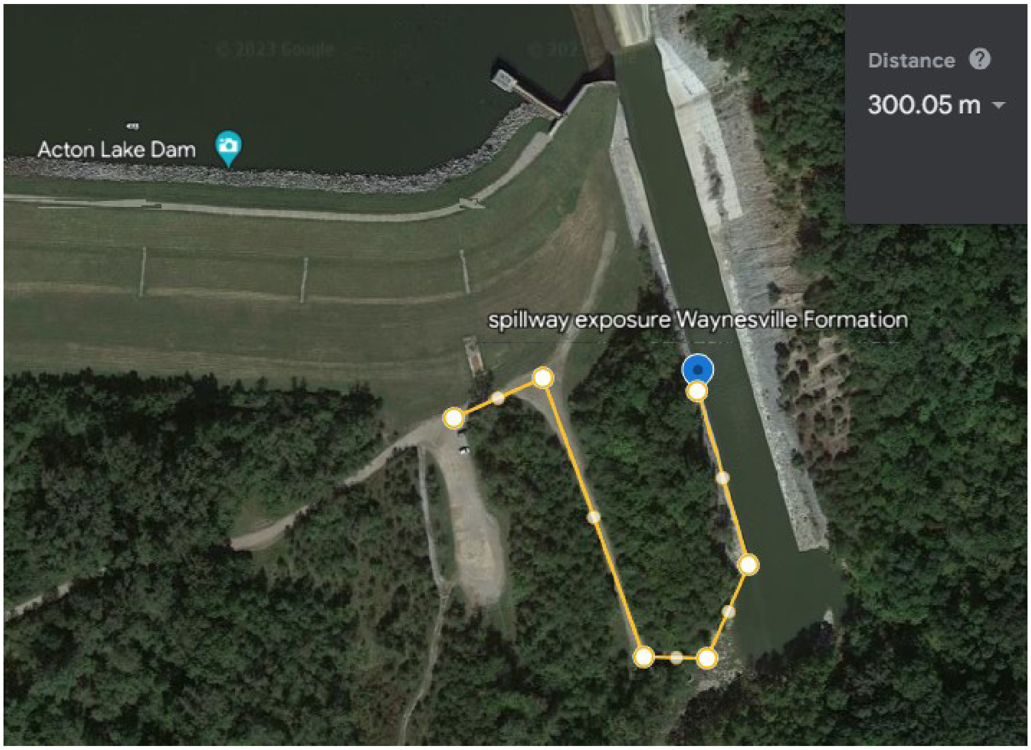


FIGURE 2-10. Stop 2 walking route (~300 m) from parking area at the end of Buckley Road to spillway exposure of the Waynesville Formation. See Road Log for GPS coordinates and directions. Map created on Google Earth.

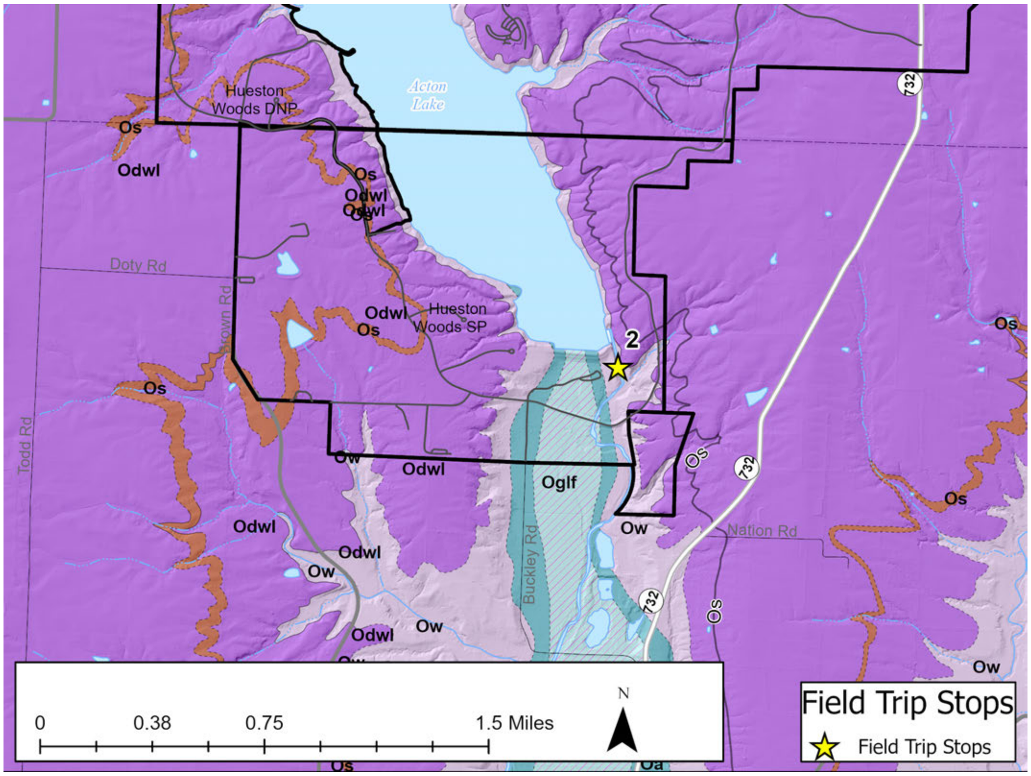


FIGURE 2-11. Geologic bedrock map showing Stop 2 (yellow star) in the dam spillway of Acton Lake in Hueston Woods State Park. The relevant symbol "Ow" (light gray-pink color) represents the Ordovician Waynesville Formation.

The Waynesville (this stop) and Liberty (Stop 4) formations (Katian; Richmondian of North America) are exposed in numerous natural and human-made exposures in southwestern Ohio and southeastern Indiana (Nickles, 1902, 1903). The village of Waynesville, the type locality for the Waynesville Formation (Nickles, 1903), is located in Warren County, Ohio.

This stop provides an opportunity to view a humanmade exposure of the Waynesville Formation in the spillway of Acton Lake at Hueston Woods State Park. Participants will park in the lot at the eastern end of Buckley Road and walk east and then south to the spillway (see road log for precise directions). Following the west side of the spillway heading first northeast and then north, participants will access a concrete walkway that borders a low exposure on the west side of the spillway, just below the dam. This exposure (fig. 2-12) is partially obscured by slumping clay and limestone talus and is starting to become overgrown with vegetation. A taller, more vertical exposure of the Waynesville Formation is visible on the opposite (east) side of the spillway (fig. 2-13). This exposure reveals the thick intervals of clay and shale ("shale") beds alternating with infrequent thin, tabular limestone and siltstone ("limestone") beds characteristic of the Waynesville Formation. The formation has an average ratio of approximately 70% gray to bluish-gray shale to 30% limestone (Schumacher and others, 2013). For a discussion of the chronostratigraphy and sequence stratigraphy pertaining to the Waynesville Formation, the reader is referred to the field trip by Waid and others (2023), pages 1–54 of this guidebook.

FIGURE 2-12. Human-made exposure of the Waynesville Formation on the west side of the spillway (facing north) below the dam of Acton Lake in Hueston Woods State Park. This exposure is easily accessed if water levels in the spillway are not too high. Slumping shales, limestone talus, and vegetation partially obscure the exposure; however, this cut affords an opportunity to examine and collect fossils. Exposure ranges from about 3 to 5 m high.

FIGURE 2-13. Vertical exposure of the Waynesville Formation on the east side of the spillway below the dam of Acton Lake in Hueston Woods State Park. This view (facing east) of this exposure from the opposite side of the spillway reveals the high ratio of shale to limestone characteristic of the Waynesville Formation. Exposure is roughly 10 m high.

Delicate, dorso-ventrally compressed brachiopods such as *Rafinesquina ponderosa* (fig. 2-14) and *Cincinnetina meeki* (fig. 2-15) are common in the Waynesville. The morphology of the valves (shell halves) of these brachiopods may have been an adaptation for living on a muddy bottom, with the large surface area-to-volume ratio giving the brachiopods the ability to remain buoyant atop a soft substrate, the so-called “snowshoe effect” (Thayer, 1975).

Experimental studies employing flumes and other methods have investigated the living orientation of *Rafinesquina* sp. brachiopods, which lacked the pedicle (“stalk”) attachments that some brachiopods used to adhere to a firm substrate. Some authors have favored a concave-up orientation and others have favored a convex-up orientation. For a summary of the literature, see Plotnick and others (2013). Based on an experimental study of the force required to press these brachiopods into a soft mud, these authors concluded that although the convex-up orientation required more force to sink the shell, unless the bottom muds were much less firm (that is, “soupier”) than estimated the shell would have been sufficiently buoyant in either orientation. The authors suggested that the primary advantage to a convex-up orientation may have been to prevent the shell from flipping over in currents, particularly with the shell open for feeding (Plotnick and others, 2013).

Because *Rafinesquina* provided a smooth, firm attachment site, these brachiopods are frequently encrusted with bryozoans and other epibionts. The prevalence and type of encrusting organisms has also been used to argue for a convex-up orientation of this brachiopod (Lescinsky, 1995). In addition to bryozoans, *Rafinequina* brachiopods are frequently colonized by cornulitids and inarticulate brachiopods, and occasionally by echinoderms (for example, crinoid holdfasts, edrioasteroids and cyclocystoids). The fossil collector is often rewarded by paying these brachiopods close attention.

FIGURE 2-14. Thin-shelled *Rafinesquina ponderosa* brachiopods in a wackestone from talus at the bottom of the Waynesville Formation spillway exposure. This species has a wide range not limited to either the Waynesville Formation or the Richmondian.

FIGURE 2-15. Delicate *Cincinnetina meeki* brachiopod (brachial valve) eroded from a clay or shale bed on the Waynesville Formation spillway exposure. This small species occurs in high abundance in some beds of this formation. Scale bar shows centimeters and millimeters.

Other common fossils at this Waynesville Formation exposure include *Cyclonema* sp. gastropods (fig. 2-16), with original calcite shell preservation (unlike most Cincinnatian gastropods, which had aragonitic shells that are not typically preserved); bivalves; delicate trepostome bryozoans; occasional *Flexicalymene* trilobites; and abundant pieces of the large trilobite *Isotelus,* Ohio's official State Invertebrate Fossil (Shrake and Peter, 2023). This trilobite is estimated to have attained lengths of half a meter or more. Many of the large complete *Isotelus* trilobite specimens in museums have been collected from "trilobite" shales of the Waynesville Formation (Schumacher and Shrake, 1997; fig. 2-17). For identification of some common Richmondian fossils, refer to Appendices 2-3 and 2-4 of this chapter.

FIGURE 2-16. Gastropods of the genus *Cyclonema* are common in the Waynesville Formation exposure in the Acton Lake spillway. Unlike most Cincinnatian gastropods, the shell of *Cyclonema* was made of calcite, rather than aragonite, and original shells with ornament are preserved. Scale is in centimeters and millimeters.

FIGURE 2-17. Large *Isotelus maximus* trilobite excavated by Thomas T. Johnson (with permission) from the Waynesville Formation on the floor of the U.S. Army Corps of Engineers (U.S.A.C.E.) emergency spillway at Caesar Creek State Park in Warren County, Ohio. This specimen, which measures approximately 30 cm long, is on display at the U.S.A.C.E. Visitor Center. Brown pieces of this large trilobite are ubiquitous in most Cincinnatian formations.

STOP 3: HUESTON WOODS STATE PARK NATURE CENTER (6301 PARK OFFICE RD, COLLEGE CORNER, OH 45003) (39.5817° N, 84.7614° W)

Stop 3 is at the Hueston Woods State Park nature center (fig. 2-18) and an adjacent picnic grove to break for lunch. The new nature center, dedicated in June 2022, features exhibits including an introduction to the park's geology and fossils; a walk in Hueston Woods through all four seasons; a living beehive; and a wall of native fishes, amphibians, and reptiles. Restroom facilities are located in attached structure on the north end of the nature center. Immediately north of the nature center are enclosures for raptor rehabilitation. A number of resident native birds of prey can be viewed here.

FIGURE 2-18. Hueston Woods State Park nature center. The nature center features a small exhibit explaining the park's geology and its fossils, in addition to exhibits about park wildlife and ecology and live native fishes, amphibians, and reptiles.

STOP 4: EAST FORK, FOUR MILE CREEK (39.5925 ° N, 84.7678° W)

(Park in the picnic area just east of Hedgerow Rd. and the covered bridge on Camden College Corner Rd.; figs. 2-19 and 2-20).

FIGURE 2-19. Walking route (~500 m) from the entrance of the picnic area on Camden College Corner Rd. just east of Hedgerow Rd. and the covered bridge over Four Mile Creek to the small waterfall shown in Figure 2-22. See Road Log for GPS coordinates and directions. Map created on Google Earth.

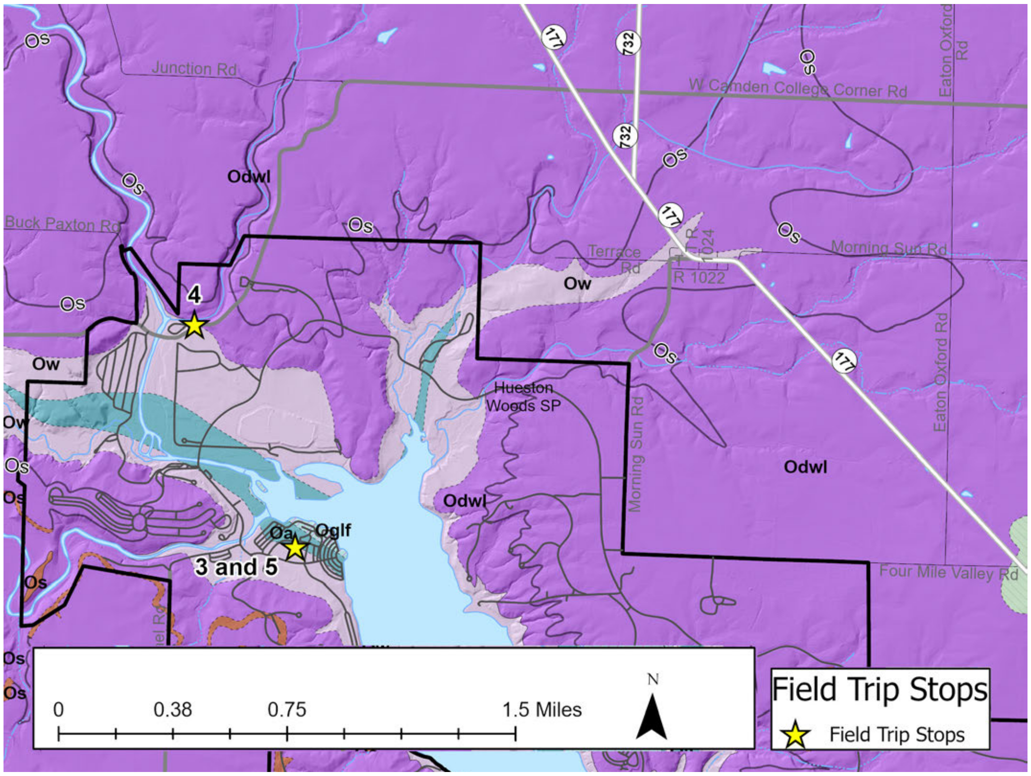


FIGURE 2-20. Geologic bedrock map showing Stops 3–5 in Hueston Woods State Park. Relevant bedrock map symbols for Stop 4: Ow=Ordovician System, Waynesville Formation; Odwl= Ordovician System, Drakes, Whitewater, and Liberty Formations, undivided.

This stop provides an opportunity to view natural stream exposures of the Liberty Formation (and possibly the overlying Whitewater Formation) in East Fork, Four Mile Creek at Hueston Woods State Park and to collect fossils. Participants will park in the picnic area just east of the covered bridge and enter East Fork, Four Mile Creek near the beginning of the loop road in the picnic grove. There is a pull-off parking area large enough for small buses near the entrance from Camden College Corner Road, just before the beginning of the road loop. A short dirt path leads into the creek bed. Note: the creek may be difficult or impossible to traverse after periods of high precipitation, when the creek is likely to be flooded. This site is best avoided during certain periods during the spring when water levels tend to be higher.

Walking upstream from the entry point, participants will encounter a low waterfall (~1 m), several low cut bank exposures (fig. 2-21), and one higher cut bank exposure before coming to a small (~2 m high) waterfall approximately 500 m from the entry into the creek. This second waterfall (fig. 2-22) is still within the park boundary, but walking a short distance upstream would take one outside the limits of the park.

FIGURE 2-21. A low cut-bank exposure within the Liberty Formation on East Fork, Four Mile Creek. Backpack is approximately 0.5 m high. Note decreased thickness of shale partings between limestone beds as compared to the Waynesville Formation. Note: beware overhanging beds; it is also advised not to grab tree roots for support (could result in a rain of soil from above).

FIGURE 2-22. A low (~2 m high) waterfall, possibly in the Whitewater Formation, near the northern boundary of the park on East Fork, Four Mile Creek. Note the relatively continuous limestone beds and greater ratio of limestone to shale compared to the Waynesville Formation.

Compared to the Waynesville Formation (Stop 2, above), the Liberty Formation contains thicker limestone beds on average (10 vs. 5 cm) and a higher percentage ratio of limestone to shale (Shrake, 1992). The Liberty Formation averages approximately 50% shale and 50% limestone in Butler and Preble Counties, and consists of interbedded planar to irregular-bedded, fossiliferous limestones and sparsely fossiliferous gray to bluish-gray shales (Schumacher and others, 2013).

Beds with edgewise (normal to bedding) stacked valves of *Rafinesquina* sp. brachiopods are a common occurrence in the Liberty Formation and because this is not the inferred life position of these brachiopods, beds with edgewise-stacked shells (fig. 2-23) may represent storm deposits with realignment by currents (Brett and others, 2020; Meyer and Davis, 2009). Other beds contain fragmented branching trepostome bryozoans that were likely broken by a storm event but not transported far from their original living space, considering their concentration (fig. 2-24).

FIGURE 2-23. Packstone of edgewise-stacked valves of *Rafinesquina* brachiopods, interpreted as a deposit under the influence of deep storm waves and currents (Brett and others, 2020). Normal living position for these brachiopods was interpreted to be recumbent on the seafloor with the convex side of the shell facing up (Plotnick and others, 2013). Some fragmented trepostome bryozoans are also preserved in the center of the slab. Scale bar is in centimeters and millimeters.

FIGURE 2-24. Broken-up colonies of branching trepostome bryozoans in a bed which likely represents a tempestite (storm deposit). Scale bar is in centimeters and millimeters.

Whereas the limestone beds in the Liberty Formation are relatively planar and continuous, limestone beds of the overlying Whitewater Formation, named for the Whitewater River near Richmond, Indiana, are thinner. Limestone beds here average about 5 cm and are wavy-bedded, discontinuous, and argillaceous; shale layers in the Whitewater Formation are thin and fissile (Shrake, 1992). For a discussion of the chronostratigraphy and sequence stratigraphy pertaining to the Liberty Formation and Whitewater Formation, the reader is referred to the field trip by Waid and others (2023) pages 1–54 of this guidebook.

A characteristic fossil for the Whitewater Formation is the coiled cephalopod, *Charactoceras baeri* (fig. 2-25), although these are not particularly abundant fossils. The problematic fossil *Tetradium* (Appendix 2-4) is often used as an index fossil for the Whitewater Formation (Brett and others, 2020). *Tetradium* has been variously classified as a calcareous, chaetetid sponge; a tabulate coral; and a rhodophyte, or red alga (Steele-Petrovich, 2009). According to Steele-Petrovich (2009), *Tetradium* is a rhodophyte; this reclassification from an animal to an alga also necessitates a name-change (to *Prismostylus*) to avoid taxonomic priority of angiosperm trees of the same name (Steele-Petrovich, 2011).

FIGURE 2-25. Partial specimen of the coiled cephalopod *Charactoceras baeri* from the Whitewater Formation near Camden, Preble County, Ohio (author's collection). Scale bar is in centimeters and millimeters.

STOP 5: HUESTON WOODS STATE PARK NATURE CENTER (6301 PARK OFFICE RD, COLLEGE CORNER, OH 45003) (39.5817° N, 84.7614° W)

This final stop is a return to the nature center for a quick restroom break before the return trip to the conference hotel.

RESOURCES

BOOKS

A Sea Without Fish (Meyer and Davis, 2009)
Cincinnati Fossils: An Elementary Guide to the Ordovician Rocks and Fossils of the Cincinnati, Ohio, Region (Davis, 1998, ed.)
Excursion to Caesar Creek State Park in Warren County, Ohio: a classic Upper Ordovician fossil-collecting locality (Shrake, 1992)
Fossils of Ohio (Feldmann and Hackathorn, eds., 1996, 2005)
Ohio Fossils (La Rocque and Marple, 1955)(out of print; pdf available through Ohio State University Knowledge Bank: https://kb.osu.edu)

MUSEUMS

Cincinnati Museum Center: cincymuseum.org
Karl E. Limper Geology Museum (Oxford, Ohio): miamioh.edu/cas/centers-institutes/limper-geology-museum
Orton Geological Museum (Columbus, Ohio): ortongeologicalmuseum.osu.edu

FOSSIL SOCIETIES

Cincinnati Dry Dredgers: drydredgers.org
Kentucky Paleontological Society (Lexington): uky.edu/OtherOrgs/KPS

WEBSITES

A Guide to the orders of trilobites: by Sam Gon III: trilobites.info
Digital Atlas of Ordovician Life: ordovicianatlas.org
GeoFair: (Cincinnati): geofair.com
Herrmann Studio: www.herrmannstudio.com
Kentucky Geological Survey: uky.edu/KGS
Ohio Geological Survey: geology.ohiodnr.gov
UGA Stratigraphy Lab: stratigrafia.org/cincy/fauna
The Paleobiology Database: paleobiodb.org

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ROAD LOG

Depart Radisson Hotel Cincinnati Riverfront (39.1008° N, 84.5163° W)

1. Turn left on Philadelphia St. — 240 ft
2. Turn left onto W. 4th St. — 184 ft
3. Keep left at the fork, follow signs for I-71 S./I-75 S. — 0.6 mi
4. Keep right, follow signs for Pike St./12th St./Covington — 0.2 mi
5. Keep left at the fork and merge onto I-71 N./I-75 N. entering Ohio — 1.3 mi
6. Keep left at the fork to continue on I-75 N., follow signs for Dayton — 3.6 mi
7. Take exit 4 for I-74 W./US-52 W./US-27 N. toward Indianapolis — 0.8 mi
8. Continue onto I-74/US-27 N./US-52 W. Continue to follow I-74/US-52 W. — 9.5 mi
9. Take exit 9 to merge onto I-275 N. toward I-75/Dayton — 2.8 mi
10. Keep left at the fork to continue on I-275 E. — 2.4 mi
11. Take exit 33 for US-27/OH-126/Colerain Ave. — 0.3 mi
12. Turn left onto OH-126 W./US-27 N./Colerain Ave./US-27 N. Continue to follow US-27 N. — 10.8 mi
13. Turn left onto Millville Oxford Rd./US-27 N. Continue to follow US-27 N. — 9.5 mi
14. Turn left onto E. High St. — 607 ft
15. Turn left onto Laws Dr. — 423 ft
16. Continue onto Bishop Cir. — 719 ft

Stop 1 will be on the right (39.5077° N, 84.7313° W)

(Note: parking for bus in lot immediately E. of Millett Hall, 500 E. Sycamore St., Oxford, OH 45056; directions are for drop off. Parking passes for Miami University can be purchased in advance online.)

Depart Stop 1: Karl E. Limper Geology Museum

1. Head east on Bishop Cir. toward Bishop Path — 190 ft
2. Turn left onto S. Patterson Ave. — 784 ft
3. Turn left onto E. High St. — 0.2 mi
4. Turn right onto Tallawanda Rd. — 0.3 mi
5. Turn left onto E. Sycamore St. — 0.6 mi
6. Turn right onto Brown Rd. — 4.0 mi
7. Turn right onto Main Loop Rd. — 1.6 mi
8. Turn left onto Buckley Rd. — 0.3 mi

Stop 2 will be straight ahead (39.5561 ° N, 84.7336° W)

Note: park in lot at end of Buckley Road. Use path at N. end of lot to head N.E. for 38 m, S.S.E. for 122 m, E. for 15 m to spillway, N.N.E. along spillway bank for 43 m, and N.N.W. for 62 m on concrete walkway on W. side of spillway.

Depart Stop 2: Acton Lake Spillway at Hueston Woods State Park

1. Head west on Buckley Rd. toward Main Loop Rd. — 0.3 mi
2. Turn right onto Main Loop Rd. — 2.9 mi
3. Turn right onto Park Office Rd. — 0.2 mi
4. Turn left into parking lot— 210 ft

Stop 3 will be on the left (39.5817° N, 84.7614° W)

Depart Stop 3: Hueston Woods State Park Nature Center

1. Head south toward Park Office Rd. — 210 ft
2. Turn right onto Park Office Rd. — 0.2 mi
3. Turn right onto Main Loop Rd. — 0.4 mi
4. Turn left onto Hedgerow Rd. — 0.4 mi
5. Turn right onto Camden College Corner Rd. — 300 ft
6. Turn left into picnic area E. of covered bridge; park bus on right side of road before loop

Stop 4 will be on the left (39.5925 ° N, 84.7678° W)

Note: Enter creek from N.E. corner of picnic area near the beginning of the loop drive. Walk upstream past multiple low exposures of the Liberty Formation on E. side and a higher exposure on W. side for ~500 m to a 2 m-high waterfall in the main stream channel, or as far as time permits. Return the same way downstream to the entry point.

Depart Stop 4: East Fork, Four Mile Creek

1. Head southwest on Camden College Corner Rd. toward Hedgerow Rd. — 300 ft
2. Turn left onto Hedgerow Rd. — 0.4 mi
3. Turn right onto Main Loop Rd. — 0.4 mi
4. Turn left onto Park Office Rd. — 0.2 mi
5. Turn left into parking lot — 210 ft

Stop 5 will be on the left (39.5817° N, 84.7614° W)

Depart Stop 5: Hueston Woods State Park Nature Center

1. Head south toward Park Office Rd. — 210 ft
2. Turn right onto Park Office Rd. — 0.2 mi
3. Turn right onto Main Loop Rd. — 240 ft
4. Turn left onto Butler Israel Rd. — 1.2 mi
5. Turn left onto Todd Rd. — 2.7 mi
6. Turn left onto College Corner Pike/US-27 S. — 1.6 mi
7. Turn right onto N. Locust St.— 0.8 mi
8. Turn left onto W. Chestnut St. — 0.4 mi
9. Continue straight onto E. Chestnut St. — 0.6 mi
10. Turn right onto Millville Oxford Rd./Oxford Millville Rd./US- 27 S. Continue to follow Millville Oxford Rd./US- 27 S. — 8.9 mi
11. Turn right onto US-27 S./Walnut St. Continue to follow US-27 S. — 10.6 mi
12. Turn right to merge onto I-275 W. toward I-74/Indianapolis — 5.2 mi
13. Take exit 28 on the left to merge onto I-74/US-52 E. toward Cincinnati — 9.9 mi
14. Take the exit onto I-75 S./US-27 S./US-52 E. toward US-127 S./Lexington. Continue to follow I-75 S./US-52 E. — 3.8 mi
15. Keep right to continue on I-75 S., entering Kentucky — 1.2 mi
16. Take exit 192 toward Covington — 853 ft
17. Merge onto W. 5th St. — 361 ft
18. Turn left — 220 ft
19. Turn left. Destination will be on the left — 220 ft

Conclude field trip upon return to Radisson Hotel Cincinnati Riverfront (39.1008° N, 84.5163° W)

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APPENDIX 2-1

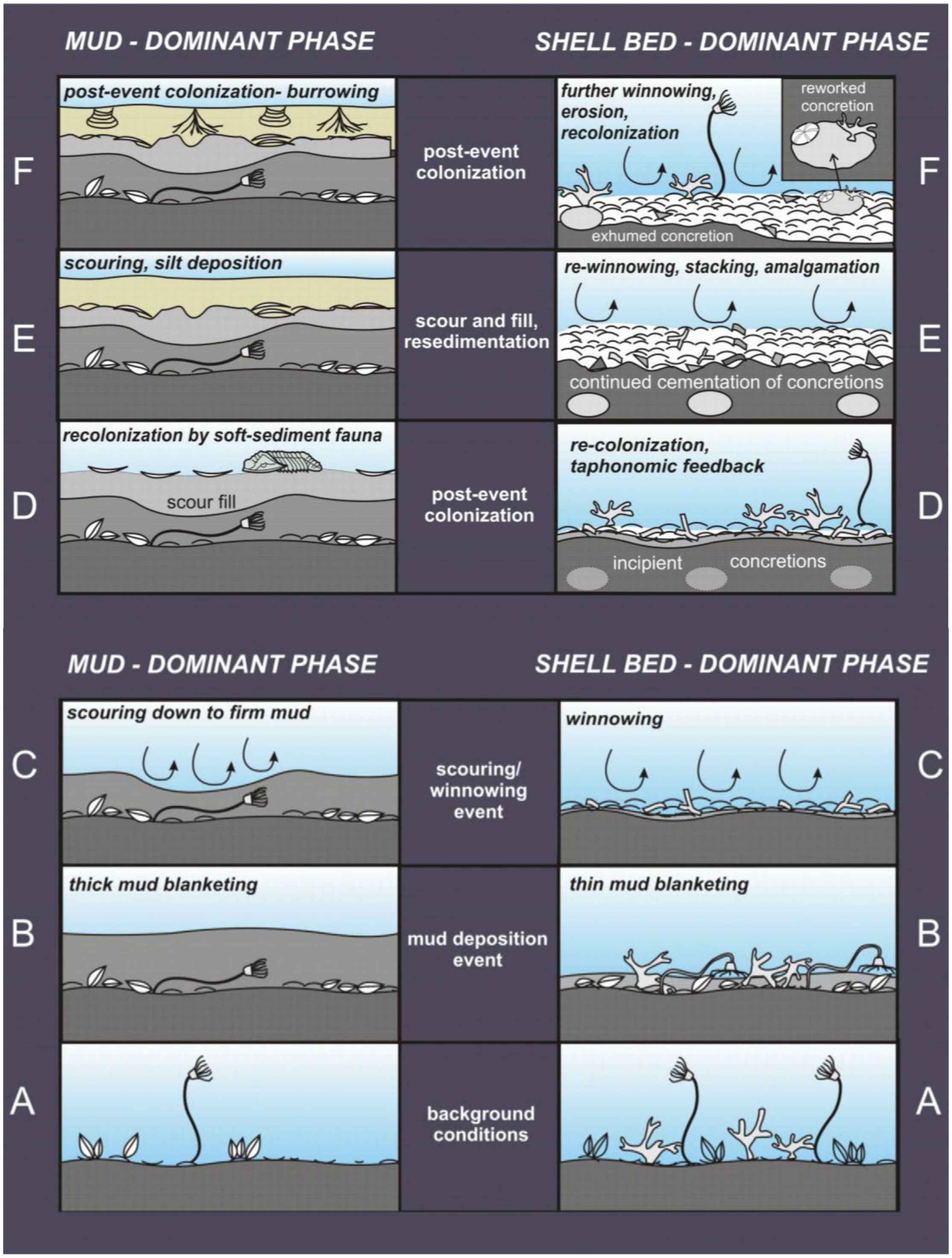
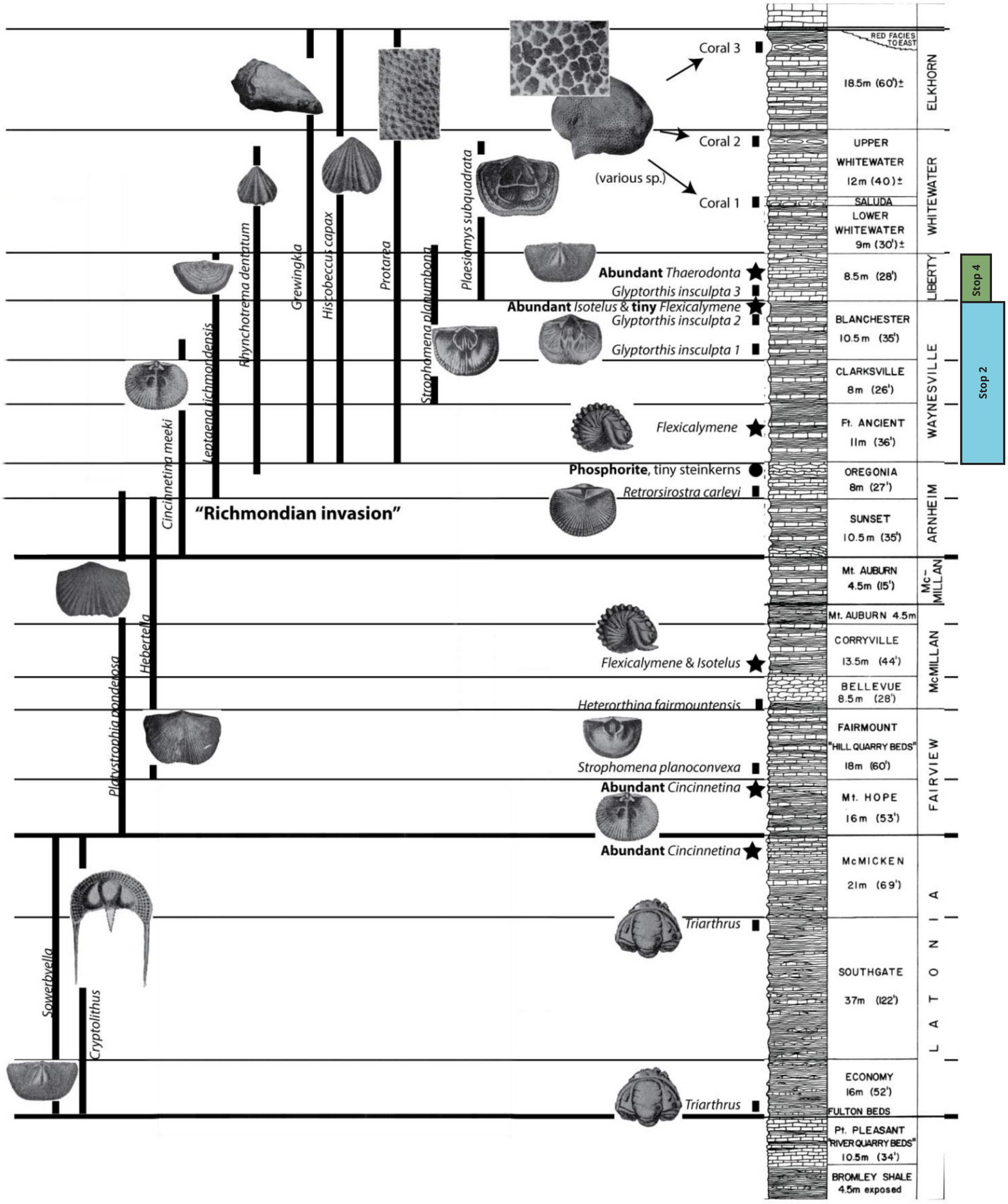


Diagram showing the development of muddy and shelly horizons in the Cincinnatian. Shell beds develop during periods of low siliciclastic sediment supply. Mud beds develop during times of high sediment supply. Storms (or other high-energy events like tsunamis) affect both types of beds, and do not constitute the critical difference between them; all are tempestites (Dattilo and others, 2013, modified from Brett and others, 2008).

APPENDIX 2-2



This range chart shows the approximate stratigraphic position of each field trip stop, as well as the ranges of easily recognized common but stratigraphically restricted fossils. The stratigraphic names on the right are the older "traditional" names applied in Cincinnati and southeastern Indiana. Stratigraphy and ranges modified from Caster and others (1955, 1961). Fossil images from Cummings (1907). Chart modified from Dattilo and others (2013); composite sections measured elsewhere.

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APPENDIX 2-3

Life in Ancient Ohio

Late Ordovician (445 million years ago)

Artwork by Kyle Hartshorn of Cincinnati, Ohio

Key

(numbers correspond to those on p. 92)

Arthropoda

- Chelicerata
  1. *Megalograptus* sp. (eurypterid, or "sea scorpion;" not reported from the park)
- Trilobita
  2. *Isotelus maximus* (Ohio State Invertebrate Fossil)
  3. *Flexicalymene retrorsa*
  4. *Tricopelta breviceps*

Brachiopoda

5. *Eochonetes clarksvillensis*
6. *Hiscobeccus capax*
7. *Leptaena richmondensis*
8. *Plaesiomys subquadrata*

Bryozoa

9. Unidentified bryozoans
10. Unidentified bryozoans
11. *Spatiopora* sp. (encrusting cephalopod shell)

Cnidaria

12. *Cyathophylloides stellata* (colonial rugose coral)
13. *Grewingkia canadensis* (solitary rugose "horn" coral)

Chordata

14. *Amorphognathus ordovicicus* (zonal conodont; not reported from the park)

Echinodermata

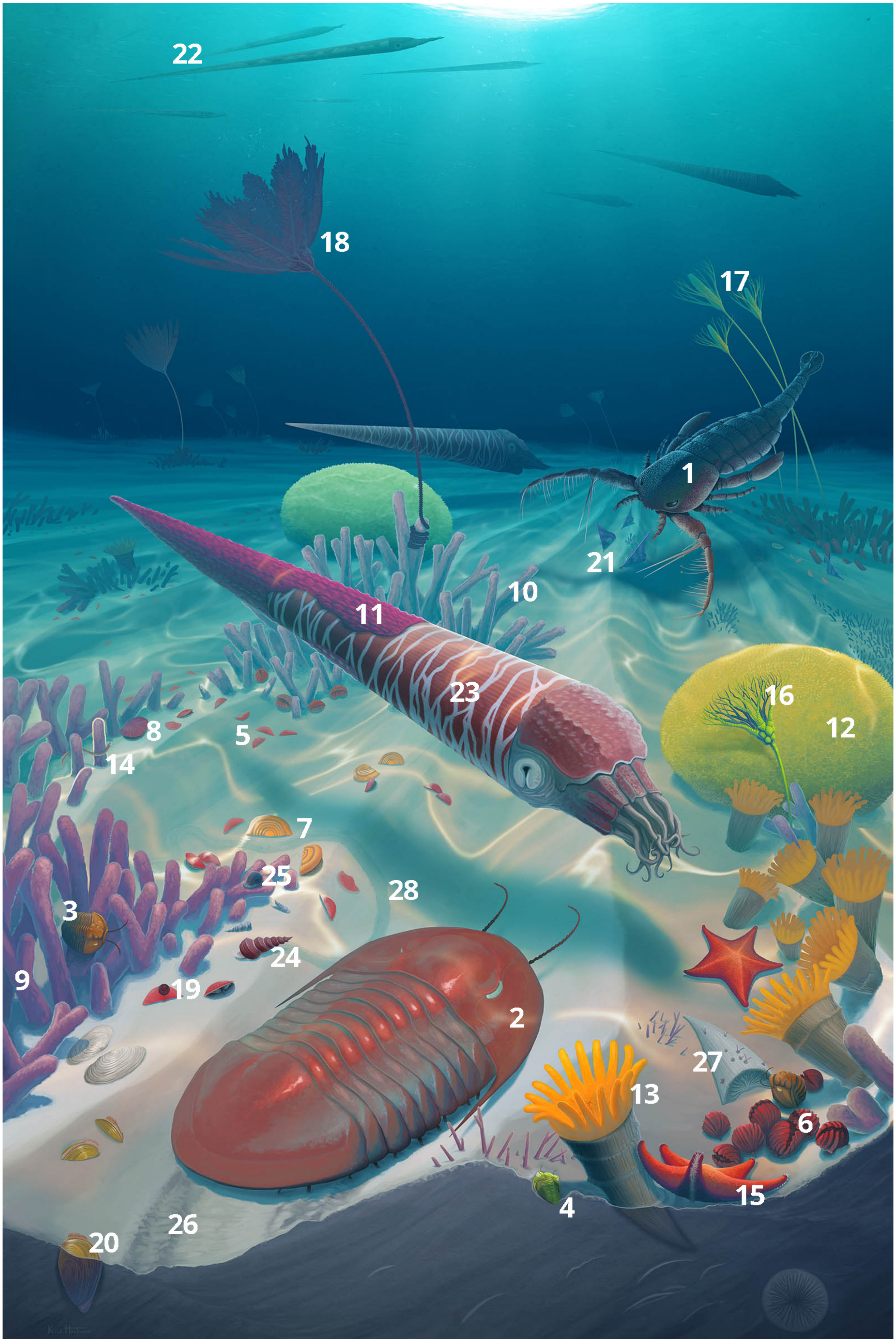
- Asteroidea
  15. *Jugiaster speciosus* (sea star)
- Crinoidea
  16. *Cupulocrinus polydactylus*
  17. *Plicodendrocrinus casei*
  18. *Xenocrinus baeri*
- Edrioasteroidea
  19. *Isorophus* sp. (on *Eochonetes* brachiopod)

Mollusca

- Bivalvia
  20. *Modiolopsis* sp.
  21. *Opisthoptera casei*
- Cephalopoda
  22. *Pleurorthoceras clarksvillensis*
  23. *Treptoceras duseri*
- Gastropoda
  24. *Paupospira* sp.
  25. *Phragmolites dyeri*

Ichnotaxa

26. *Cruziana* ichnosp. (trace produced by *Isotelus* trilobite)
27. *Trypanites* ichnosp. (borings on *Grewingkia* corals)
28. *Scolicia* ichnosp. (snail trail)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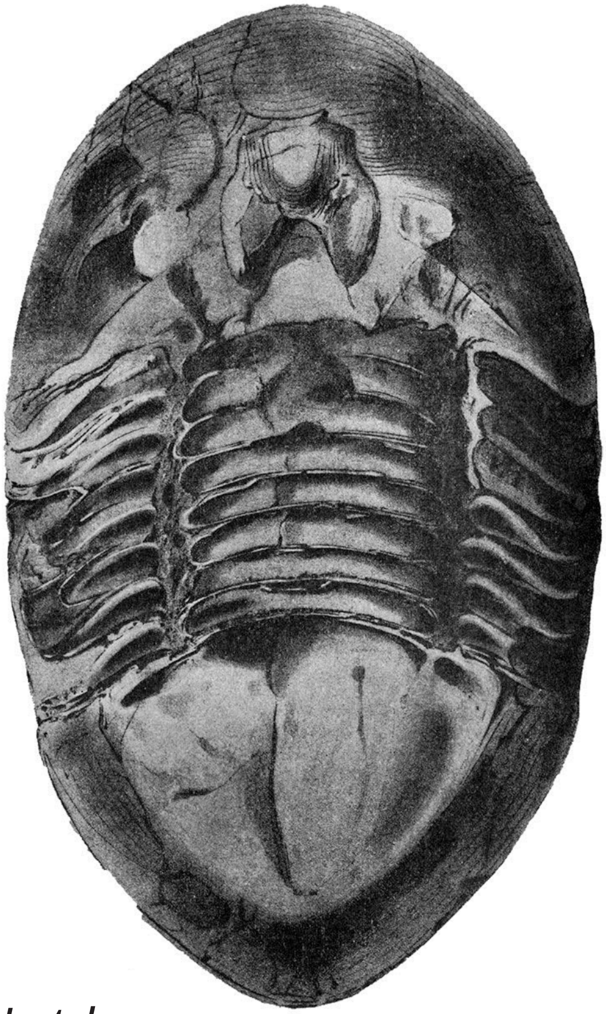
APPENDIX 2-4
Guide to Hueston Woods Fossils

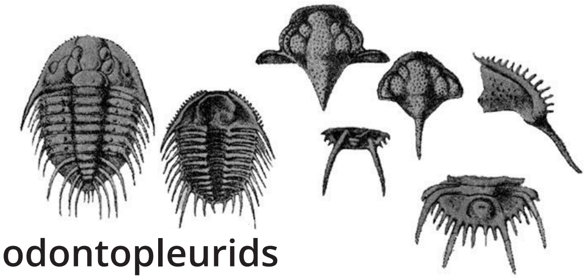
Modified from Dattilo and others (2013); includes fossil images from Cummings (1907).

Trilobites (and ostracods)



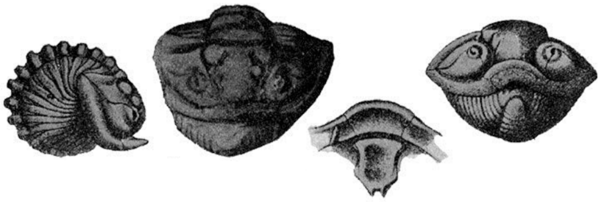
Isotelus

Isotelus is one of the largest trilobites. Finding one whole usually requires digging. They are very common as fragments. Recent work with the forked mouthpart (the *hypostome;* seen between the eyes on this reconstruction) suggests that it was used like the claws in a hammer to pry worms out of burrows.



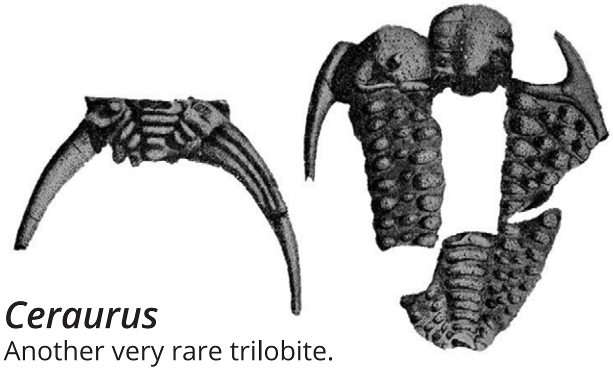
odontopleurids

Whole odontopleurids are very rare, but their parts are actually common in certain beds. These pictures illustrate the different types of “trilobits” that you might find while looking for trilobites.



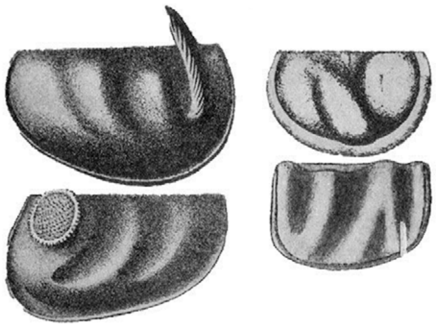
Flexicalymene

The classic Cincinnati trilobite. Most of the small fragments you find will belong to this trilobite.



Ceraurus

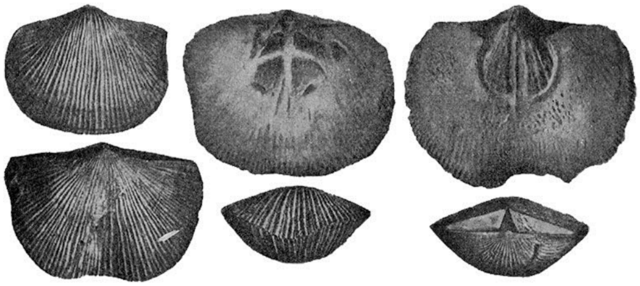
Another very rare trilobite.



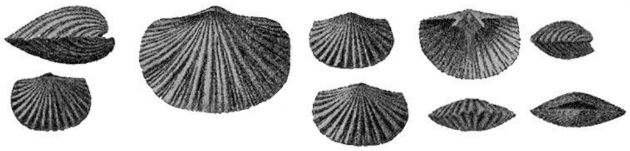
ostracods (enlarged)

Ostracods are bivalved arthropods still common today. As Ordovician fossils, they are common and generally less than 1 mm across, so they are usually overlooked.

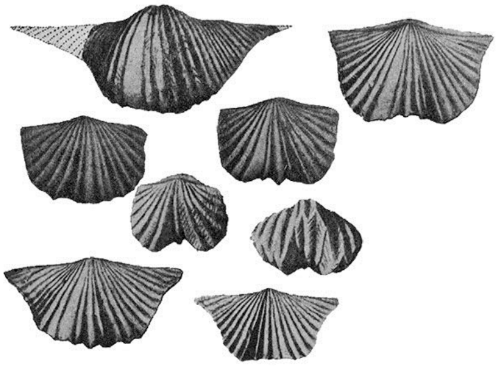
Brachiopods



Hebertella

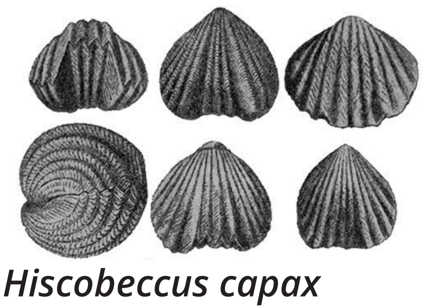


Plectorthis



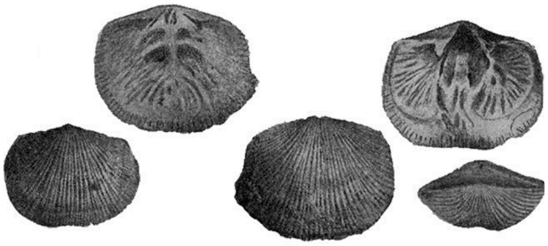
Platystrophia

It has recently been reassigned to the genus *Vinlandostrophia* by someone from northern Europe. There is some grumbling about this by North American paleontologists.



Hiscobeccus capax

Also known as *Lepidocyclus*. Similar to *Playstrophia* in appearance, but entirely different ancestry. Descended from earlier forms of *Rhynchotrema*.

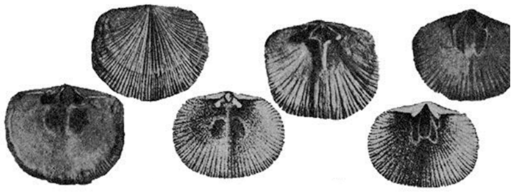


Glyptorthis insculpta

Plaesiomys subquadrata

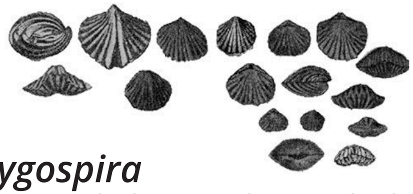
Retrorsirostra carleyi

This distinctive species is restricted to a narrow zone near the base of the Richmondian. One of the Richmondian invaders that failed to thrive.



Cincinnetina

The brachiopod formerly known as *Onniella, Dalmanella,* or *Resserella.* Several species, each of which can be found in some abundance at one stratigraphic level or another, have recently been reassigned to *Cincinnetina.*



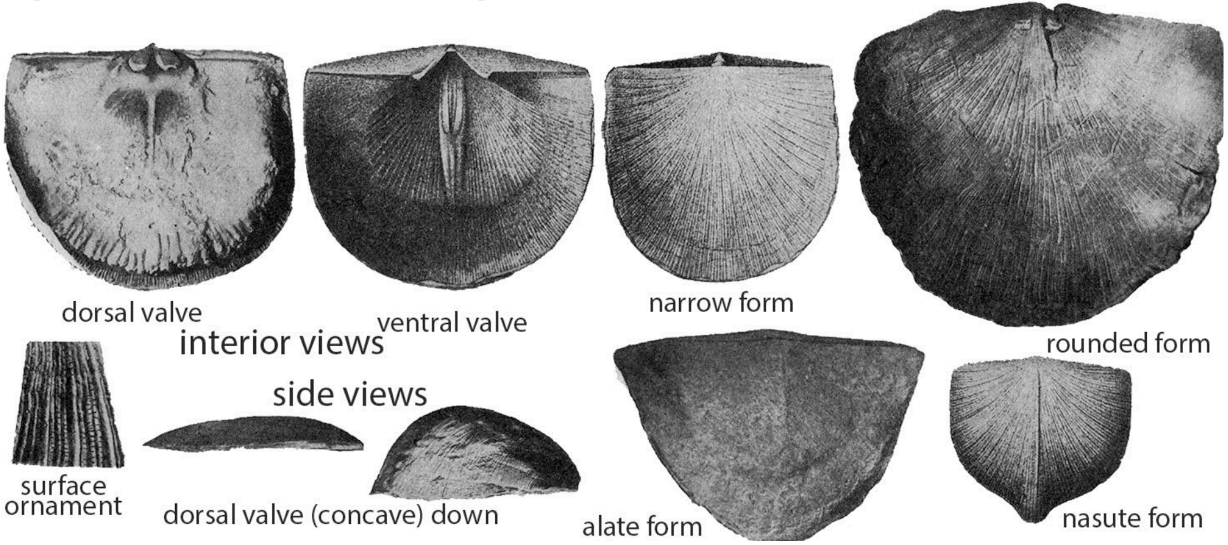
Zygospira

These look like little *Platystrophia* but are not even close—examine the classic "lamp shell" pedicle opening in the dorsal valve. Can be very abundant.

Rhynchotrema dentatum

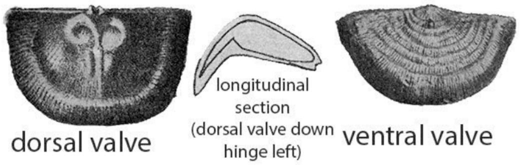
Resemble *Zygospira,* but more triangular.

Strophomenate Brachiopods



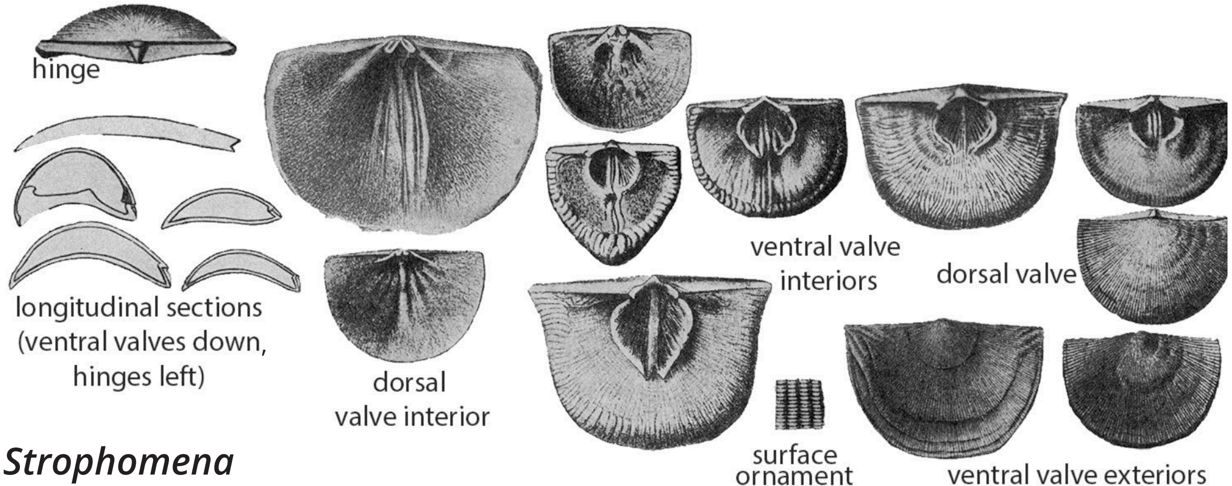
Rafinesquina
Arguably the most common large brachiopod in the world, life mode long disputed, species taxonomy nearly hopeless.

Eochonetes (Thaerodonta)



Leptaena
An extremely long-ranging form known for colonizing after mass extinction; marks the Maysvillian–Richmondian boundary.

Holtedahlina sulcata



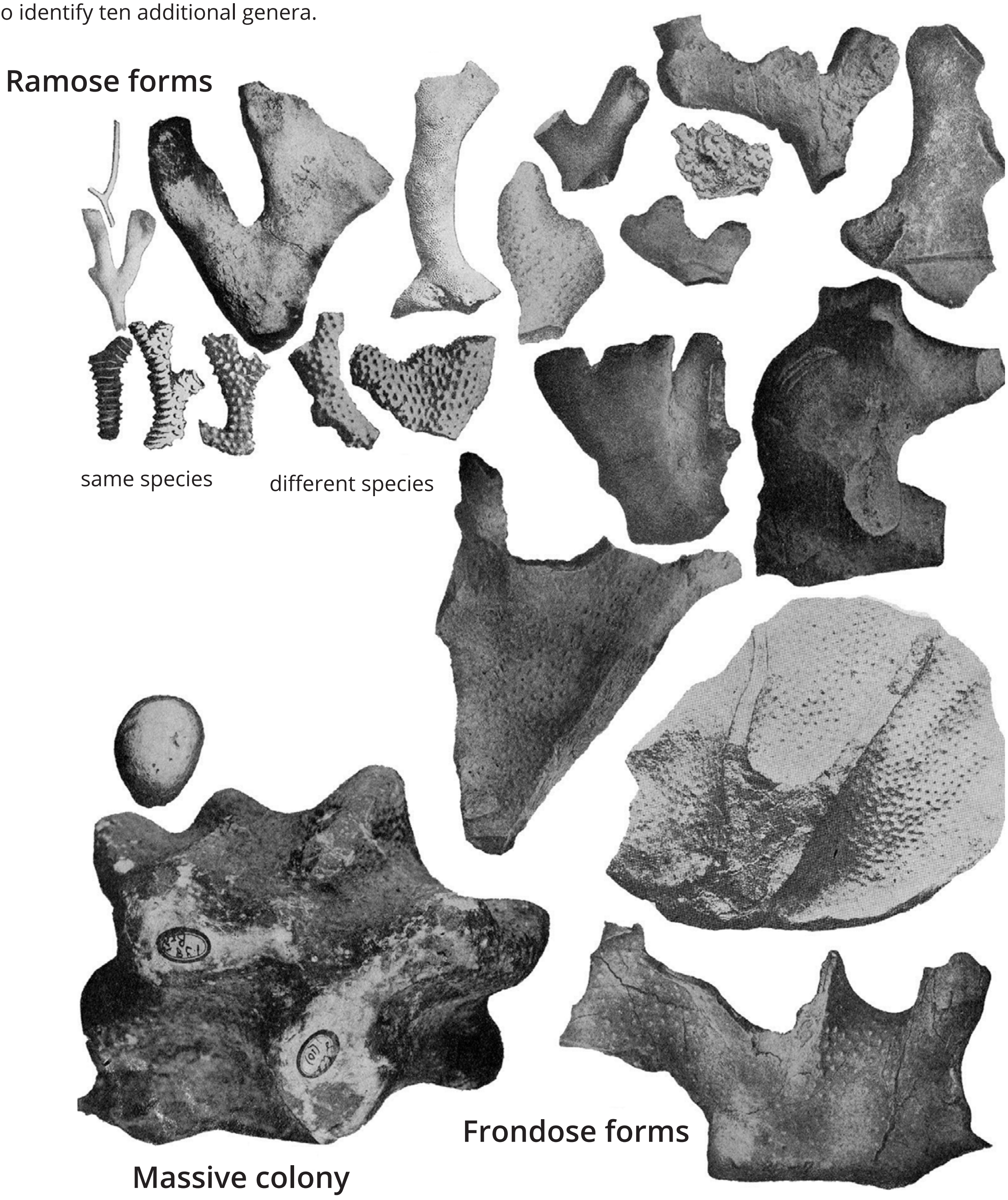
Strophomena
(several species and variants)

Trepostome Bryozoans

Gross surface characteristics are unreliable. The three specimens on the left are the same species (middle specimen shows two patterns), while the three on the right are different species, but show the same pattern.

There are more bryozoans and more different kinds of bryozoans than any other Cincinnatian fossil. Unfortunately, they are rather difficult to identify. This page shows a range of external shapes you might encounter. Sometimes these shapes help identify genus, but are more often a result of the environment. Generally bryozoans look like corals with much smaller openings.

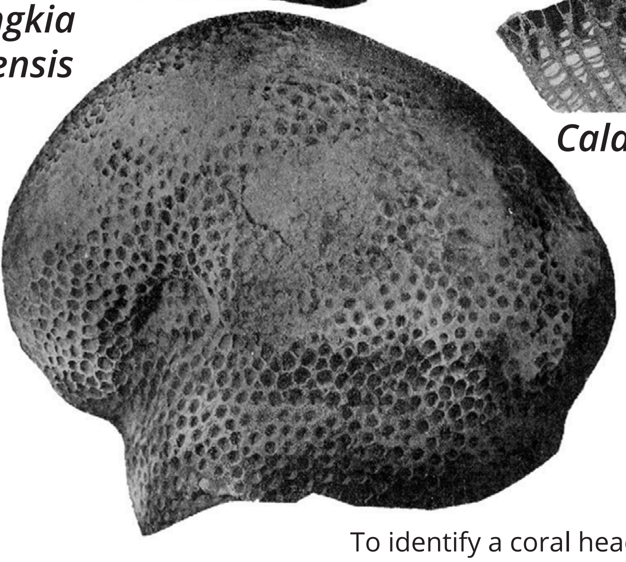
The gumdrop shape is usually the same genus, *Prasopora*. With a few months' work, you might be able to identify ten additional genera.

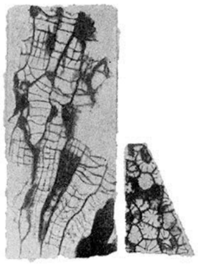


Corals

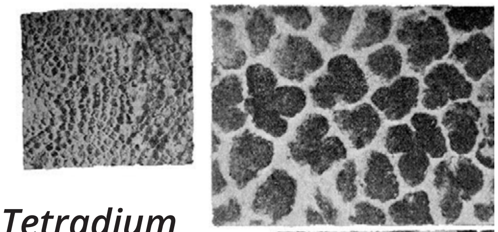
Streptelasma

Grewingkia canadensis





Cyathophylloides
Septae are well developed.



Tetradium
Is it a coral, sponge, or algae? Everyone has an answer, but nobody knows.

Longitudinal section through *Tetradium.*

Calapoecia

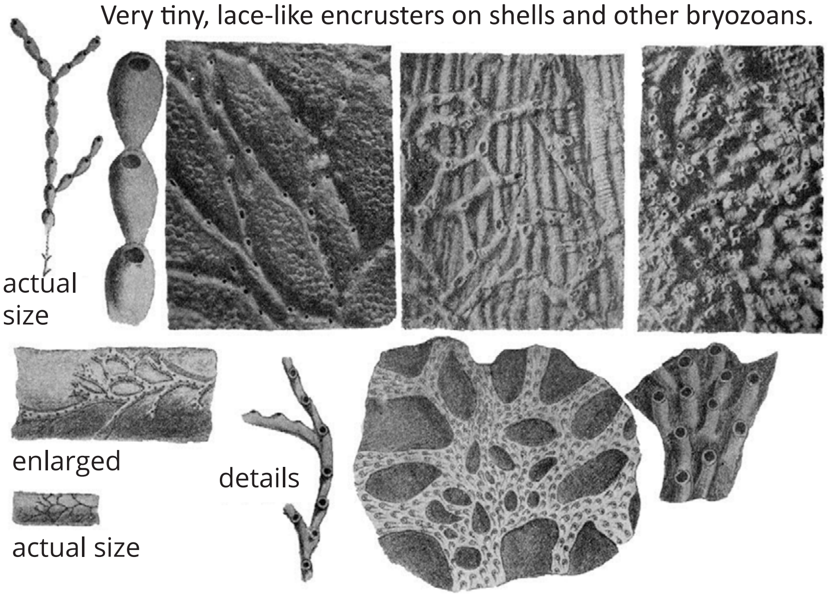
Protarea
Often found encrusting shells.

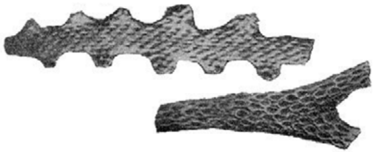
To identify a coral head, you need to look at the corallites and see if there are any septae.

Bryozoans

cyclostomes (greatly enlarged)

Very tiny, lace-like encrusters on shells and other bryozoans.





cryptostomes (enlarged)

Cryptostomes are common and commonly overlooked.

cystoporids

Constellaria
This is one of the most easily identified bryozoans, characterized by its flower or star-like surface pattern.

Echinoderms

Articulated echinoderms are always worth keeping, or turning over to the field trip leader. It is very easy to overlook whole specimens because the cup is often as small as the stem.

Crinoids

Crinoids consist of an attachment base, a column (stem), a cup, and arms (the cup and arms form the "head"). They look a bit like modern flowers.

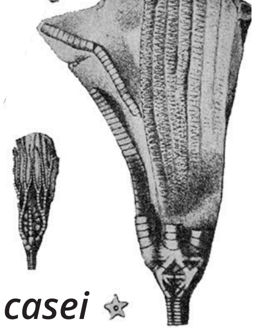
Anomalocrinus incurvus

Cincinnaticrinus pentagonus

C. varibrachialus

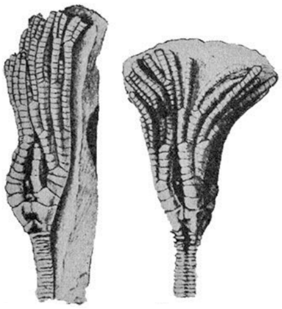
Cupulocrinus polydactylus

Possible to find anywhere in the Richmondian.



Plicodendrocrinus casei ★

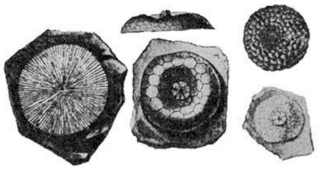
Mostly in the Waynesville and Liberty Formations.



Iocrinus subcrassus

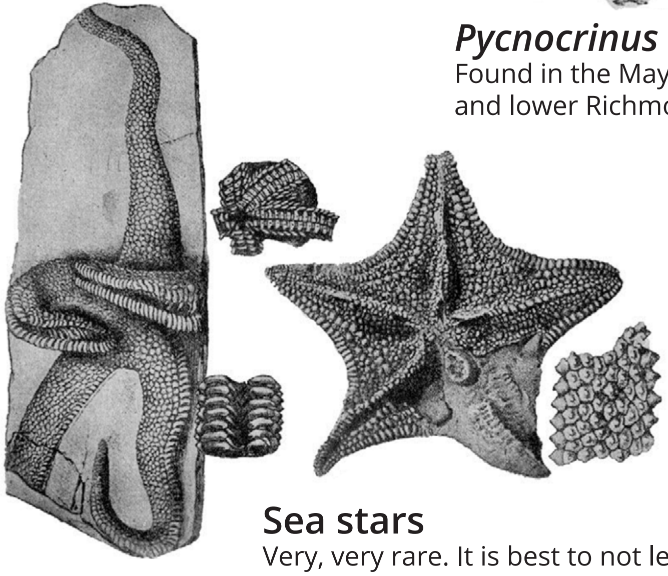
Pycnocrinus dyeri

Found in the Maysvillian and lower Richmondian.



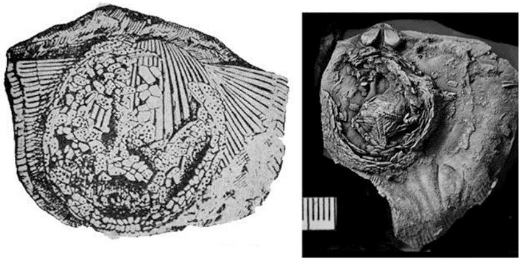
crinoid holdfasts

Holdfasts are attachment bases for the crinoid. They are often preserved without the rest of the animal.



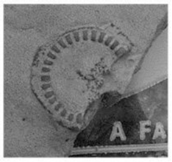
Sea stars

Very, very rare. It is best to not let anyone know that you found one.



Edrioasteroids

Edrioasteroids look like sea stars on a coin. They are usually attached to the brachiopod *Rafinesquina.* They are rare, but not extremely rare.



Cyclocystoids

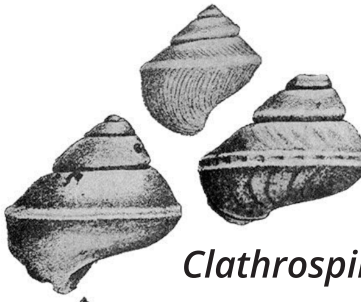
Cyclocystoids are very rare. They consist of a ring of large ossicles surrounding a thin disk of small ossicles.

Snails

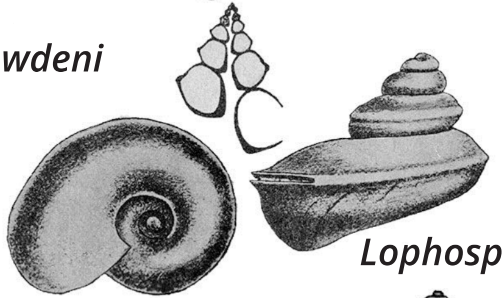
Cyclonema

Cyclonema is the only genus of gastropod with an originally calcitic shell, so its shell is preserved more readily than the shells of other snails. It is often found attached to the anal openings of crinoids and may have been capable of boring.

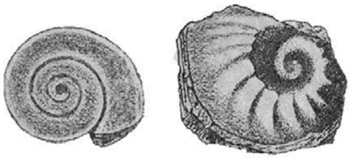
Loxoplocus bowdeni



Clathrospira

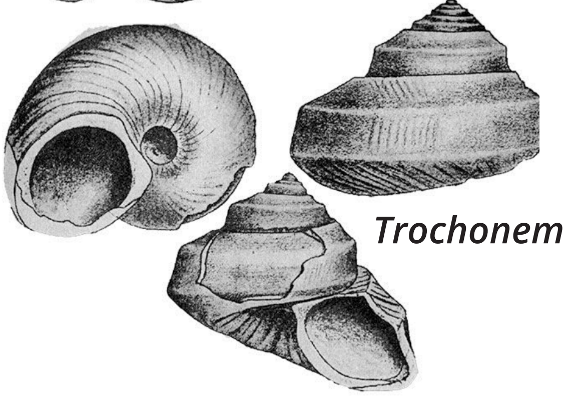


Lophospira



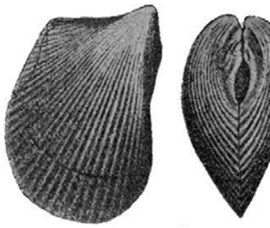
Cyrtolites

Liospira



Trochonema

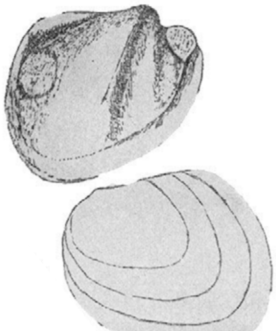
Bivalves



Ambonychia

Anomalodonta gigantea

Anomalodonta costata

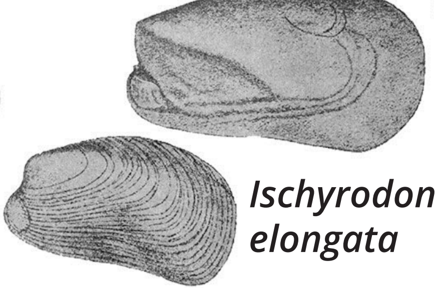


Ischyrodonta ovalis

Caritodens

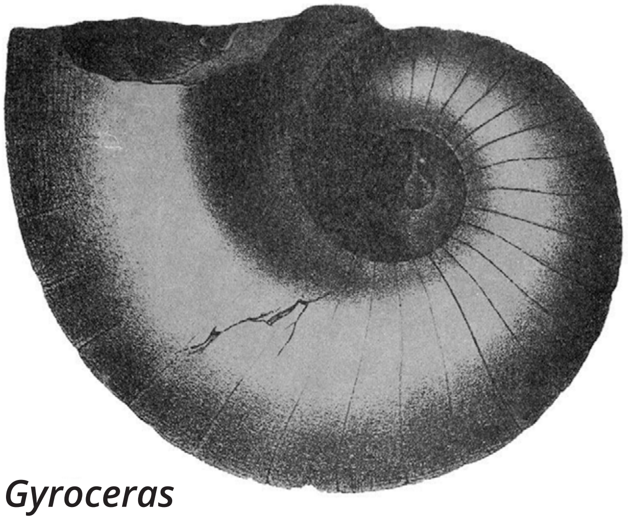
Like both the scallops and oysters that descended from it, this bivalve had an outer calcite shell and an inner aragonite shell. It is the only one whose shell is regularly preserved.

Cymatonota



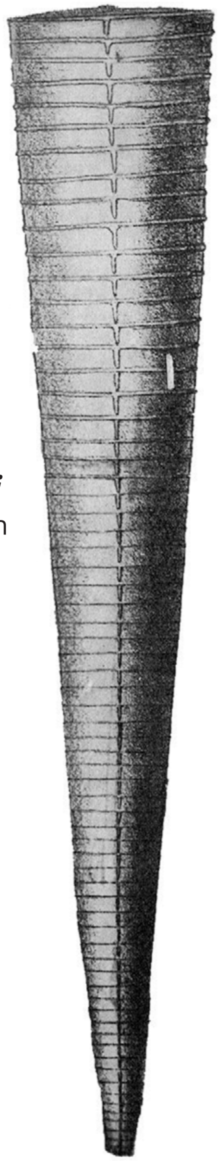
Ischyrodonta elongata

Cephalopods



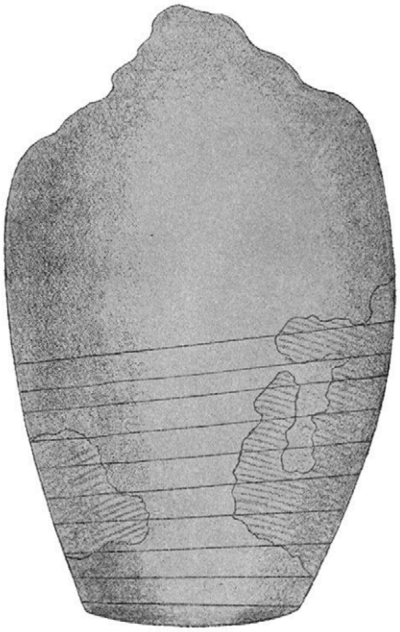
Gyroceras

Actinoceroids
Generally straight shells with "beaded"-looking siphuncles.

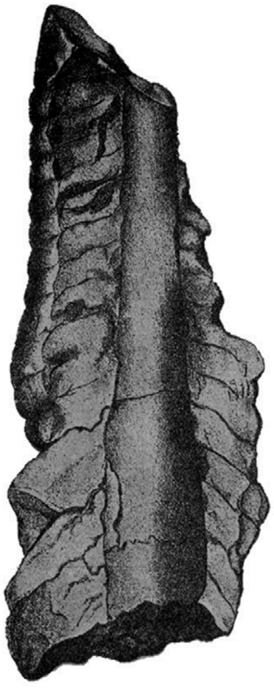


Treptoceras duseri
One of the more common Cincinnatian orthoconic actinoceroids.

"Cyrtoceras"



Gomphoceras
These are rather rare.



Endoceroids
Endoceroids are characterized by straight shells with fat, cone-shaped siphuncles.

Tentaculites
Not a cephalopod! *Tentaculites* is something else. These are rather small.

CHAPTER 3

Revisiting the Wisconsin depositional history of the southernmost extent of the Scioto Sublobe, Ohio

OHIO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES

American Institute of Professional Geologists
60th Anniversary Conference 2023

Geologic Field Trip

Revisiting the Wisconsin depositional history of the southernmost extent of the Scioto Sublobe, Ohio

Field trip leaders: T. Andrew Nash[*,1], Tyler A. Norris[*,1], and Thomas R. Valachovics[*,1]

Ohio Geological Survey

*** Field trip guide author.**

[1] Ohio Department of Natural Resources, Division of Geological Survey

Field trip cover photo: View of the Reesville Moraine, looking northeast along Stone Road, Clinton County, Ohio (39.4941° N, 83.7090° W).

INTRODUCTION

TRIP OVERVIEW

This one-day trip will trace the deglaciation of the Scioto Sublobe from its last glacial maximum (LGM) position in Clinton County into neighboring Fayette County (fig. 3-1A). We will review the sedimentological, chronologic, and geomorphic evidence used to interpret the glacial history of these two counties. Clinton and Fayette Counties are home to both striking and subtle glacial geomorphic features, all of which will be highlighted as we traverse through our field trip stops. In addition to tracing the retreating ice, we will also metaphorically and physically retrace the steps of renowned geologists who made significant contributions to the study of Quaternary geology in this region.

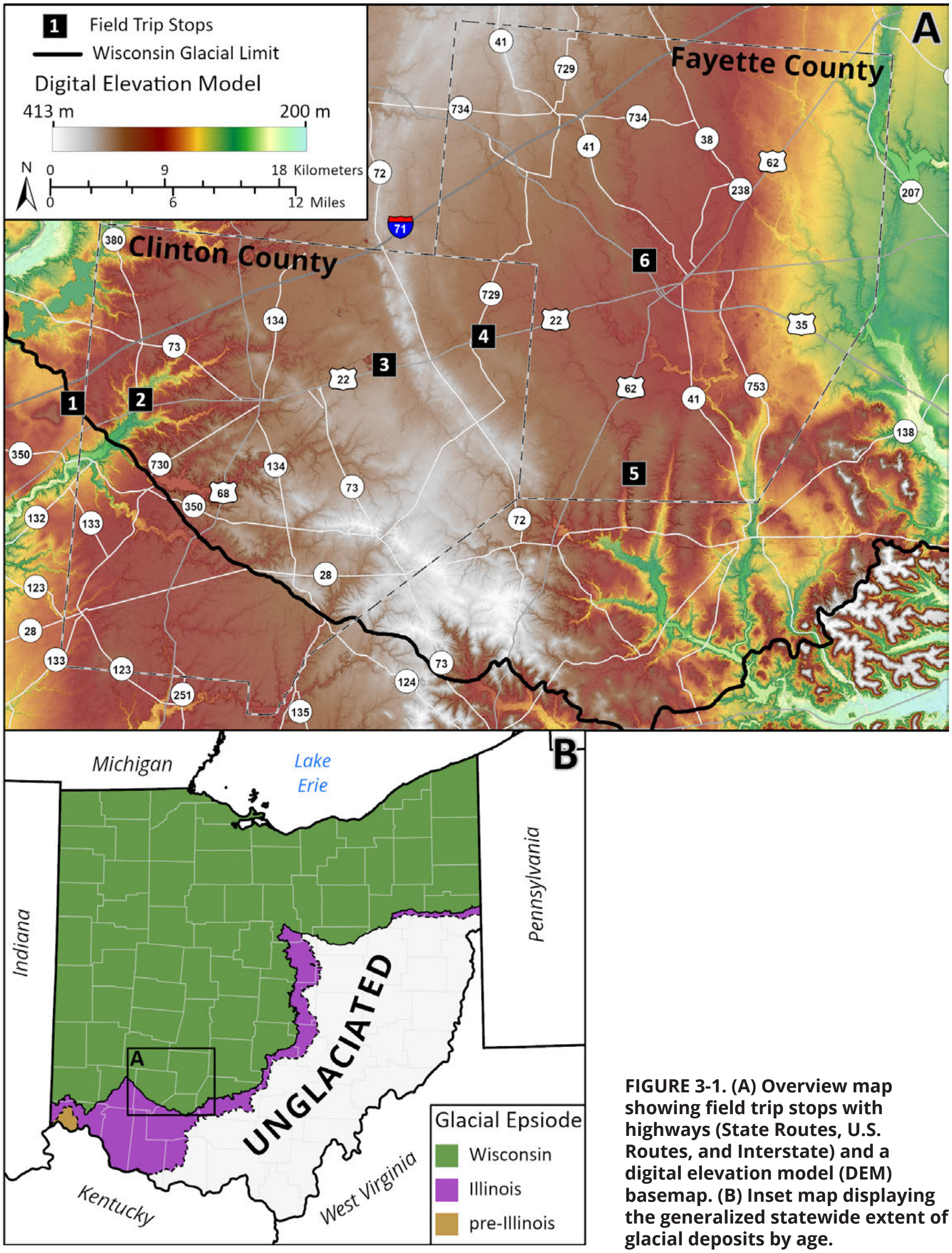


FIGURE 3-1. (A) Overview map showing field trip stops with highways (State Routes, U.S. Routes, and Interstate) and a digital elevation model (DEM) basemap. (B) Inset map displaying the generalized statewide extent of glacial deposits by age.

This trip begins at the Radisson Cincinnati Riverfront Hotel in Covington, Kentucky as participants travel northeast along the Wisconsinan terminal margin of the Miami Sublobe before entering our field trip area. The first stop of the trip, just west of Clinton County, shows the geomorphology of the Cuba Moraine Complex, the terminal moraine of the Wisconsinan Scioto Sublobe, and deposits associated with an unnamed associated proglacial lake. Our second stop takes us to an outcrop on the bank of Todd Fork where Caesar Till and radiocarbon-dated organic inclusions are exposed. From there, we travel to Melvin Stone Quarry just south of the Reesville Moraine to examine a fresh exposure of the Caesar Till and the contact with the underlying Silurian-aged dolomite. After a stop for lunch, we traverse across the Reesville Moraine and into Fayette County to examine the Darby Till at the Zimmerman Road site. At our final stop, we examine the geomorphology of the Washington Esker (which crosscuts the Jonesboro Moraine) and discuss the local chronology of glacial deposition and the evidence for palimpsest features.

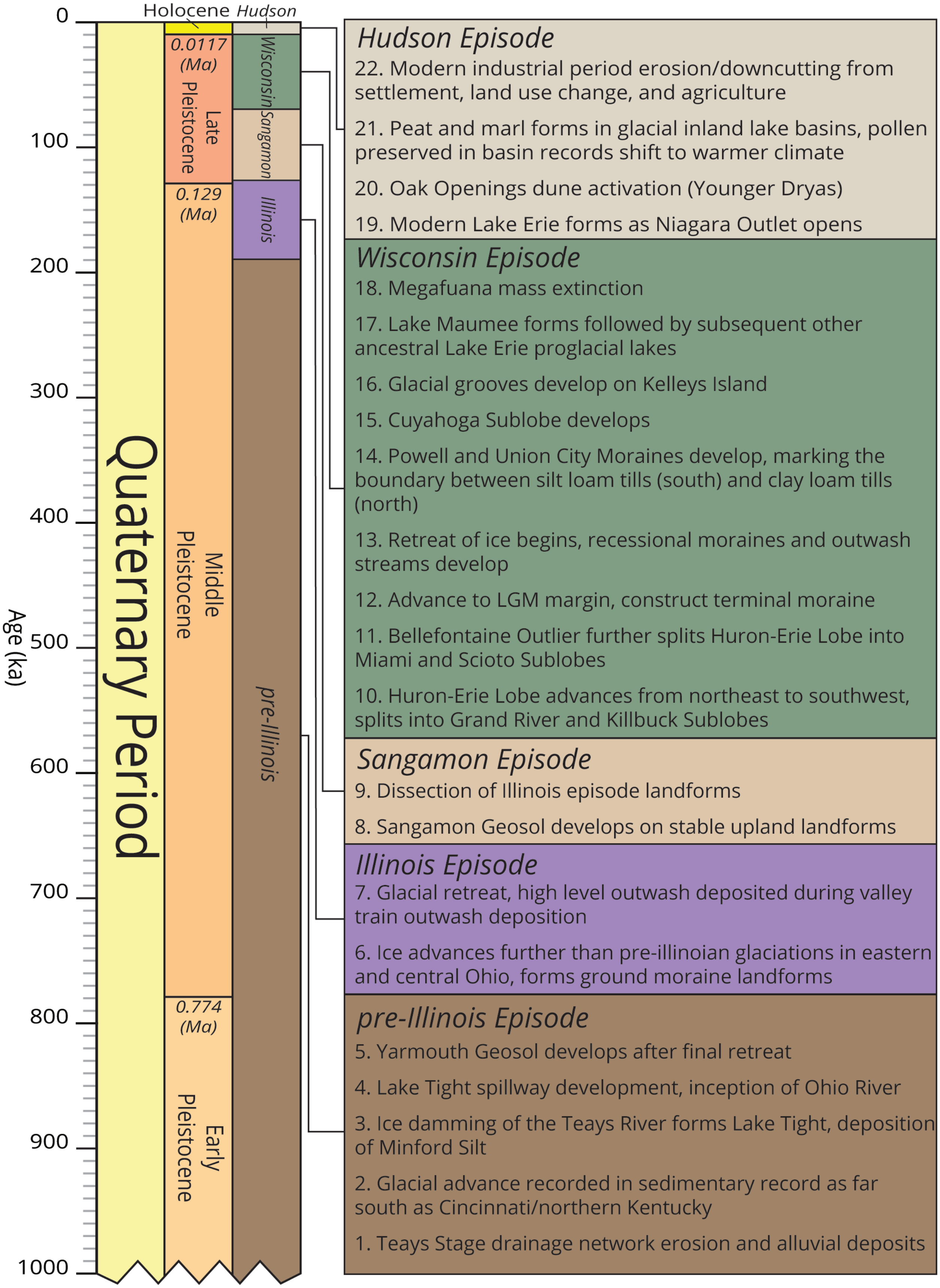
This guide was created to accompany the field trip associated with the 2023 AIPG 60th Anniversary National Conference, hosted in Covington, Kentucky. This trip was designed to last approximately 8 hours, including transportation between the field trip area and conference hotel in the morning and evening. Many of the field trip stops described in this guide are located on private property and should be respected as such. Permission to visit stops in the future should be granted from current landowners.

OHIO'S GLACIAL HISTORY

At the beginning of the Quaternary Period, global climate conditions and long-scale cooling trends led to the development of continental ice sheets that would eventually terminate in states across the northern United States, including Ohio. At least three periods of glaciation occurred in Ohio during the Pleistocene Epoch, covering around three quarters of the state (fig. 3-1B). Glacial sediments from pre-Illinois glaciations, the Illinois Glaciation, and the Wisconsin Glaciation were deposited across the state. Evidence for major geologic events that occurred during the Quaternary Period are preserved within these sediments (fig. 3-2).

Preglacial

Between the Paleozoic Era, when Ohio's sedimentary bedrock formed, and the beginning of the Quaternary Period, there is a gap in the sedimentary record that lasted for approximately 250 million years. During this unconformity, the North American craton rifted away from the supercontinent Pangaea and Ohio remained, relatively speaking, tectonically stable. The Appalachian Mountains, which developed at the end of the Paleozoic Era, established the headwaters of rivers that drained surface water westward towards the midcontinent. These rivers developed over this 250-million-year unconformity by eroding Paleozoic bedrock and cutting gorges and valleys through the uplifted landscape. The master stream responsible for draining much of Ohio during this time was the Teays River (fig. 3-3). The Teays River and its tributaries moved water from the surface of Ohio in a generally westward direction into modern-day Indiana, before eventually reaching a confluence with the ancestral Mississippi River in central Illinois. The Teays River drainage network was responsible for the fluvial erosion that occurred between the Paleozoic Era and the Quaternary Period and is marked by the lowest elevation valleys mapped on current bedrock topography maps (Brockman and others, 2003; Blake and Nash, 2018; Norris and others, 2022). The initial pre-Illinoian glaciations that occurred during the Quaternary Period began burying the Teays River Valley and reorganization of existing watersheds through modifications like stream piracy and drainage reversals.



Hudson Episode

22. Modern industrial period erosion/downcutting from settlement, land use change, and agriculture

21. Peat and marl forms in glacial inland lake basins, pollen preserved in basin records shift to warmer climate

20. Oak Openings dune activation (Younger Dryas)

19. Modern Lake Erie forms as Niagara Outlet opens

Wisconsin Episode

18. Megafuana mass extinction

17. Lake Maumee forms followed by subsequent other ancestral Lake Erie proglacial lakes

16. Glacial grooves develop on Kelleys Island

15. Cuyahoga Sublobe develops

14. Powell and Union City Moraines develop, marking the boundary between silt loam tills (south) and clay loam tills (north)

13. Retreat of ice begins, recessional moraines and outwash streams develop

12. Advance to LGM margin, construct terminal moraine

11. Bellefontaine Outlier further splits Huron-Erie Lobe into Miami and Scioto Sublobes

10. Huron-Erie Lobe advances from northeast to southwest, splits into Grand River and Killbuck Sublobes

Sangamon Episode

9. Dissection of Illinois episode landforms

8. Sangamon Geosol develops on stable upland landforms

Illinois Episode

7. Glacial retreat, high level outwash deposited during valley train outwash deposition

6. Ice advances further than pre-illinoian glaciations in eastern and central Ohio, forms ground moraine landforms

pre-Illinois Episode

5. Yarmouth Geosol develops after final retreat

4. Lake Tight spillway development, inception of Ohio River

3. Ice damming of the Teays River forms Lake Tight, deposition of Minford Silt

2. Glacial advance recorded in sedimentary record as far south as Cincinnati/northern Kentucky

1. Teays Stage drainage network erosion and alluvial deposits

FIGURE 3-2. Detailed Quaternary timescale with major glacial and interglacial events that occurred in Ohio.

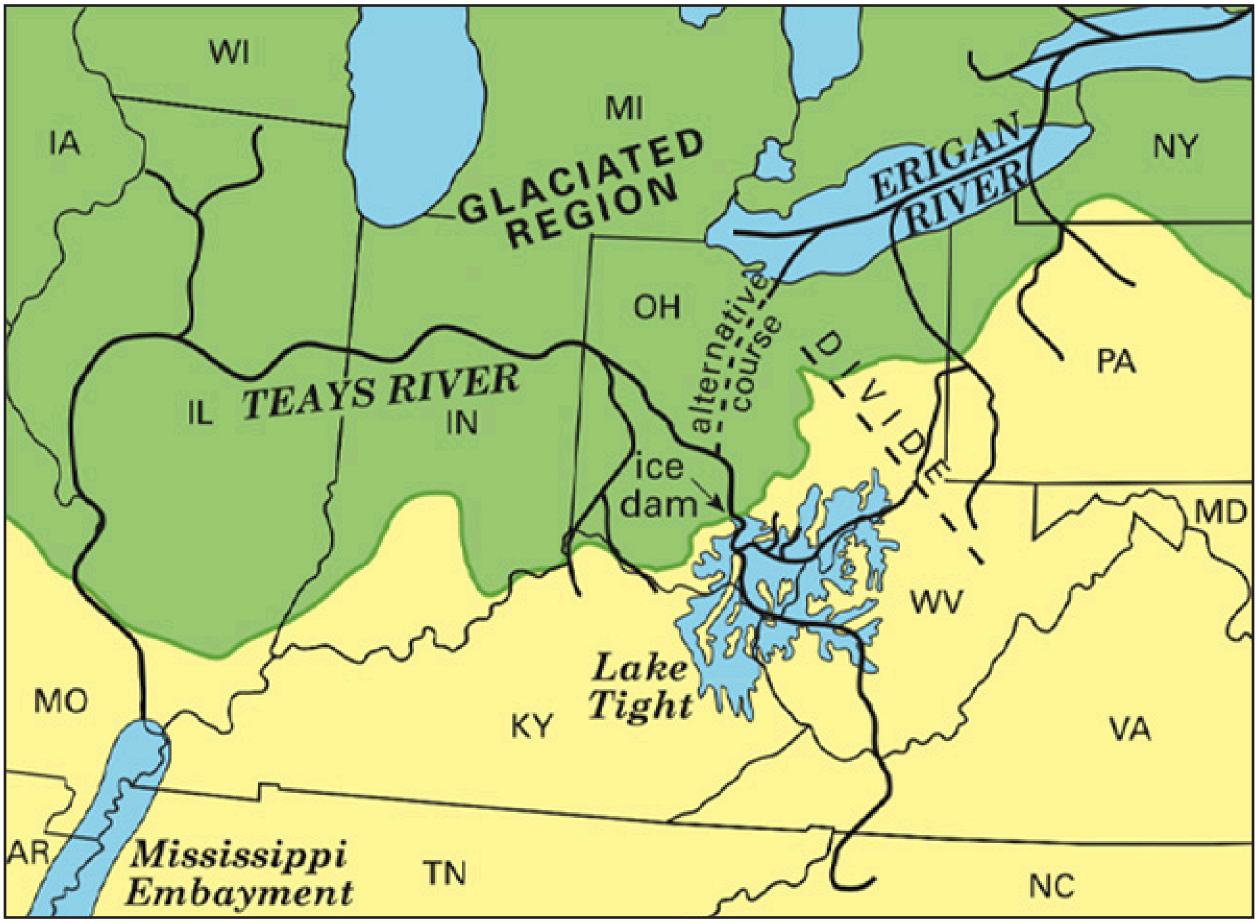


FIGURE 3-3. Conceptual map displaying major ancestral stream drainage (thick black lines) across several southeastern and midwestern states before Pleistocene glaciations. Also shown is the extent of the now-drained pre-Illinoian Lake Tight.

Pre-Illinois glaciations

Pre-Illinoian glaciations occurred during the early and middle Pleistocene and are primarily characterized by the reversed polarity of magnetic matrix minerals, indicating ages greater than 780,000 years before present (Bonnett and others 1991). These initial glaciations dammed the Teays drainage network, leading to the creation of the proglacial Lake Tight and the deposition of fine-grained lacustrine deposits (Tight, 1903). The waters of Lake Tight rose above preexisting drainage divides in southern Ohio, West Virginia, and Kentucky, and began the reorganization of surface watersheds in the region that largely developed in the time between the pre-Illinois and Illinois glaciations. In southeastern Ohio, Minford Silt is only preserved within preglacial Teays-aged valleys and on high terraces (Tight, 1903).

Glacial tills directly deposited by pre-Illinoian-aged glaciers are only preserved at the surface in southwestern Ohio, but have been observed in outcrops across southern Ohio, especially near the Illinoian glacial margin. Pre-Illinoian ground moraines around Cincinnati exhibit more dissection than other glacial landforms around the state because they have been exposed to fluvial erosion for much greater time periods. The degradation of glacial landforms and human development around southwestern Ohio and the greater Cincinnati metropolitan area make it difficult to interpret specific glacial events that could have occurred during these pre-Illinoian glaciations. Between pre-Illinoian and Illinoian glaciations, an interstadial event marked by the Yarmouth Geosol occurred but is rarely preserved within Ohio.

Illinois Glaciation

The Illinoian Glaciation was the penultimate glaciation in Ohio, occurring around 190,000–125,000 years before present. The Illinoian glacier advanced further than any other episode of Quaternary glaciation over much of Ohio and into Kentucky. Glacial deposits from the Illinois Episode are best exposed in southwestern Ohio, especially in Clermont, Brown, and Adams Counties (fig. 3-4). In these counties, Illinois-aged glacial

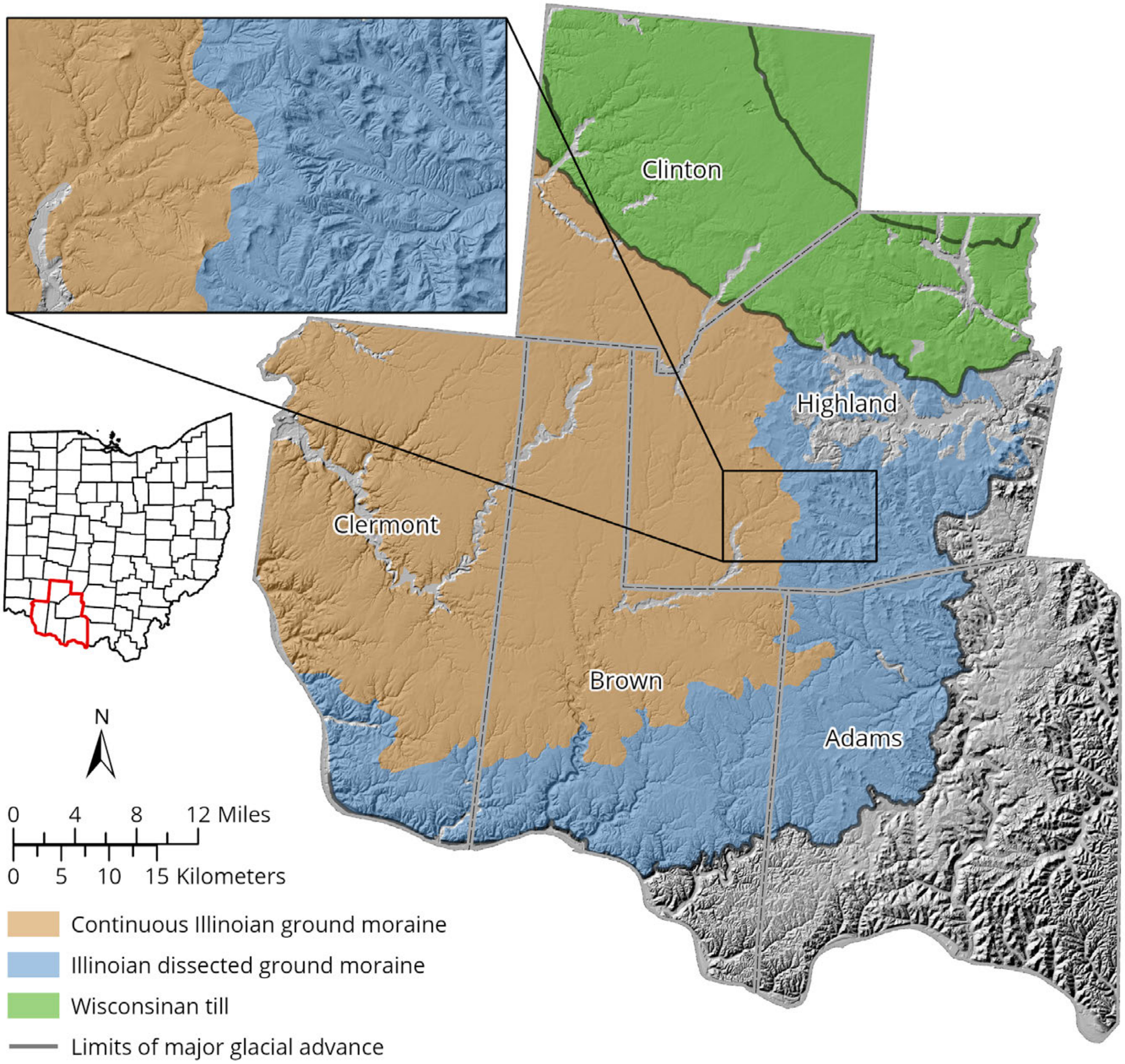


FIGURE 3-4. Map of southwestern Ohio displaying ground moraine extents with hillshade terrain basemap. Note the geomorphic contrast between the continuous Illinoian ground moraine (west) and the dissected Illinoian ground moraine (east) on the inset map. Modified from Pavey and others (1999).

tills were deposited over gently rolling hills of Ordovician-aged limestone and shale. Over the past 125,000 years, these till plains have been dissected by fluvial processes, often revealing the underlying bedrock. Illinois Episode glacial deposits north of these counties are restricted to the subsurface, if they are preserved at all.

The primary Illinois Episode landforms preserved in Ohio are ground moraines and outwash terraces. In southwestern Ohio, the ground moraine is expansive and generally exhibits higher magnitude dissection closer to the Illinoian glacial limit. In central, eastern, and northeastern Ohio only a thin band of Illinois Episode ground moraine is preserved just outside of the Wisconsinan glacial margin. This Illinois Episode ground moraine is heavily dissected, likely caused by initial deposition of till on the rugged terrain of the Allegheny Plateau and over 100,000 years of additional weathering and erosion. Illinois Episode outwash terraces are concentrated along rivers and streams that drained meltwater from this glaciation. The Ohio River, Scioto River, and Muskingum River Valleys were major pathways for Illinois Episode meltwater. In these valleys, Illinoian-aged terraces are preserved high above the modern floodplain and exhibit higher degrees of weathering than younger, lower elevation terraces. Illinois Episode end moraines, proglacial lakes, and kames are rarely preserved but have been noted during detailed mapping (Forsyth, 1966;

Rosengreen, 1974; Quinn and Goldthwait, 1985). The general lack and variety of well-preserved Illinoian-aged glacial landforms in Ohio makes interpreting the glacial history of this episode difficult.

Between the Illinoian and Wisconsinan Glaciations there was a warm interglacial period in which Ohio remained free of ice for tens of thousands of years. During this time the landscape was altered as streams eroded unconsolidated Illinoian-aged glacial deposits and Paleozoic bedrock, while soils formed in stable upland areas where erosion was minimal or not existent. This interglacial soil, known as the Sangamon Geosol, is preserved in areas where it was buried by later deposition. In stable upland areas where Illinois Episode glacial deposits are subaerially exposed, surface processes continued to modify the Sangamon Geosol into the modern soil.

Wisconsin Glaciation

The Wisconsin Glaciation, which covered parts of Ohio in ice between 30,000 and 14,000 years ago, was the last glaciation to occur in the state. Most unconsolidated deposits in Ohio are associated with this glacial episode. This Wisconsin Episode also has the best-preserved glacial geomorphic features. These factors result in a more detailed history of glaciation and deglaciation in Ohio during this time.

The Wisconsin Glaciation began with the advance of the Huron-Erie Lobe of the Laurentide Ice Sheet into Ohio. Heavy mineral assemblages from Michigan indicate that the Huron-Erie lobe advanced regionally along a northeastern–southwestern path (Dworkin and others, 1985). The Huron-Erie Lobe encountered topographic impediments to ice flow that further divided it into four main sublobes (fig. 3-5). The Grand River Sublobe and Killbuck Sublobe of northeast Ohio formed as the Huron-Erie Lobe advanced over the Allegheny Plateau. The Scioto Sublobe and Miami Sublobe formed as the Huron-Erie Lobe advanced around, and eventually over, the Bellefontaine Outlier.

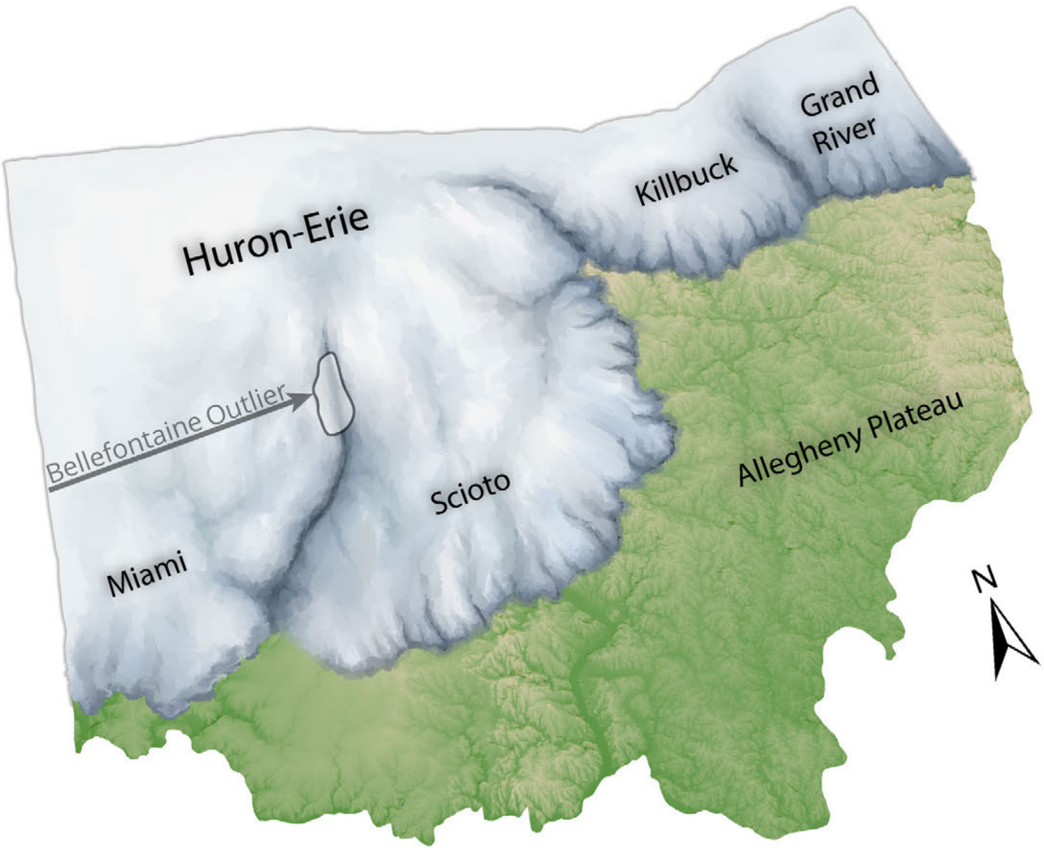


FIGURE 3-5. Artistic depiction of the Wisconsinan ice sheet over Ohio during the LGM with the Huron-Erie Lobe and associated sublobes labelled.

Wisconsinan ice reached its southern-most extent during the LGM, around 27,500 to 24,000 years ago (Clark and others, 2009; Nash, 2020). At this time, a terminal moraine formed in southern and central Ohio where the lower-relief topography was more suited to moraine-building processes than in the northeastern areas of the state. Ice began retreating shortly after the LGM as warming climate trends, driven through orbital forcing and incoming solar radiation, altered the mass balance of the Laurentide Ice Sheet. The retreat of the ice sheet is marked by recessional moraines (fig. 3-6) and includes brief periods of readvance. The most significant of these moraines that formed along the Scioto Sublobe and Miami Sublobe margin were the Powell and Union City Moraines, respectively. These end moraines developed contemporaneously during a readvance and mark the boundary between the silt loam tills to the south and the clay loam tills to the north.

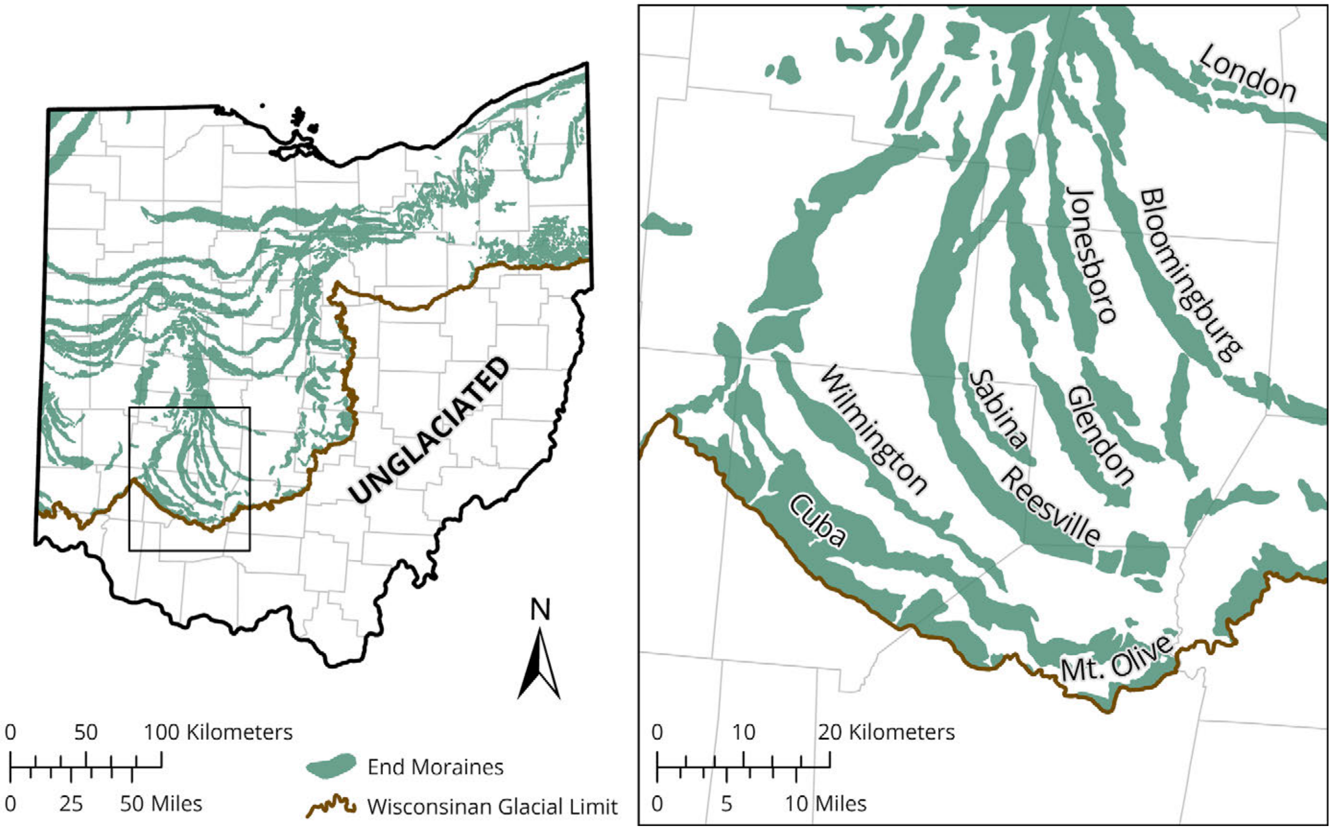


FIGURE 3-6. Map showing major end moraines in Ohio developed during the Wisconsin Glaciation (left) and named moraines labelled within the field trip area (right).

As the icefront retreated northward to what would become the Lake Erie Basin, proglacial lakes became more prevalent (fig. 3-7). A series of major proglacial lakes began forming in this area about 17,000 years ago (Fisher and others, 2015; Jones, 2021). As the Laurentide Ice margin fluctuated within northern Ohio and southern Ontario, so did the water level in these proglacial lakes. Stable ice margin conditions led to a stable shoreline and the development of beach ridges, spits, and other geomorphic features composed of sand. These stages of lake development occurred for about 5,000 years before the Huron-Erie Lobe retreated north of the modern Niagara River outlet establishing early Lake Erie. Around the same time these early proglacial lakes were forming, glacial erosion on Kelley's Island was developing the glacial grooves in the underlying Columbus Limestone (Snow and others, 1991). These iconic glacial features were exposed during modern quarrying of the island and are preserved today as a National Natural Landmark.

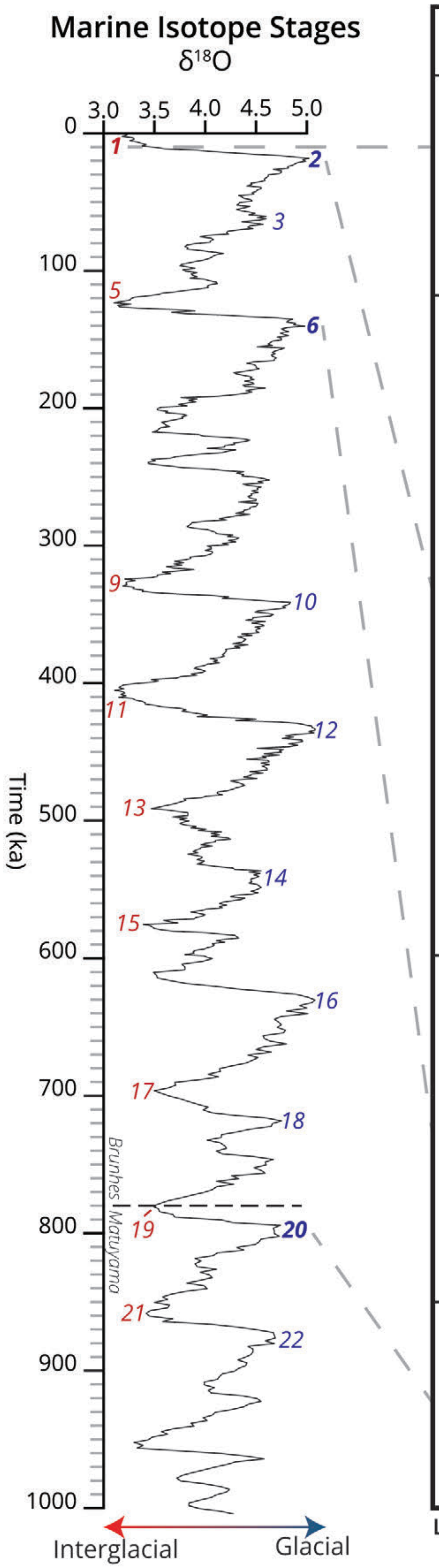
The late Pleistocene landscape of Ohio was dominated by large herbivores and ice age predators during the Wisconsin Glaciation. Remains of these megafauna are preserved in glacial sediments from this time, especially in glacial lake and peat deposits. The collapse of Pleistocene megafaunal populations occurred around 15,000 to 14,000 years ago, which coincides with changes in vegetation types and an increase in wildfires (Gill and others, 2009). However, there is still debate surrounding the primary causes of megafauna extinction at the end of the Pleistocene Epoch.

FIGURE 3-7. Map depicting the extent of proglacial Lake Maumee and the probable ice margin of the Huron-Erie Lobe during lake development (Jones, 2021).

Towards end of the deglaciation in Ohio, an abrupt return to near glacial conditions known as the Younger Dryas began around 12,900 years ago (Campbell and others, 2011). During this cold period, numerous environmental factors led to the decline of stabilizing vegetation on sandy landforms leading to remobilization of proglacial lake shorelines into eolian dunes (Campbell and others, 2011). This process was especially prevalent in northwestern Ohio where large amounts of eolian sands form the Oak Openings region near the city of Toledo. The Younger Dryas ended around 11,700 years ago, leading to a more typical modern climate in Ohio and a halt to eolian dune activity (Alley, 2000; Campbell and others, 2011). The end of the Younger Dryas marks the beginning of the Holocene Epoch (Walker and others, 2019). At the beginning of the Holocene, the Wisconsin-aged Laurentide Ice Sheet had retreated north of Ohio and did not directly affect the deposition of new sediment.

REGIONAL QUATERNARY STRATIGRAPHIC FRAMEWORK

The Quaternary-aged sediments of this region are organized into a stratigraphic framework defined by their lithology and chronology. This chronolithologic framework was first established in Clinton County (Nash, 2020) and expanded upon in Fayette County (Valachovics and others, 2022) and relies on an established diachronous event framework for the Great Lakes region (Johnson and others, 1997). Nash (2020) described three lithologically distinct diamicton (till) units that were associated with separate depositional events during the Illinois and Wisconsin Glaciations (fig. 3-8). The Caesar and Darby Tills are Late Wisconsinan diamictons associated with two advances of the Scioto Sublobe in central Ohio (fig. 3-9).



Episode (MIS)	Till Units	Other Units
Hudson (11.7–0 ka) *MIS 1*	—	alluvium colluvium
Late Wisconsin (28–18 ka) *MIS 2*	**Darby Till**	Worthington Outwash (Paint Creek) Washington Esker
		Worthington Outwash (Anderson Fork) Melvin Silt
	Reesville Moraine	*Circleville Fan*
	Caesar Till	Circleville Outwash (Dutch Creek, Todd Fork, Lytle Creek,Cowan Creek)
		Circleville Outwash (East Fork Little Miami, East Fork Todd Fork, Todd Fork) Cuba Lakes
Illinois (190–125 ka) *MIS 6*	**Rainsboro Till**	Illinois Outwash
pre-Illinois (>780 ka) *MIS >20?*	—	—

Lithology color key: diamicton (till), glaciofluvial, glaciolacustrine, ice-contact, loess

FIGURE 3- 8. Marine Isotope Stages (MIS) plotted against age with labelled stages. These stages correspond to glacial depositional events that occurred in Clinton and Fayette Counties, Ohio.

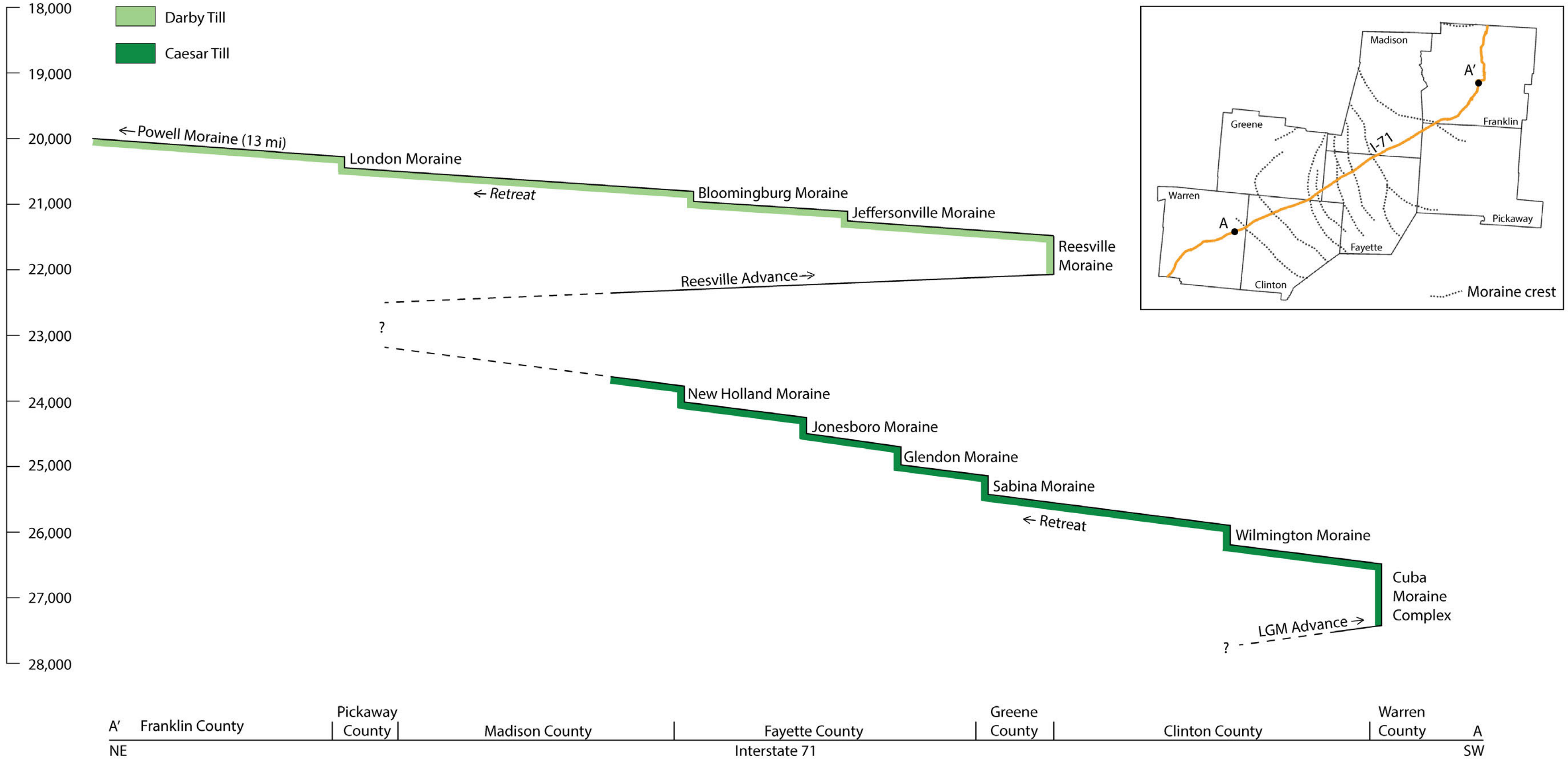


FIGURE 3-9. Schematic time-distance diagram depicting the advance and retreat of the Scioto Sublobe in central Ohio during the Wisconsin Glaciation along modern-day Interstate-71. The location of Interstate-71 in relation to county boundaries and ice margins is shown in the inset map.

In both Clinton and Fayette Counties, glacial till and outwash units can be correlated using absolute and relative chronologic control. The nomenclature of outwash units was first defined by terrace elevations and profiles (Kempton and Goldthwait, 1959). These elevation profiles help define ice marginal positions through the connection of outwash plains and fans to terminal moraines and valley-train outwash terraces landforms. For example, the Reesville Moraine is the boundary between the older Caesar Till to the south and the younger Darby Till to the north (figs. 3-8 and 3-9). The Circleville Fan, an outwash fan along the eastern edge of the modern Scioto River Valley, formed along the correlated margin to the Reesville moraine and was the headwater for the youngest Circleville Outwash. Therefore, the transition between both the Caesar and Darby Tills, as well as the Circleville and Worthington Outwashes, can be attributed to this ice marginal position (fig. 3-8).

These depositional events can be broadly related to global records of glaciation. Measurements of foraminifera test oxygen isotopic signature preserved in oceanic sediments are a well-established proxy record of global land ice volume and sea level (Lisiecki and Raymo, 2005). Trends from this proxy record can be divided into time periods known as Marine Isotope Stages (MIS; Railsback and others, 2015). The MIS framework allows for quick continental and global correlation of localized Quaternary units and is therefore useful to apply in Clinton and Fayette Counties.

The earliest record of ice advance into Fayette and Clinton Counties is marked with the deposition of the Rainsboro Till. The Illinoian Glaciation was the penultimate glaciation in Ohio and occurred during MIS 6. The Rainsboro Till is primarily found on the ground moraine till plains of southwestern Clinton County. This till is characterized by its dark-gray color, loamy texture, deep weathered surface, and compaction. The Rainsboro Till was likely deposited near the MIS 6–MIS 5 transition as the Illinoian ice front was at its furthest extent 20 miles to the southeast. No glacial geomorphic features, other than the dissected ground moraine, were preserved through subsequent glacial advance in Clinton or Fayette Counties to provide further evidence about the history of till deposition during MIS 6.

Both counties remained ice free after the Illinois Episode deglaciation until the initial advance of the Scioto Sublobe into the area during the Wisconsinan Glaciation (MIS 2). The Scioto Sublobe reached its maximum extent in Clinton County, constructing the terminal Cuba Moraine Complex around 27,500 years ago (Nash, 2020). The instability or oscillation of this ice margin created a morainal complex with three distinct crests and dissected steep slopes. This terminal moraine is composed of the Wisconsinan-aged Caesar Till. This till is primarily characterized by its blue-gray matrix and thick overlying loess deposits. Caesar Till was deposited in Clinton County during the advance and initial retreat of the Scioto Sublobe around the LGM, including the construction of the Wilmington Moraine shortly after the deglaciation from the terminal moraine. The Scioto Sublobe then retreated out of Clinton and Fayette Counties while continuing to deposit the Caesar Till. During the initial retreat from its maximum position, recessional moraines comprised of Caesar Till were constructed across both counties.

The Reesville Moraine marks the readvance of the Scioto Sublobe around 21,000 years ago during the beginning of the MIS 2 to MIS 1 transition. This readvance included deposition of a till distinct from the older Caesar Till. The Darby Till is typically darker and browner with a siltier texture than the older Caesar Till and is devoid of a thick loess cap. Much of the loess that blankets the Caesar Till in Clinton County was probably deposited during the construction of the Reesville Moraine, which explains the difference in loess thickness between the two tills. The Darby Till covers much of central Ohio (including Fayette County and the northeastern corner of Clinton County) and is found as far north as the Powell Moraine (Union and Delaware Counties), where the till then abruptly transitions into a much more clay-rich matrix. The large distribution of the Darby Till across central Ohio is likely due to a consistent deglaciation after the construction of the Reesville Moraine with minimal oscillation between advance/retreat of the Scioto Sublobe as the transition to MIS 1 continued to progress. Darby Till in portions of Fayette County are blanketed over Caesar Till end moraine landforms, creating palimpsest features. The Glendon, Jonesboro, and Marcy Moraines in Fayette County are all palimpsest moraines that have Caesar Till cores but are covered by Darby Till.

FIELD TRIP STOPS

STOP 1: HAGEMEYER FARMS (39.4414° N, 83.9995° W)

This stop along Wilmington Lebanon Road, just outside of Clinton County, is one of the best places to view the terminal moraine of the Scioto Sublobe (fig. 3-10). While traversing across the Illinois Episode ground moraine, there is a Silurian-aged bedrock cored plateau that rises almost 30 meters (100 ft) above the surrounding landscape. This Silurian outlier is surrounded by older Ordovician rocks of the Drakes, Whitewater, and Liberty Formations (Slucher and others, 2006). The plateau is covered by a thin mantle of loess deposited concurrently with the adjacent Cuba Moraine Complex and thin to patchy Illinoian glacial till. The plateau is surrounded mostly by Illinois Episode Rainsboro Till and Wisconsinan proglacial lacustrine deposits. The Silurian-aged carbonate bedrock core of the plateau is visible in outcrop along Wilmington Lebanon Road (fig. 3-11). Looking back to the west and southwest from the stop, the full extent of this plateau is clearly visible. The Cuba Moraine Complex (the terminal moraine of the Scioto Sublobe) is the rise visible when looking to the east and northeast from the stop. A proglacial lake once filled the lowland between these two relatively high-elevation features.

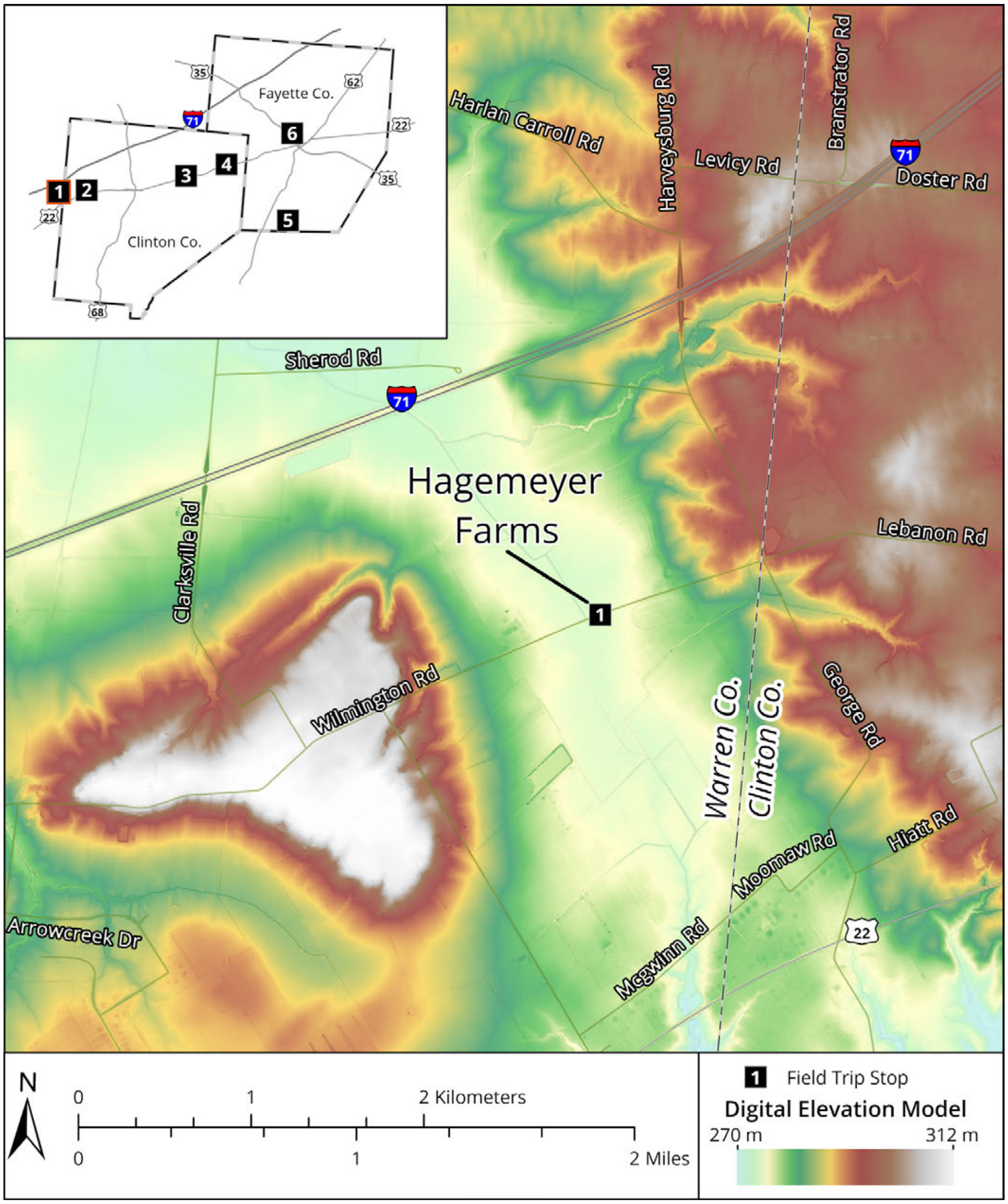


FIGURE 3-10. Map showing the location of Hagemeyer Farms (Stop 1) along Wilmington Lebanon Rd. in Warren County, Ohio. This stop is situated in the lowlands between the Cuba Moraine Complex to the east and a Silurian bedrock outlier to the west.

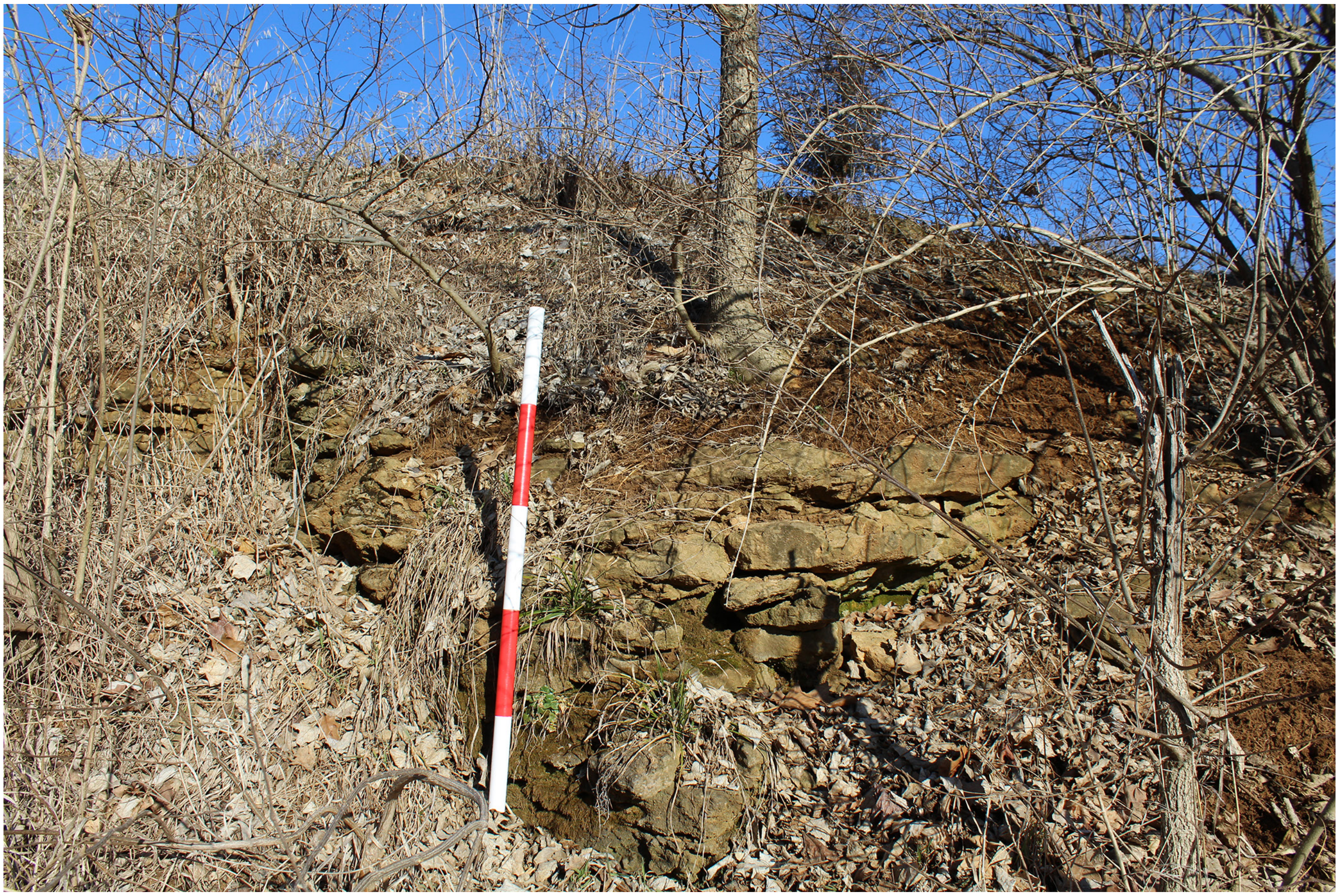


FIGURE 3-11. Photograph of Silurian carbonate bedrock exposed along Wilmington Lebanon Road (39.4368°N, 84.0130° W). White-and-red scale segments are 20 cm (0.65 ft).

Atop the Silurian outlier looking northeast along Wilmington Lebanon Road, the Cuba Moraine Complex and Hagemeyer Farms are visible (fig. 3-12). As we approach our first stop, we will drop from the outlier to the proglacial plain between the outlier and Cuba Moraine Complex. The lowland position of this stop gives 360° views of higher-elevation Wisconsinan and Illinoian landforms and facilitates a discussion about their differences. The surrounding Wisconsin Episode lacustrine deposits, with almost no relief and minimal dissection, are a stark contrast to the nearby weathered and highly dissected Illinoian Episode ground moraine landforms. The Illinoian Rainsboro Till was deposited between 160,000 and 125,000 years ago, meaning there was an extra 100,000 years of exposure and weathering relative to younger Wisconsin Episode deposits. These older deposits would eventually become the substrate that the Wisconsin Episode ice constructed the Cuba Moraine Complex on some 100,000 years later. The Cuba Moraine Complex is a dissected terminal moraine with at least three distinct crests. These moraine crests were likely constructed as the ice margin fluctuated due to climatic forcing (Lowell and others, 1999).

Multiple small proglacial lakes formed along the southern margin of the Scioto Sublobe during the construction of the Cuba Moraine Complex. These lakes were concentrated in relatively flat, lowland areas of the adjacent Illinois Episode ground moraines, where meltwater had no obvious drainage pathway, or the pre-Wisconsinan drainage flowed northward. Examples of these lakes can be traced across the southern edge of the Scioto Sublobe in Warren and Clinton Counties (fig. 3-13). The proglacial lake at Hagemeyer Farms wrapped around the small plateau to the southwest, creating a temporary island (fig. 3-13). Further study of this lake could be useful for understanding the complex history of moraine construction during the local LGM of the Scioto Sublobe. This basin represents an ideal capture zone for terrestrial organic material to be blown or washed into and deposited on the silty clay lake bottom. If these organic deposits are preserved within these lake sediments, future radiocarbon dating analysis could indicate the timeframe of lake development, which is expected to correspond to the age of moraine construction, which could help further constrain the development of the Cuba Moraine Complex.

FIGURE 3-12. (A) A photograph showing the view along Wilmington Lebanon Road looking northeast towards Hagemeyer Farms and the Cuba Moraine Complex. The flat lowlands between these topographic highs are filled with glaciolacustrine sediment. (B) The view of the Cuba Moraine Complex from Hagemeyer Farms.

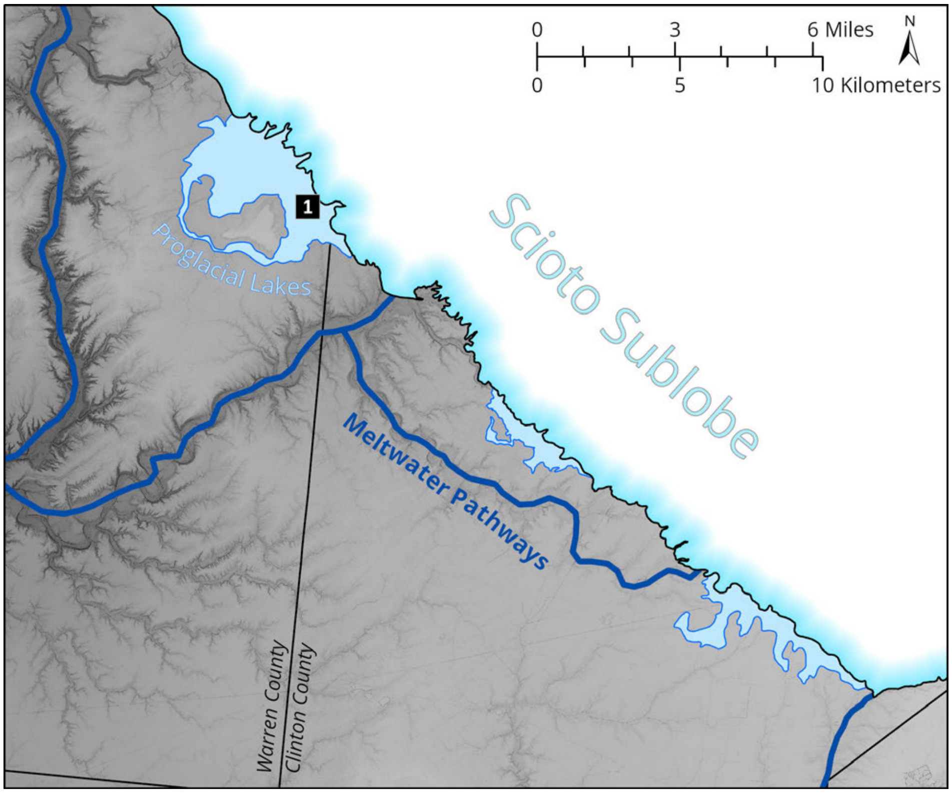


FIGURE 3-13. Map of the Scioto Sublobe at its LGM terminal position. A series of proglacial lakes formed within closed basins between meltwater pathways.

STOP 2: TODD FORK CUT (39.4449° N, 83.9375° W)

The Todd Fork site is a well-studied outcrop of Caesar Till within the Cuba Moraine Complex. Situated along the western bank of Todd Fork, the outcrop is only about 150 m (500 ft) from State Route 380 (fig. 3-14). The accessibility, height, lithology, stratigraphy, and longevity of this outcrop have made this an important site for numerous studies of the Quaternary geology in Clinton County. One of the first studies examining the Quaternary geology of Clinton County recognized the presence of wood noted in water well drilling records in the vicinity of Todd Fork (Austin, 1930). Teller (1964) appears to be the first geologist to describe the outcrop at Todd Fork during his mapping of the county, although unpublished radiocarbon dates from Todd Fork by Jane Forsyth in 1964 indicate that this might have been a collaborative effort (Table 3-1). Teller (1964) also examined an outcrop of till with wood below an outwash terrace about 2.5 miles southeast of the Todd Fork site. The wood imbedded within this till was radiocarbon dated and found to be >37,000 years old, which led to an interpretation of an Illinois Episode age for basal tills in this area (Teller, 1964). More recent dating in the vicinity of OH-380 and US-22 confirms the presence of >60,000-year-old

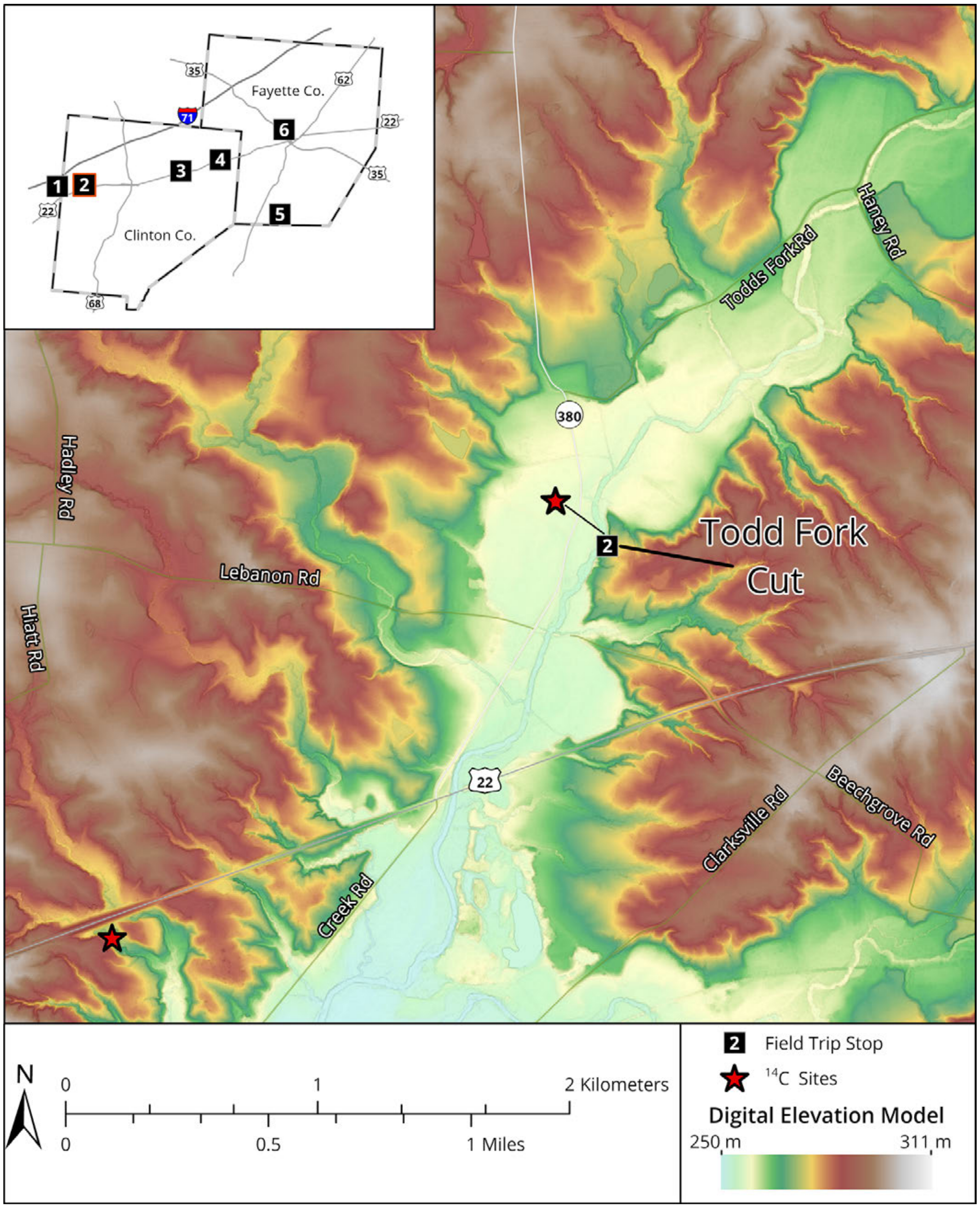


FIGURE 3-14. Map showing the location of Todd Fork Cut (Stop 2) within the Todd Fork valley and adjacent to State Route 380. Two sites with preserved organic material, which was radiocarbon dated, are marked with red stars on the map.

organic matter preserved in till deposits just above the Quaternary-Paleozoic contact (Nash, 2020). However, radiocarbon dates from the basal till at the Todd Fork site confirm that this basal till unit is significantly younger till than the basal till unit further downstream (Teller, 1964; Nash, 2020).

A renewed interest in the Todd Fork site occurred during the earlier half of the 1990s. Dell (1991) described the Todd Fork outcrop and studied the gastropods preserved there. At this time, the outcrop was split into two sections by a large, central slump (Dell, 1991). Dell (1991) described two outcroppings of complex glacial sequences, which include till and outwash deposits, on either side of this central slump. Although this study includes a detailed description of the outcrop, the focus of the overall study was the identification of the gastropods preserved here and their use as a paleoenvironmental indicator. Dubois (1996) revisited the Todd Fork site with an interest in understanding the Late Wisconsinan Glaciation glacial processes that deposited these sediments and constructed the Cuba Moraine Complex. The stratigraphy of the site as described by Dubois (1996) is summarized in Figure 3-15. The sequence and interpretation of glacial deposition at the Todd Fork outcrop is anchored by a series of eight radiocarbon dates on wood collected from in-situ stumps in the sheared paleosol (Dubois, 1996). These ages can be averaged into an age of 23,180 ^{14}C yr BP, or about 25,510 cal yr BP (Dubois, 1996). All historic and published radiocarbon ages from the Todd Fork Cut are summarized in Table 3-1. The Todd Fork site was a key outcrop for determining that multiple advances of the Scioto Sublobe compounded together to form the multiple ridges of the Cuba Moraine Complex (Dubois, 1996).

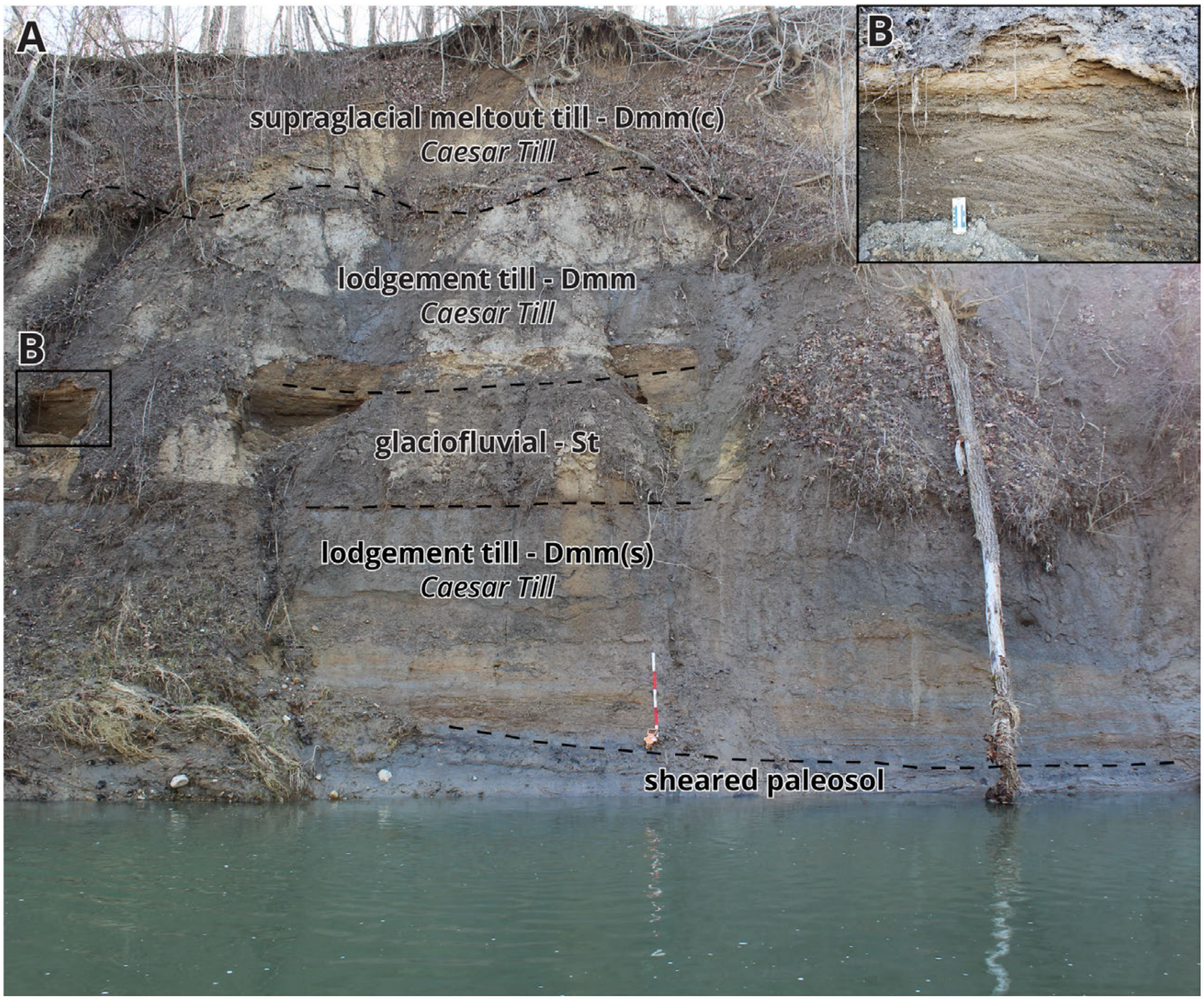


FIGURE 3-15. (A) Annotated photograph of the Todd Fork Cut showing different lithologic units and till facies. The base of the outcrop, at present stream level, is a sheared paleosol that contains organic material and terrestrial gastropod shells. This paleosol has an abrupt contact with overlying lodgement till of the Caesar Till. A glaciofluvial deposit separates upper and lower Caesar lodgement till deposits. The uppermost Caesar Till at the Todd Fork Cut is a supraglacial meltout till facies. White-and-red scale segments are 20 cm (0.65 ft). (B) Close-up view of the cross bedded glaciofluvial sands.

TABLE 3-1. ***Radiocarbon dating results from samples collected at the Todd Fork site. All reported calendar ages have been calibrated with the IntCal20 Northern Hemisphere radiocarbon age calibration curve (Reimer and others, 2020).***

Lab Number	Material Dated	Fraction Modern	±	δ^{14}C (‰)	^{14}C age (BP)	±	Cal Year (BP)	±
221205	spruce needles	0.0421	0.0004	-957.9	25,450	70	27,719	342
221206	spruce needles	0.0418	0.0004	-958.2	25,500	80	27,748	355
221596	spruce needles	0.0413	0.0005	-958.7	25,600	90	27,968	187
221597	spruce needles	0.0407	0.0005	-959.3	25,720	90	28,074	128
ISGS-2935	wood	—	—	—	23,160	180	25,520	268
ISGS-2936	wood	—	—	—	23,250	210	25,555	285
ISGS-2939	wood	—	—	—	23,150	180	25,516	271
ISGS-2940	wood	—	—	—	23,110	240	25,451	390
ISGS-3067	wood	—	—	—	23,230	400	25,421	907
ISGS-3068	wood	—	—	—	23,150	240	25,485	365
ISGS-3066	wood	—	—	—	23,540	300	25,884	595
OWU-159	wood	—	—	—	21,140	143	23,528	310
OWU-160	wood	—	—	—	22,255	165	24,575	482

Although the Scioto Sublobe advanced over Todd Fork multiple times, only one till unit was deposited here. In fact, all the glacial till deposited during the construction of the Cuba Moraine Complex and the nearby Wilmington Moraine belong to the same unit, the Caesar Till (Nash, 2020). The Caesar Till is a gray (10YR 5/1), massive, loamy diamicton that is generally calcareous (unweathered) and sparsely pebbly with a well-developed prismatic structure. Another defining characteristic of Caesar Till is the presence of 0.5–1 m (2–3.5) ft of loess-capping surficial till deposits. Caesar Till is commonly associated with soils of the Fincastle, Reesville, Treaty, and Xenia series of Clinton County. The Crouse and Miamian soil series developed on slopes and colluviated Caesar Till deposits, especially along the Cuba Moraine Complex.

The glacial history of the region and mechanism for the construction of the Cuba Moraine Complex can be described through the interpretation of the sediments exposed at the Todd Fork outcrop. The basal unit exposed just above the modern stream level is a paleosol developed in silty overbank deposits which overlie interglacial channel alluvium. This sequence is representative of a riparian environment which likely developed throughout the Sangamon Interglacial. Stumps, plant macrofossils, and gastropods preserved in this paleosol are indicative of a boreal forest environment. The age of this paleosol has been determined through radiocarbon dating by multiple studies and is summarized in Table 3-1. The shearing of stumps preserved in-situ is an indication that the Caesar Till that caps this paleosol represents the initial advance of the Scioto Sublobe over the site to the outer crest of the Cuba Moraine Complex. The sand and gravel outwash overlying this basal Caesar Till represents a short interstadial in which the Todd Fork site was ice free. Overlying these interstadial outwash deposits is another unit of Caesar Till deposition representing the readvance of the Scioto Sublobe, this time to the inner crests of the Cuba Moraine Complex. The uppermost unit at the site is a silty supraglacial meltout till which represents the final stage of Cuba Moraine Complex construction and the retreat of the Scioto Sublobe to the Wilmington Moraine. The silty nature of this meltout facies could be influenced by the known relatively thick loess caps diagnostic of the Caesar Till.

STOP 3: MELVIN STONE QUARRY (39.4722° N, 83.71506° W)

Upon leaving the Todd Fork site, we travel through the northeastward edge of the Cuba Moraine complex in the county. The Wilmington Moraine appears on the left (north) side of OH-73 E soon after the 68 Xenia–Wilmington exit. We cross the Wilmington Moraine about one mile before exiting OH-73 E onto US-22 E, approximately at the Prairie Rd. overpass bridge. The remaining distance traveled along US-22 E takes us over mostly flat ground moraine composed of Caesar Till, which we will observe in detail at Melvin Stone Quarry (fig. 3-16).

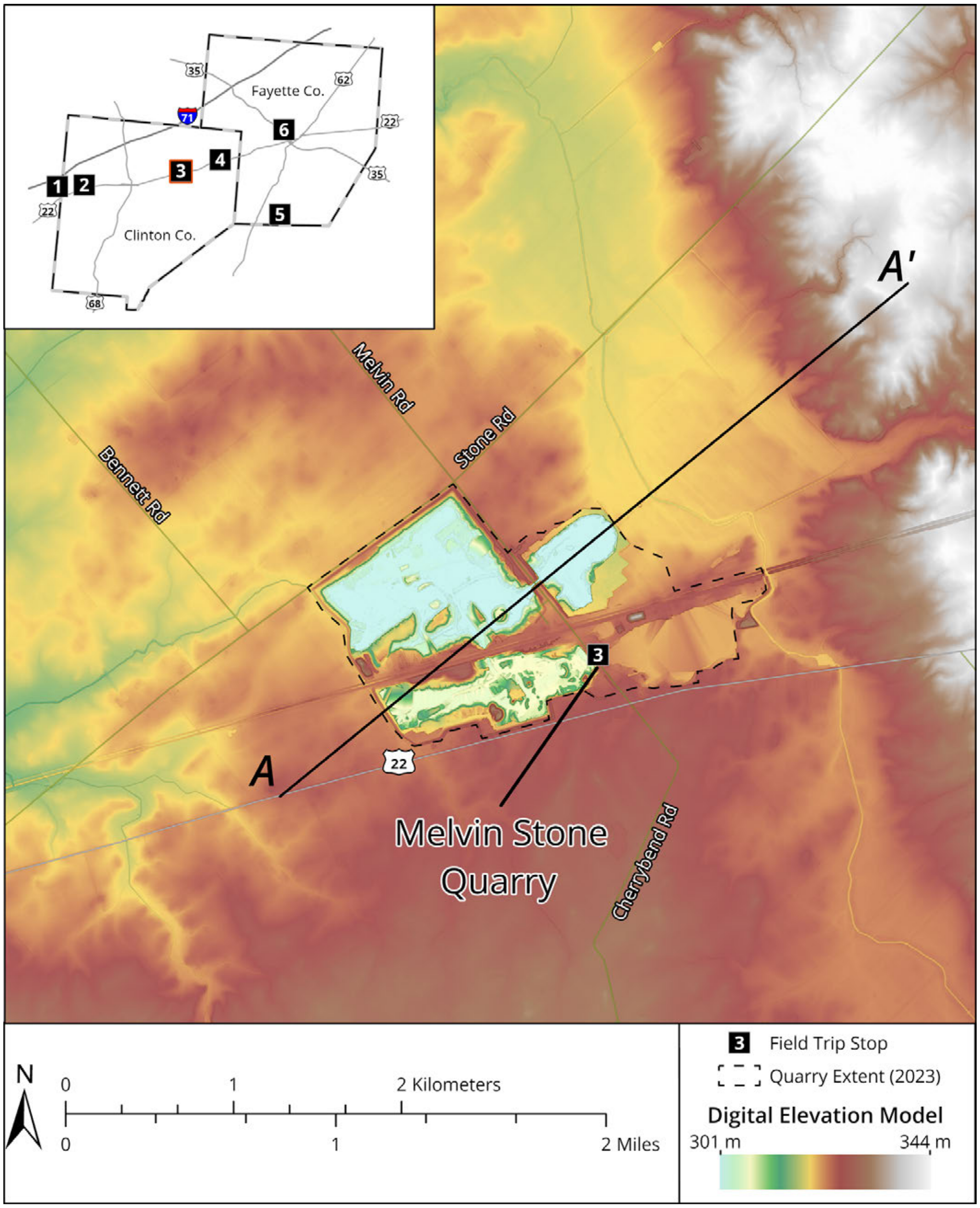


FIGURE 3-16. Map showing the location of Melvin Stone Quarry (Stop 3). The cross section (fig. 3-19) extends from U.S. Route 22 (A, through the quarry) and ends at the Reesville Moraine (A′).

This quarry site was once visited during the INQUA meeting of 1965, where Quaternary geologists travelled from Edwardsville, Illinois all the way to Niagara Falls, Ontario to examine notable Quaternary features in the Great Lakes Region. Today, we revisit this iconic stop with additional insight gained since 1965, along with new exposures brought about by continued quarry operations (fig. 3-17).

The bedrock being mined at the quarry is Silurian-aged Cedarville Dolomite, which is used mostly for aggregate and a minor portion of ag-lime (Wright, 2022). The quarry is situated over a slight bedrock high “dome” that may be a subtle structural feature. Fresh bedrock top exposures exhibit southwest-oriented striations parallel with the Scioto Sublobe ice flow direction. Above the bedrock is a thin overburden package of blue-gray silt-loam diamicton (till) with a >100 cm (>40 in) silt cap (loess). Although this diamicton was previously described as “typical Darby Formation” (INQUA, 1965), it is now interpreted to be consistent with the earlier Caesar Till (Nash, 2020) due to the characteristic thick loess cap that drapes most of the materials southwest of the Reesville Moraine. This relatively thick loess cap is classically interpreted as wind-blown silt (Melvin Silt), mostly sourced from nearby outwash (fig. 3-18), that blanketed the Caesar Till during stagnation of the Scioto Sublobe ice at the Reesville Moraine. However, some areas of the silt cap are described as lacustrine silt; minor proglacial lakes may have developed in front of this margin. As a result, these wind-blown silt particles may have been trapped in these small basins and were deposited in a lacustrine setting.

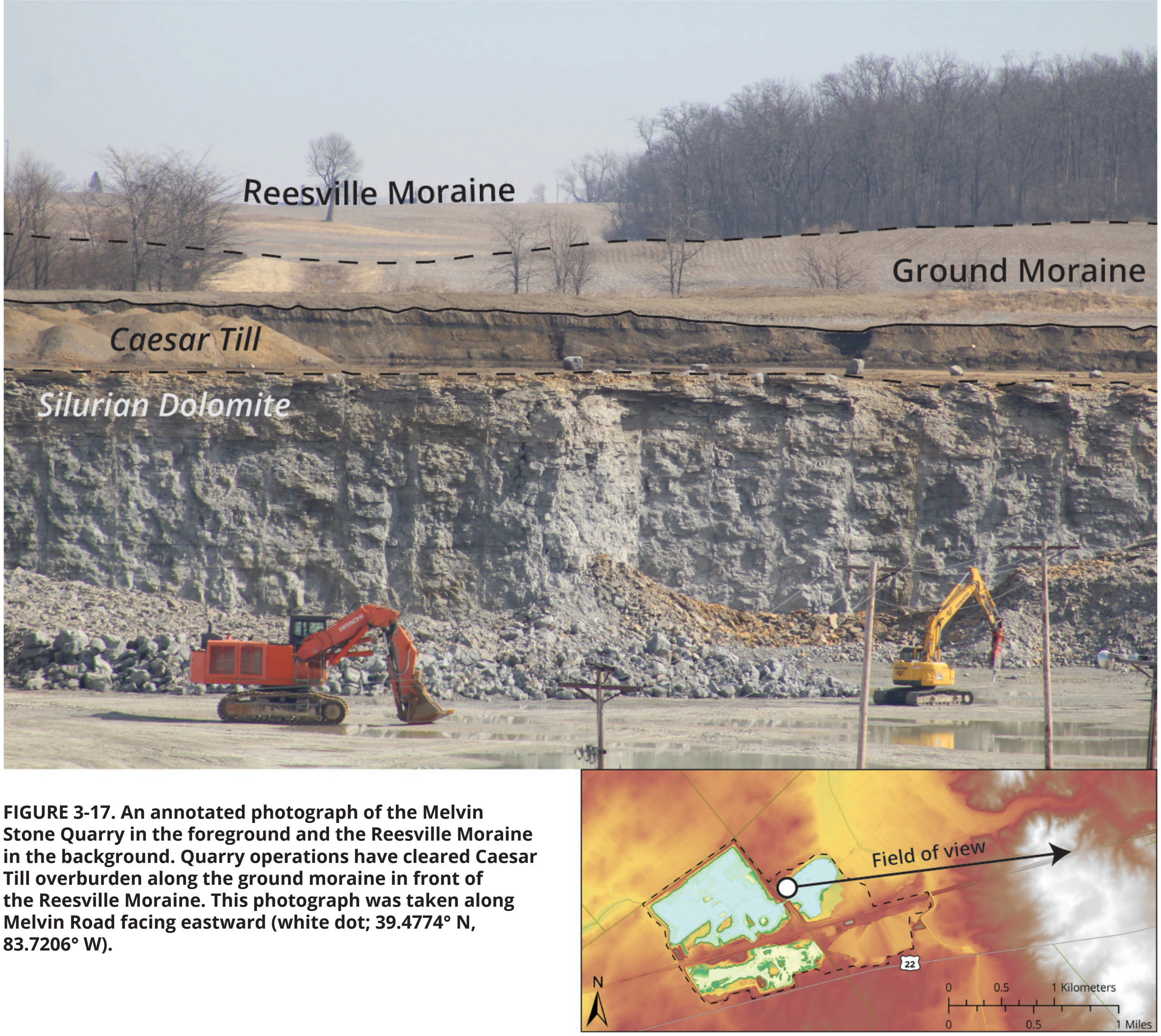


FIGURE 3-17. An annotated photograph of the Melvin Stone Quarry in the foreground and the Reesville Moraine in the background. Quarry operations have cleared Caesar Till overburden along the ground moraine in front of the Reesville Moraine. This photograph was taken along Melvin Road facing eastward (white dot; 39.4774° N, 83.7206° W).

The Reesville Moraine creates a break in glacial history, marking the transition between the deposition of the older Caesar Till and younger Darby Till associations. The Darby Till, which composes the Reeseville Moraine and is highlighted in future stops, is differentiated from the Caesar Till by its lack of a thick loess cap, siltier texture, and slightly darker gray or brownish color (Nash, 2020). While ice was stagnating at the Reeseville Moraine, the Darby Till Plain would have been covered with ice while the Caesar Till was exposed and covered with loess (figs. 3-18 and 3-19).

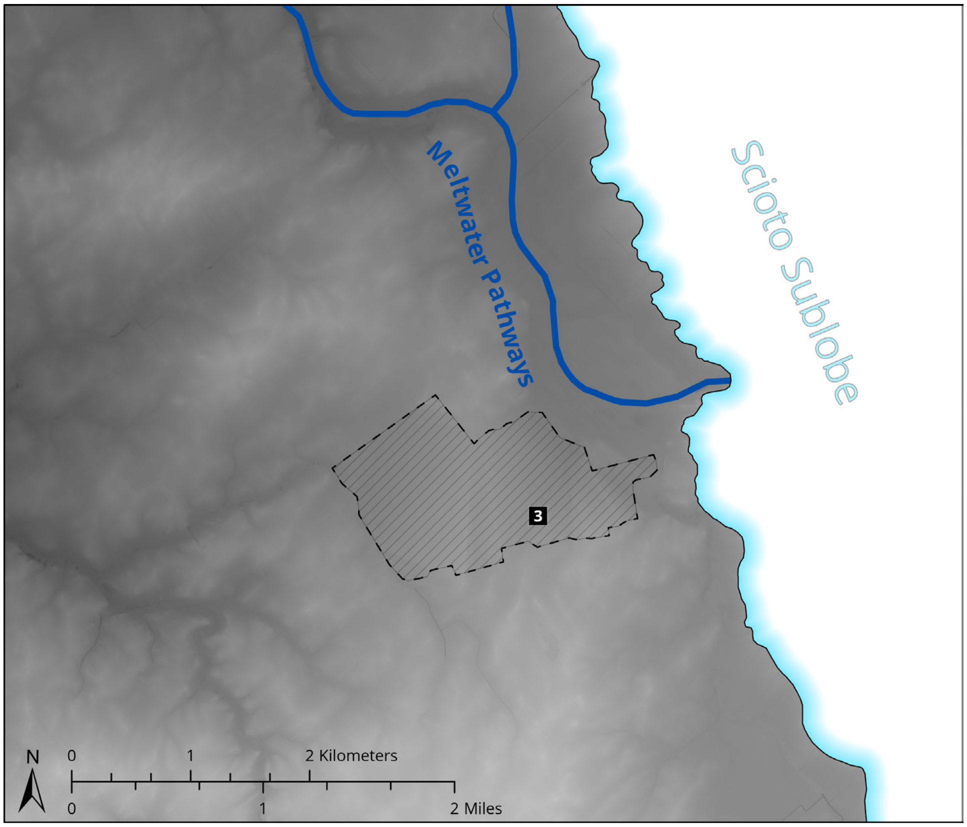


FIGURE 3-18. Map showing the position of the Scioto Sublobe and location of meltwater pathways during a readvance to the Reesville Moraine. Modern-day quarry location is marked by diagonal hatching with dashed boundary lines.

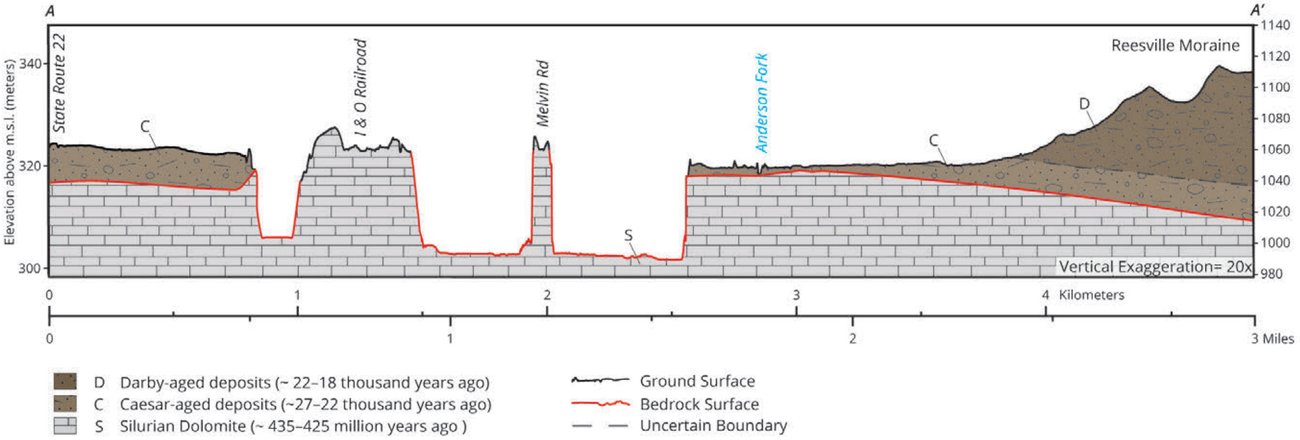


FIGURE 3-19. Cross section showing the quarrying of Silurian Dolomite and overlying Quaternary till deposits. The Caesar Till was deposited as a ground moraine during the first recession following the LGM. This till is capped by the Darby Till in the Reesville Moraine to the northeast (A').

STOP 4: RICHLAND TOWNSHIP PARK (39.4932° N, 83.6247° W)

To get from the Melvin Stone Quarry to the Richland Township Park, we must cross over the Reesville Moraine. The crest of the moraine is near the intersection of Stone Rd. and Spencer Rd. Chamberlin (1883) initially identified this moraine as the terminal position for the Early Wisconsin glacier, however this interpretation was later superseded by Leverett in 1902, who marked the Cuba Moraine as the true terminal moraine of the Scioto Sublobe in this region.

After transitioning briefly into Darby Till ground moraine downslope of the Reesville Moraine, we encounter a subtle hummocky ridge moraine within the town of Sabina. The Sabina Moraine is a recessional moraine, standing about 3–9 m (10–30 ft) above the surrounding ground moraine, and was identified by Nash (2020) based on a higher concentration of surface boulders and characteristic hummocky topography visible on higher resolution Light Detection and Ranging (LiDAR) DEM data. This moraine and some others observed on this field trip may be palimpsest moraines due to ice readjustment or readvance, which is indicated geomorphically by tracing subtle overriding ridgelines, fluting, and as we will observe at a later stop, crosscutting by an esker (Valachovics and others, 2022). The Wilmington Moraine we travelled across in Stop 3 may also be an older feature overridden by ice, as evidenced by radiocarbon dating results from peat within the moraine that provide a much older age (27–29 ka) than expected (Nash, 2020). At this stop, we will eat lunch at the northeastern edge of the Sabina Moraine (fig. 3-20).

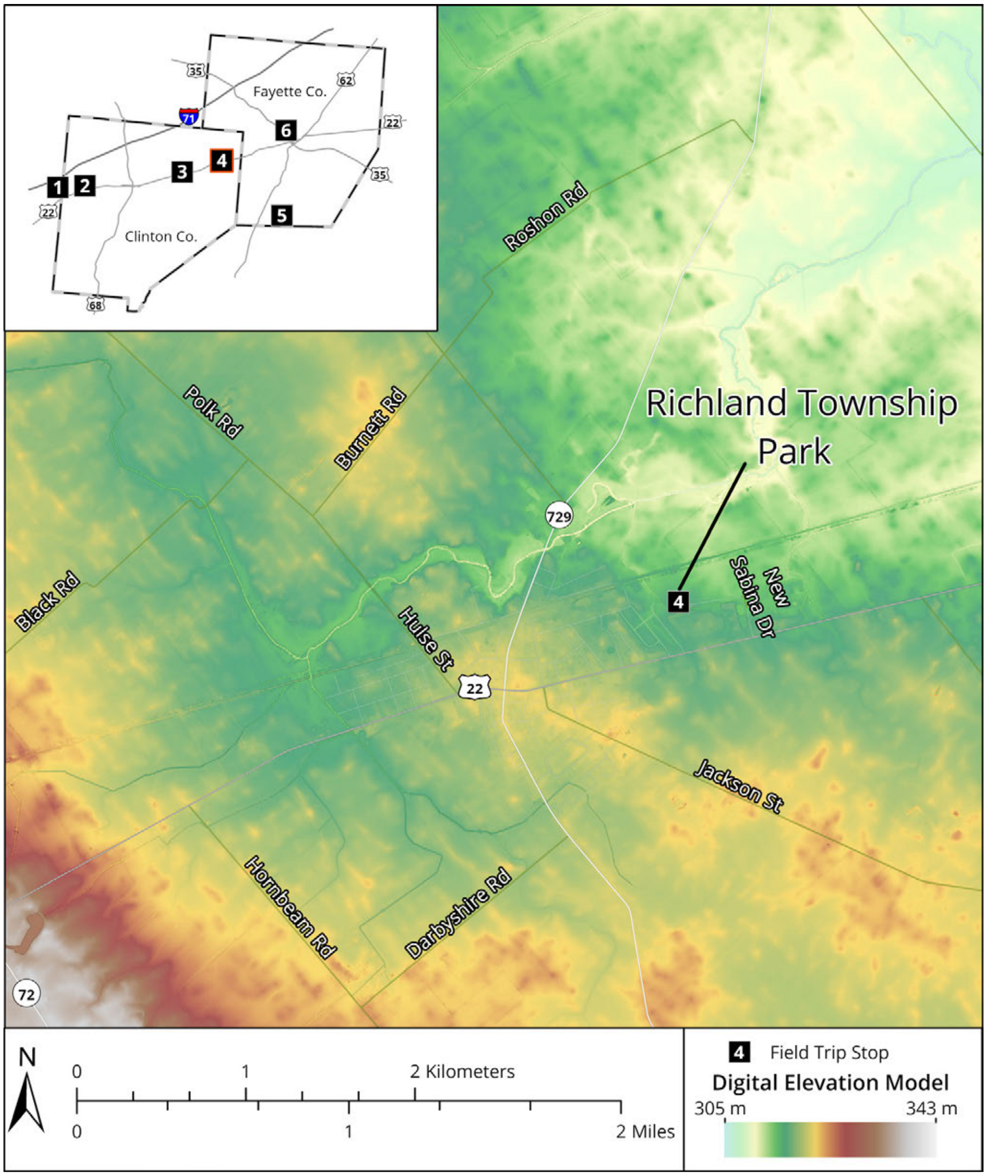


FIGURE 3-20. Map showing the location of Richland Township Park (Stop 5) just east of Sabina, along U.S. Route 22.

STOP 5: ZIMMERMAN ROAD SITE (39.3971° N, 83.4856° W)

The deeply incised Rattlesnake Creek and tributaries create the best Darby Till exposures in Fayette County. The Zimmerman Road site is located 0.25 mi south of Zimmerman Road; however, access is good due to the location being the site of a private campground (fig. 3-21). The small unnamed tributary south of the campground lodge provides multiple exposures of Darby Till. The largest of these exposures is located just downslope from the camp lodge beneath the furthest east cabin. This 4-m (13-ft) exposure has little weathering within the till.

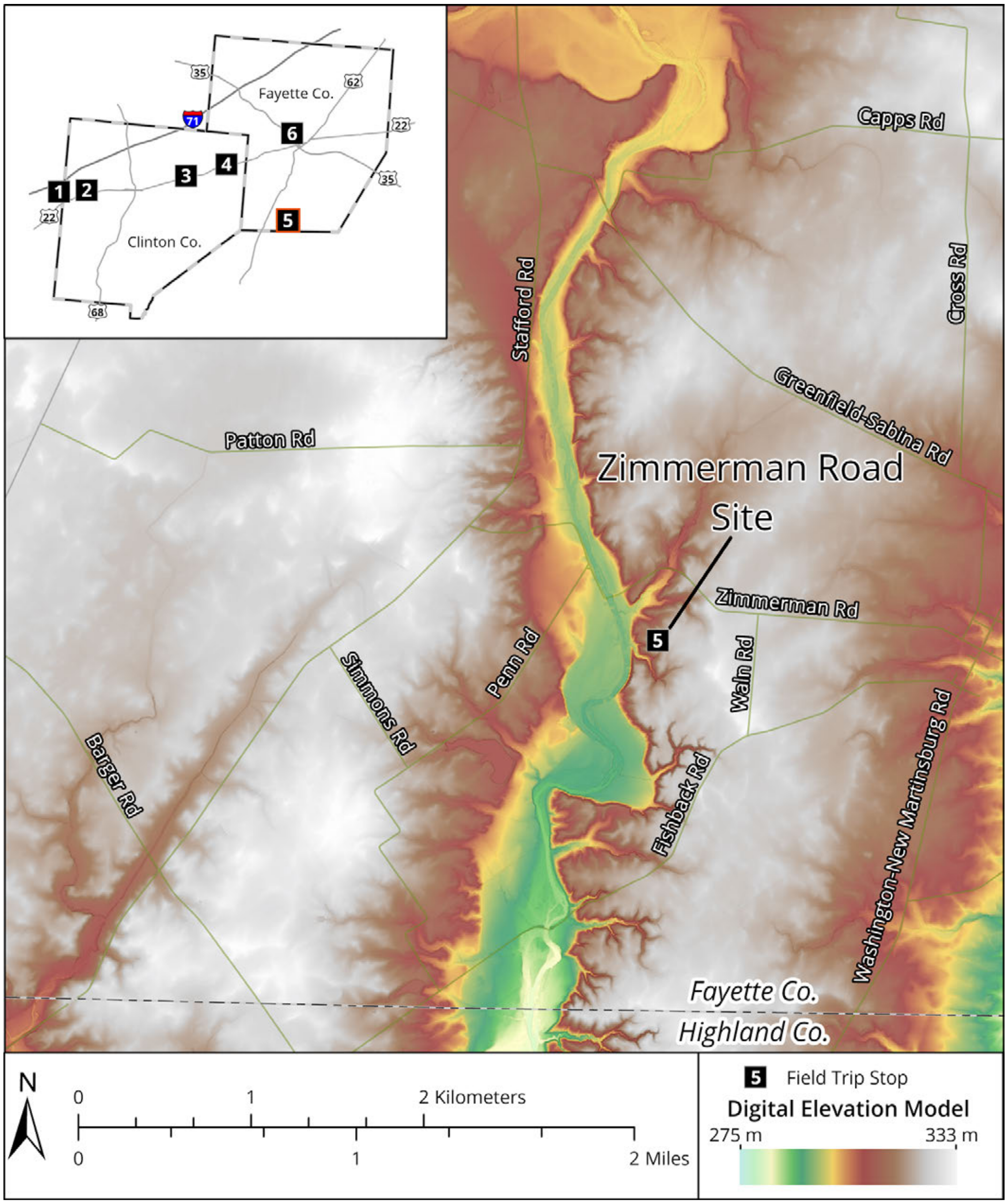


FIGURE 3-21. Map showing the location of the Zimmerman Road Site (Stop 5) near the intersection of Rattlesnake Creek and Zimmerman Road.

The Darby Till is associated with the readvance to the Reesville Moraine. The most noticeable difference from the Caesar Till is the absence of a significant silt (loess) cap on the Darby Till. This lack of a silt cap also creates a notable soil difference with a change from Miami 6O soils on Caesar Till and Miami 6A soils on the Darby Till (Rosengreen, 1974). The Darby Till has been split into two tills in the past, an "Upper till" interpreted here as an ablation till, and a "Lower till" interpreted as a lodgment till (fig. 3-22).

Unit A: “Upper Darby Till” (ablation till)

Unit A1 (350–400 cm): This outcrop contains approximately 50 cm (1.6 ft) of heavily weathered diamicton. Soil processes, such as leaching and oxidation of the till, have created a mottled appearance. Colors range from a 10YR 7/8 to a 10YR 7/1 very near the surface where the till becomes more red. Although the overall blocky texture of the ablation till remains, this portion of the unit is significantly less cohesive as clay minerals are broken down. Much of this highly weathered portion of the till has been eroded here; however, it is visible in outcrops up stream and may have been up to 9 m (30 ft) thick.

Unit A2 (130–350 cm): Unit A2 is an unweathered continuation of Unit A1. Identified as an ablation till, this is a clay-rich diamicton. There is a distinct blocky texture seen throughout the ablation till and the density of the till is quite low. The matrix of this unit is dominated by fines with the occasional cobble. Most cobbles are oriented with a horizontal c-axis. Lithologies of cobbles throughout the outcrop are a mixture of Ohio sedimentary bedrock and igneous erratics.

Unit A3 (50–130 cm): The clay diamictons of Unit A2 and A3 are separated by a layer of matrix-supported cobbles. These cobbles are up to 20 cm (0.65 ft) along their c-axes, which are oriented horizontally. Directly beneath the oriented cobble layer is a discontinuous undulating layer of sand that thickens and pinches out between the clay matrix supporting the cobbles above and the clayey till below. The lower 50 cm (1.6 ft) of this unit is a clayey diamicton with a blocky texture and low-density characteristic of the ablation till.

Unit B: “Lower Darby Till” (lodgement till)

The lower 50 cm (1.6 ft) (Unit B) is a dense diamicton interpreted as the Darby lodgement till. It has a clay matrix but contains noticeably more sand and gravel than the till directly above it. The contact between Unit A and Unit B is wavey, but abrupt.

At this outcrop, erosion in the form of slumping has removed much of the weathered portion of the upper till; however, we are able to see higher up the sequence by looking at outcrops upstream, most notable of which is the outcrop beneath the pedestrian bridge. At the pedestrian bridge, 2 m of the weathered ablation till are visible. The bottom of this outcrop is about 3 m (10 ft) from the top of the lodge outcrop. Weathering processes within the ablation till penetrate quite deeply due to the fractured nature of the till that creates the blocky texture. There are notable “rotten cobbles” of soft siltstones within this outcrop.

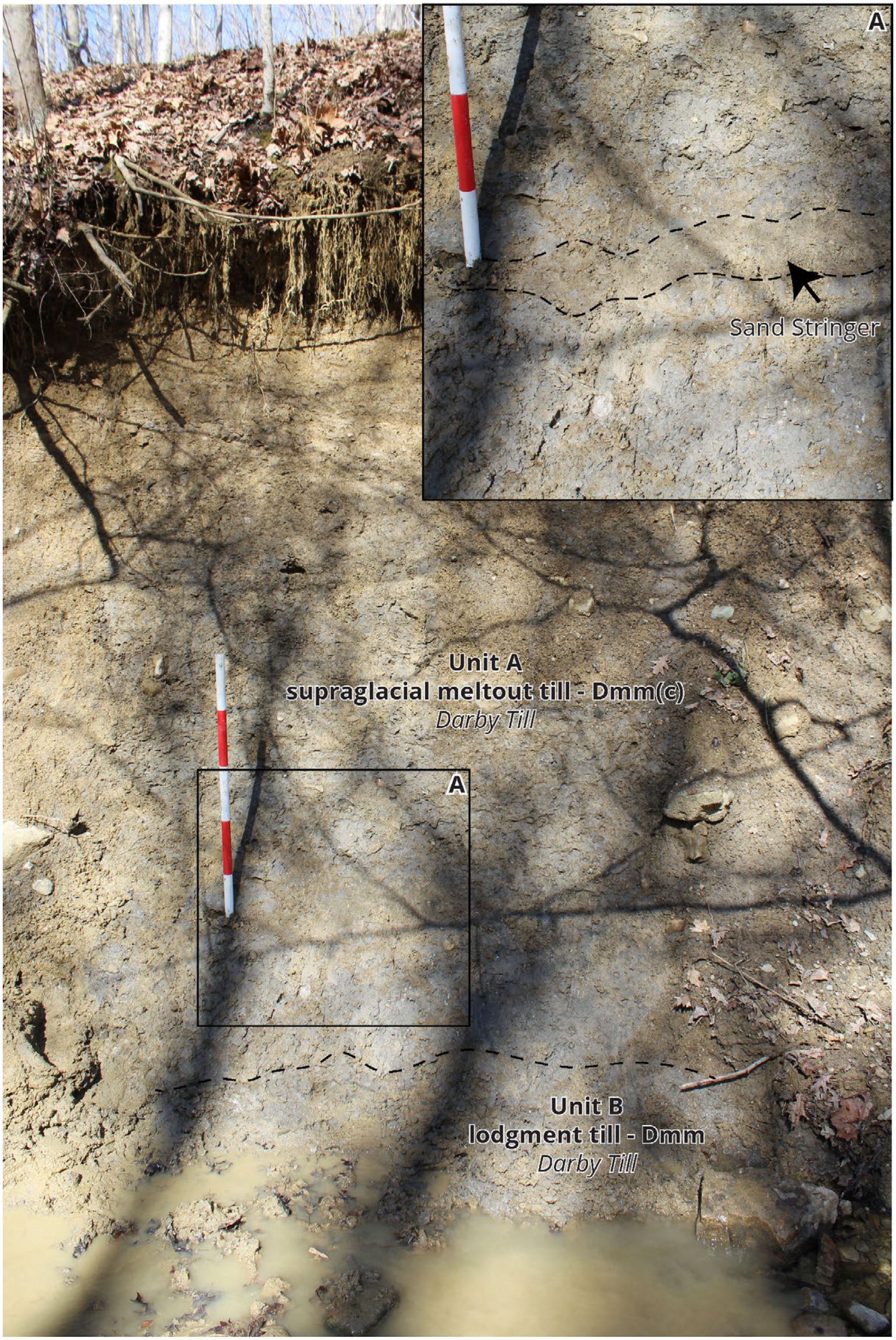


FIGURE 3-22. Photograph of the Darby Till exposed at the Zimmerman Road Site. Two till facies, Unit A: supraglacial meltout till (above) and Unit B: lodgement till (below), are seen at this site. Scale segments are 20 cm (0.65 ft). (A) a close-up of the sand stringers present at the base of the supraglacial meltout till. Scale segments are 20 cm (0.65 ft).

STOP 6: WASHINGTON ESKER 39.5484° N, 83.4781° W

As we depart the Zimmerman Rd. stop and continue northward, we cross two moraines: the Glendon Moraine and Jonesboro Moraine. The moraines do not record a gradual retreat northeastward, but instead a show a palimpsest landscape that survived the Reesville readvance. Geomorphic evidence for this readvance can be found in northwestern Fayette County where the Jeffersonville Moraine appears to overtop the Glendon Moraine (the first of the moraines crossed) before they split near the intersection of State Route 41 and Upper Jamestown Rd. (fig. 3-23). The Glendon Moraine continues due south, and the Jeffersonville Moraine makes a 15-degree bend to the east before being lost near the Jonesboro Moraine. This Jeffersonville Moraine appears to rest up to 9 m (30 ft) above and on top of the Glendon Moraine. A hollow-stem auger used to collect a core off OH-41 near the intersection of these two moraines recovered a mostly homogenous till to a depth of 15.7 m (51.5 ft).

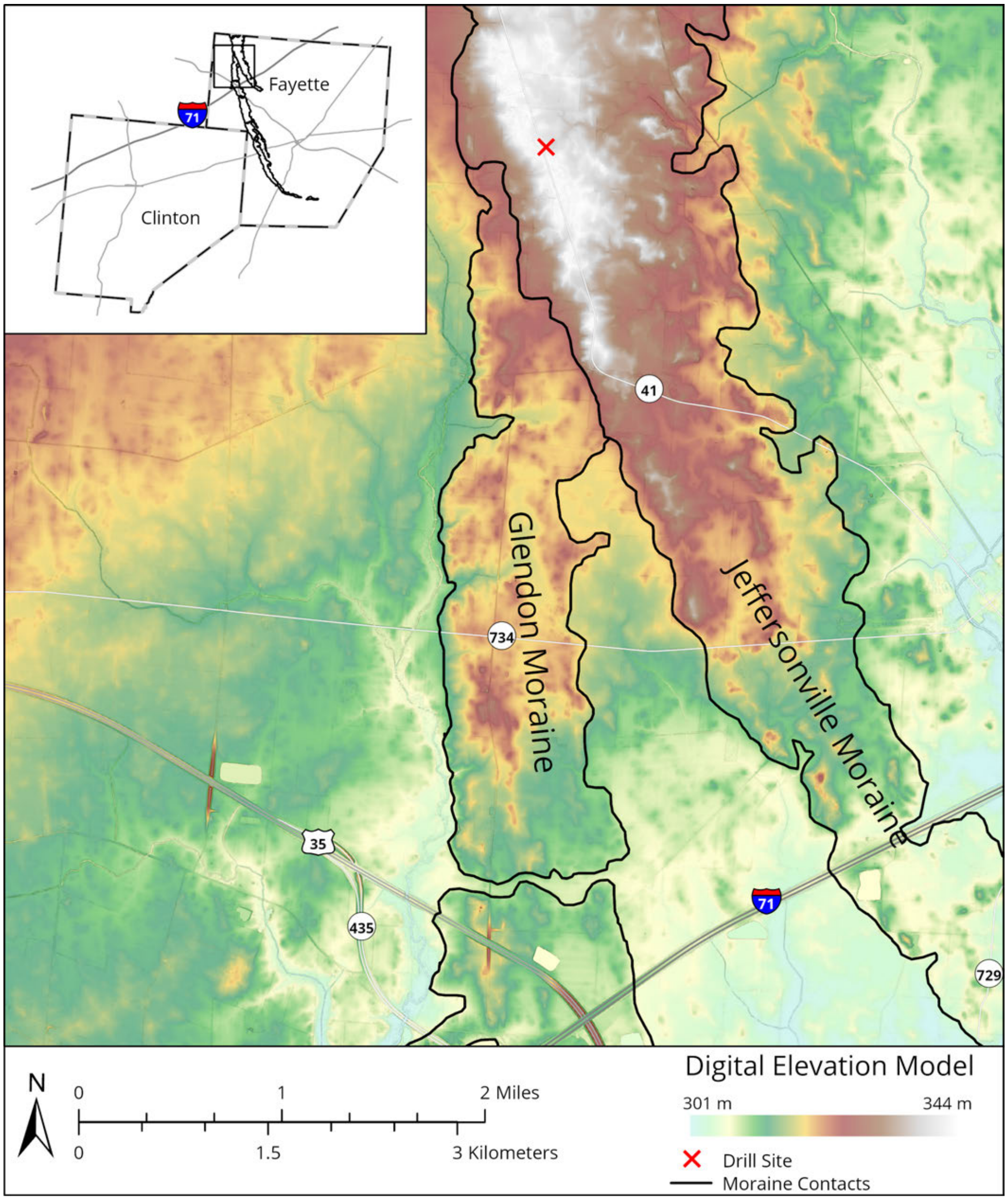


FIGURE 3-23. Map showing the crosscutting relationship between the Glendon and Jeffersonville Moraines in northwestern Fayette County. The older Glendon Moraine is palimpsest and has been overrun by ice during the construction of the Jeffersonville Moraine. A hollow-stem auger core (red "x") was collected at the intersection of these two moraines.

The previously undescribed Washington Esker we stand atop here provides even greater evidence for at least one readvance within Fayette County (fig. 3-24). Trending perpendicular to the moraines in Fayette County, the esker starts just south of Paint Creek and meanders 4.5 miles southwest to Sugar Creek and crosses over the top of the Jonesboro Moraine.

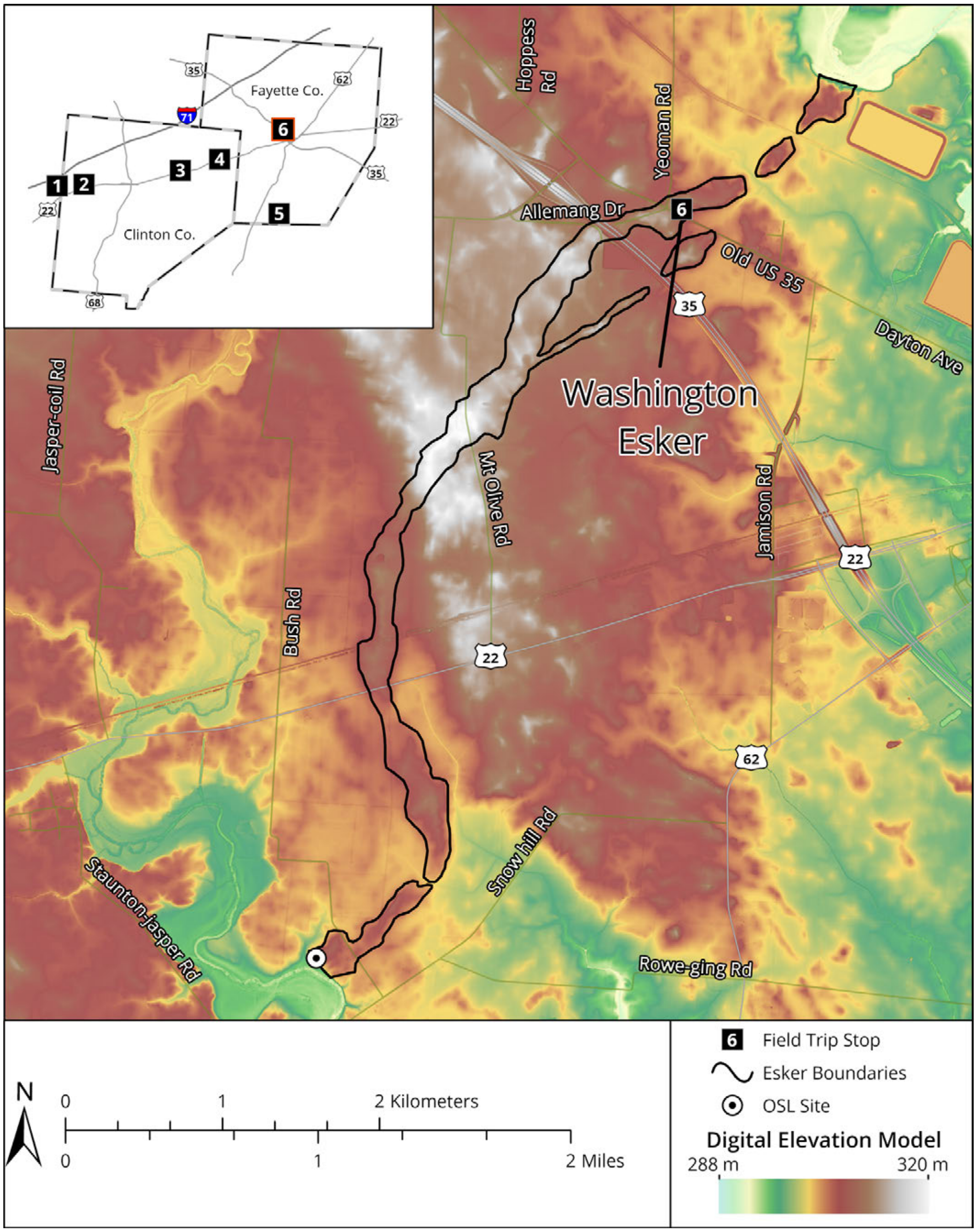


FIGURE 3-24. Map showing the location of the Washington Esker (Stop 6) just south of the city of Washington Court House in Fayette County, Ohio. This esker crosscuts the Jonesboro Moraine, which is a palimpsest moraine associated with the initial retreat of the Scioto Sublobe from its terminal LGM position in Clinton County. The Washington Esker was deposited correlatively with the Darby Till during or after the advance of the Scioto Sublobe to the Reesville Moraine. A pit (white dot with black center, fig. 3-25) was dug at the alluvial fan connecting the esker to valley train outwash along Sugar Creek.

The esker was excavated and sampled at its terminus near Sugar Creek (fig. 3-25). Excavation to a depth of about 2.5 m (8 ft) revealed a 53 cm (1.7 ft) till cap with soil development above a unit of cross bedded and rippled coarse to medium sand and gravel in a slightly fining-upward sequence. An OSL sample was collected at a depth of 85 cm (2.8 ft) and was dated to 23.5 ± 2.2 ka (Minimum Age Model). The sample had a significant partial bleaching issue (accepted aliquots 39/272) and likely provides a maximum age of deposition. The thin till on the Washington Esker and lack of any distinct till change in outcrops and cores within the county make constraining the extent of the readvance that deposited the esker difficult.

FIGURE 3-25. Photograph of pit dug to collect an OSL sample from the sands deposited at an alluvial fan at the mouth of the Washington Esker.

The timing of the retreat of the Scioto Sublobe from the Reesville Moraine is poorly constrained, but glacial ice was out of the county before about 18,000 years ago, as the ice retreated far enough to allow proglacial Lake Maumee to form in the Erie Basin (Fisher and others, 2015). Deposition of the Jeffersonville Moraine and the Washington Esker record the retreat from the Reesville. During this final retreat of ice from Fayette County, subaerial flows of meltwater from the glacier scoured the ground moraine and crosscut end moraines. Many of the smaller tributaries to these meltwater flows are erosional features; however, larger meltwater channels are filled with glaciofluvial sand-and-gravel deposits. In addition to the sand-and-gravel deposits, lacustrine silts and clays are preserved in the Rattle Snake Creek Basin between the Glendon Moraine and the Sabina Moraine and were likely deposited before meltwater eroded through the bedrock-controlled topography of the uplands to the south.

CONCLUSIONS

The history of the Scioto Sublobe glaciation is complex but well-documented by recent mapping efforts. These maps provide a stratigraphic framework for interpretation of glacial depositional landforms and events. The Scioto Sublobe advanced to its terminal margin and constructed the Cuba Moraine Complex along with associated proglacial lakes at the Warren and Clinton County border (Stop 1). This glacial margin underwent proximal fluctuation over a maximum period of 2,000 years, as seen in radiocarbon dates collected at Todd Fork and the existence of multiple packages of Caesar Till separated by glaciofluvial outwash preserved within the moraine (Stop 2). After retreating from this maximum position and forming a series of recessional moraines in Clinton and Fayette Counties, the Scioto Sublobe readvanced across the area to construct the Reesville Moraine around 22,000 years ago. As the Scioto Sublobe constructed this moraine at this ice marginal position, Melvin Silt (loess) blanketed the recently deglaciated Caesar Till ground moraines south of the glacial margin (Stop 3). The ice continued depositing the largely loess-free Darby Till during its retreat from the Reesville Moraine while forming recessional ridges, such as the Sabina Moraine, which may be palimpsest (Stop 4). The Darby Till, deposited by the Scioto Sublobe during this readvance, is devoid of surficial Melvin Silt deposits (as it would have been subglacial at the time of loess deposition) and is siltier and browner than the older Caesar Till (Stop 5). This readvance also buried older glacial landforms creating palimpsest features that are crosscut by younger glacial landforms, such as the Washington Esker (Stop 6). Ice ultimately retreated out of this region and into central Ohio (Delaware County) around 20,000 years ago.

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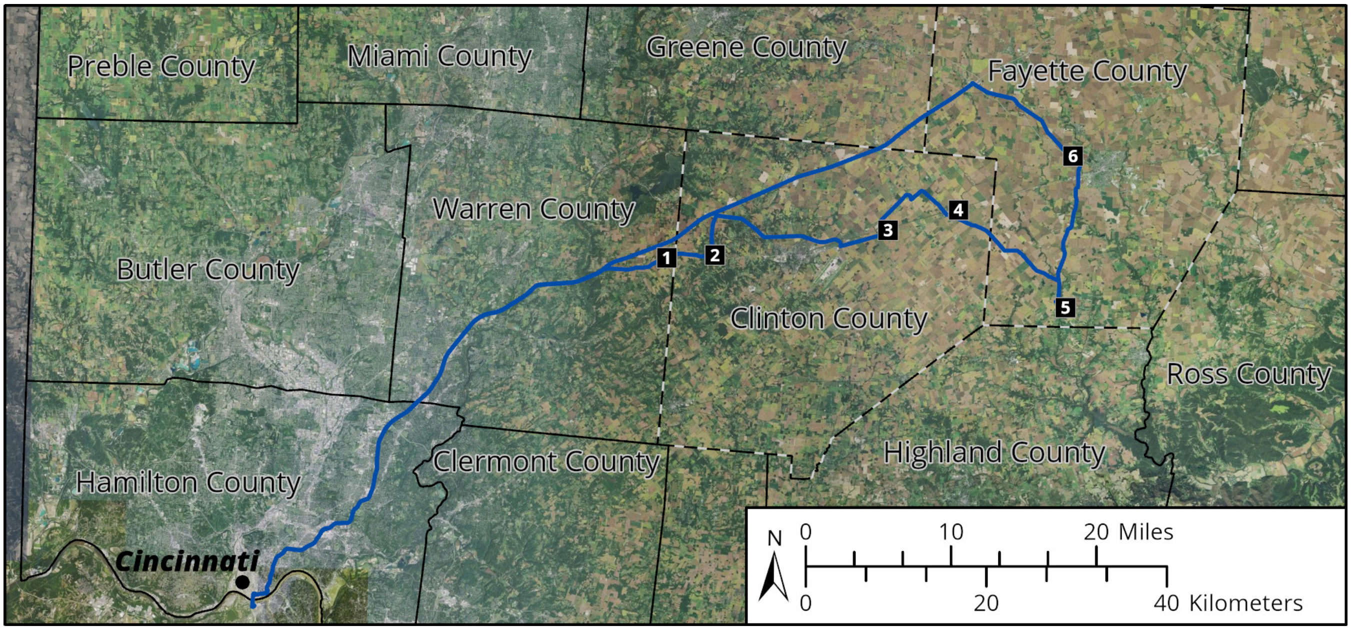

ROAD LOG

Depart Radisson Hotel Cincinnati Riverfront

1. Turn left on Philadelphia St. — **240 ft**
2. Turn left onto W. 4th St. — **180 ft**
3. Use the rightmost lane to merge onto I-71 N. via the ramp to Columbus – **36.5 mi**
4. Take exit 36 for Wilmington Rd. — **0.3 mi**
5. Turn right onto Wilmington Rd. — **4.6 mi**

Stop 1 will be on the left (39.4414° N, 83.9995° W)

Depart Stop 1: Hagemeyer Farms

1. Head east on Wilmington Lebanon Rd. — **3.0 mi**
2. Turn left onto OH-380 N – **0.3 mi**

Stop 2 will be on the right (39.4449° N, 83.9375° W)

Depart Stop 2: Todd Fork

1. Head north on OH-380 N toward Todds Fork Rd. — **2.7 mi**
2. Turn right onto OH-73 E — **9.1 mi**
3. Use the right lane to take the US-22/OH-3 ramp to Washington C. H./Wilmington — **0.3 mi**
4. Turn left onto OH-3 N/US-22 E — **3.5 mi**
5. Turn left onto Melvin Rd. — **0.2 mi**

Stop 3 will be on the right (39.4722° N, 83.71506° W)

Depart Stop 3: Melvin Stone Quarry

1. Head northwest on Melvin Rd. toward Clinton-Fayette Friendship Trail — **0.8 mi**
2. Turn right onto Stone Rd. — **2.8 mi**
3. Turn right onto OH-72 S — **0.3 mi**
4. Turn left onto Polk Rd. — **3.1 mi**
5. Continue straight onto Hulse St. — **0.3 mi**
6. Turn left onto W Washington St./US-22 E – **1.1 mi**
7. Turn left onto New Sabina Dr. — **0.3 mi**

Stop 4 will be on the right (39.4932° N, 83.6247° W)

Depart Stop 4: Richland Township Park

1. Head northwest on New Sabina Dr. — **0.3 mi**
2. Turn right onto E Washington St./US-22 W — **0.8 mi**
3. Turn left onto S Jackson St. — **0.4 mi**
4. Continue onto Greenfield Pike — **2.4 mi**
5. Continue onto Greenfield Sabina Rd. — **5.9 mi**
6. Turn right onto Stafford Rd. — **1.5 mi**
7. Turn left onto Zimmerman Rd. — **0.8 mi**

Stop 5 will be on the right (39.3971° N, 83.4856° W)

Depart Stop 5: Zimmerman Road Site

1. Head southwest on Zimmerman Rd. toward Penn Rd. — **0.8 mi**
2. Turn right onto Stafford Rd. — **3.9 mi**
3. Turn right onto US-62 E — **4.5 mi**
4. Turn left onto Jamison Rd. SW — **1.9 mi**
5. Turn left on Old U.S. 35 — **0.7 mi**

Stop 6 will be on the right (39.5484° N, 83.4781° W)

Depart Stop 6: Washington Esker

1. Head northwest on Old U.S. 35 toward Allemang Dr. — **6.3 mi**
2. Continue onto OH-435 W/OH-729 S — **2.4 mi**
3. Continue onto Old U.S. 35 — **0.1 mi**
4. Turn left to merge onto I-71 S toward Cincinnati — **0.4 mi**
5. Merge onto I-71 S — **74.0 mi**
6. Take exit 192 on the right to W 5th St. in Covington — **0.5 mi**
7. Continue on W 5th St. — **400 ft**

Conclude field trip upon return to Radisson Hotel Cincinnati Riverfront (39.1008° N, 84.5163° W)