Devonian Black Shales of the Eastern U.S.

New Insights into Sedimentology and Stratigraphy from the Subsurface and Outcrops in the Illinois and Appalachian Basins

Edited by

Juergen Schieber and Remus Lazar

Field Guide for the 2004 Annual Field Conference of the Great Lakes Section of SEPM

1926 SEPM

Society for Sedimentary Geology

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INDIANA UNIVERSITY

Indiana Geological Survey
611 North Walnut Grove
Indiana University
Bloomington, IN 47401-2208

Telephone: (812) 855-7636
Fax: (812) 855-2862
E-mail: IGSinfo@indiana.edu
Web: http://igs.indiana.edu

Field Conference Schedule

The 2004 GLS-SEPM Field Conference is scheduled to take place September 24 and 25, 2004. The participants of the 2004 GLS-SEPM Field Conference will examine the sedimentology and stratigraphy of Devonian black shales in a cored interval of well 1-3 Kavanaugh, Indiana, and three roadcuts in Kentucky (Fig. 2.1). The schedule of the field conference includes:

Day One, Friday, September 24, 2004:

5-7.00 p.m.: Registration at Holiday Inn Express in New Albany, Indiana
7.00 p.m.: Field Trip Introduction and Overview
Drill core examination

Day Two, Saturday, September 25, 2004:

7.30 a.m.: Attendees depart from hotel
Stop 1: I-65, Exit 112, Bernheim Forest, Kentucky (Illinois Basin)
Box Lunch
Stop 2: KY-52, between Richmond and Irvine, Kentucky (Appalachian Basin)
Stop 3: Junction City, Kentucky (Cincinnati Arch)
7.00 p.m.: Returning to hotel and dinner

Presentations by:
Bohacs, K.M., ExxonMobil Upstream Research Company
Rimmer, S., Department of Geological Sciences, University of Kentucky
Partin, T., Department of Geological Sciences, Indiana University
Schieber, J., Department of Geological Sciences, Indiana University

Devonian Black Shales of the Eastern U.S.: New Insights into Sedimentology and Stratigraphy from the Subsurface and Outcrops in the Illinois and Appalachian Basins

Indiana and Kentucky
September 24-26, 2004

Foreword

Black shales are organic-rich, fine-grained sedimentary rocks which, when carefully studied, can reveal a wealth of sedimentologic detail that reflects a range of depositional settings and paleoenvironmental conditions (e.g., Schieber, 2003a). In the U.S., black shales such as the Devonian Antrim, Ohio, and New Albany Shales are major gas producers (Curtis, 2002). Globally, black shales have been the main source of more than 90% of the recoverable oil and gas reserves (Klemme and Ulmishek, 1991). Understanding the formation of black shale successions is, therefore, of great importance for oil exploration. Moreover, as repositories of large amounts of organic carbon, black shales have the potential to advance our understanding of the carbon cycle and global climate-ocean system (e.g., Arthur and Sageman, 1994; Schieber and Zimmerle, 1998).

Because of their considerable importance, black shales have been the focal point of a number of detailed studies over the past decades (e.g., O'Brien, and Slatt, 1990; Ettensohn, 1992a; Leventhal, 1993; Arthur and Sageman, 1994; Bohacs, 1998; Schieber et al., 1998; Wignall and Newton, 1998; Murphy et al., 2000; Werne et al., 2002; Brett et al., 2003; Sageman et al., 2003; Schieber, 2003a; Algeo et al., 2004; Rimmer, 2004; Schieber and Riciputi, 2004). This continued interest in black shales has prompted the selection of a black shale theme for the 2004 Annual Field Conference of the Great Lakes Section of SEPM (GLS-SEPM). Field conference participants will (1) examine and discuss the sedimentology and stratigraphy of the New Albany Shale of the Illinois Basin in a drill core from southern Indiana (well 1-3 Kavanaugh) and an outcrop from western Kentucky, (2) examine its counterparts in the Appalachian Basin (Ohio Shale, eastern Kentucky), and (3) examine and discuss Devonian black shale facies where it straddles the Cincinnati Arch between the two basins. A brief introduction to Devonian black shales and their stratigraphic relationships in the Illinois and Appalachian Basins is provided within this guidebook, together with a summary description of well 1-3 Kavanaugh. The guidebook also includes papers that discuss various aspects of stratigraphy (Brett et al.), geochemistry (Dumitrescu et al.), and economics of the New Albany and Ohio Shales (Partin).

Juergen Schieber
Remus Lazar

Acknowledgements

We are grateful to BP, ConocoPhillips, Quicksilver Resources, and Shell Oil Company/Department of Geological Sciences, Michigan State University, for their generous financial support at the Gold ($1,000) level for the 2004 GLS-SEPM Annual Field Conference.

We acknowledge the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of black shale research in the eastern U.S. (grant numbers 30774-AC8, 33941-AC8, 38523-AC8 to Juergen Schieber).

We thank the Great Lakes Section of SEPM for the selection of a black shale theme for the 2004 Annual Field Conference.

We thank John Steinmetz, John Rupp, Charlie Zuppann, Agnieszka Drobniak, and Sherry Cazee for their assistance in obtaining various data from the Indiana Geological Survey.

Special thanks go to authors of accompanying papers to this guidebook (Carlton Brett and Alexander Bartholomew, University of Cincinnati; Gordon Baird, SUNY College at Fredonia; Mirela Dumitrescu, David Finkelstein, Simon Brassell, and Tom Partin, Indiana University) as well as to our invited speakers (Kevin Bohacs, ExxonMobil Upstream Research Company; Susan Rimmer, University of Kentucky; and Tom Partin, Indiana University).

We are greatly appreciative to Abhijit Basu, Lisa Pratt, Erika Elswick, Maria Mastalerz (Indiana University), Chris Maples (Desert Research Institute), Patricia Hall and Andrei Belopolsky (BP), Richard Aram and Michael Boyles (ConocoPhillips), Scott Kelley and Diane Weaver (Quicksilver Resources), Houston Brown (Shell Oil Company) and Michael Velbel (Michigan State University), and John Steinmetz and Deborah DeChurch (Indiana Geological Survey) for their support during various phases of conference preparation.

Contents

1. Summary of Observations from a 40-Meter Cored Interval of the New Albany Shale in Well 1-3 Kavanaugh, Daviess County, Indiana

by
Remus Lazar and Juergen Schieber
Department of Geological Sciences, Indiana University,
Bloomington, Indiana 47405

An essentially continuous core of the New Albany Shale (~40 m thick) from well 1-3 Kavanaugh (Daviess County, Indiana, Fig. 1.1) was studied in detail (mm- to cm-scale) for variations in lithology, sedimentary structures, macrofossils, trace fossils, and organic carbon content. The five stratigraphic subdivisions of the New Albany Shale recognized by Lineback (1970) are all present in this core. In ascending order these are the Blocher, Selmier, Morgan Trail, Camp Run, and Clegg Creek Members (Fig. 1.1), described and illustrated below.

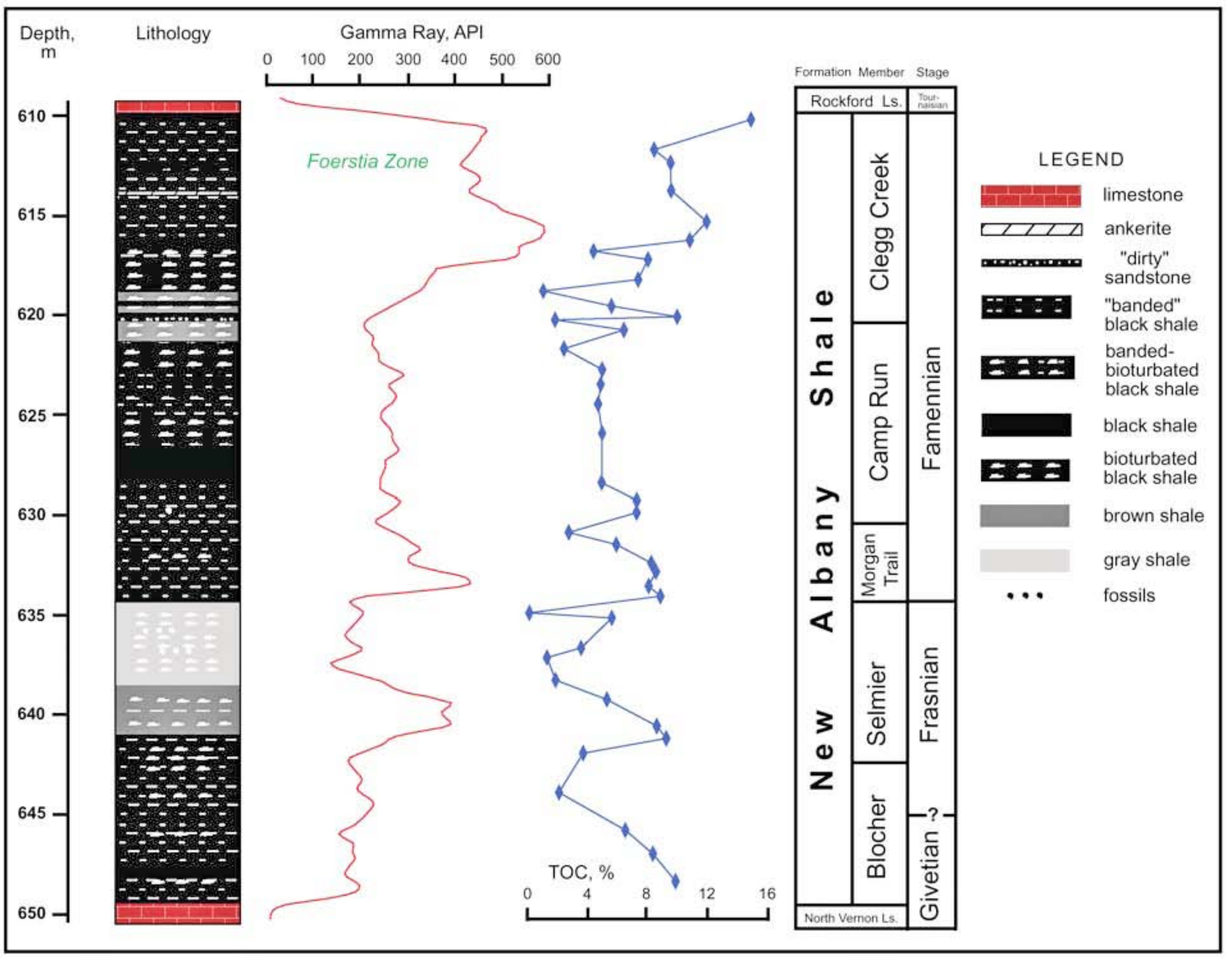


Figure 1.1: Lithology, gamma ray, total organic carbon (TOC), and stratigraphy of the New Albany Shale in well 1-3 Kavanaugh, Indiana.

Blocher Member:

648.72 m 649.44 m

Figure 1.2: Basal portion of the Blocher Member above the North Vernon Limestone (from well 1-3 Kavanaugh); red bar marks basal lag. The Blocher Shale consists primarily of banded black shale that is variably dolomitic, pyritic, and organic matter-rich (see also Fig. 1.1). Thin, brownish-black intervals with macroscopic bioturbation are also present (Fig. 1.1).

Within and at the base of the Blocher, cm-thick lag deposits consisting of a residue of coarser particles (carbonate clasts, fragments of silicified fossils, glauconite grains, quartz grains, broken and abraded fish bones, conodonts) mark laterally extensive erosion surfaces (Schieber, 1998a). For example, a 40 mm-thick basal lag (red bar, Fig. 1.2) with abundant crinoid fragments and carbonate clasts derived from the underlying North Vernon Limestone marks the unconformable basal contact of the Blocher Member. Lag deposits of variable thickness (1 mm to 2 cm) and composition (silty-sandy dolomitic, pyritic, conodont, bone fragment, and shell-bearing) occur higher up in the Blocher succession (Fig. 1.3). Their presence supports the concept of intermittent erosion within the Blocher due to intermittent lowering of sea level for thicker lags (with visible truncation of basal strata), and due to exceptionally strong but rare storms for thinner lags (Schieber, 1998a). Although these lags should eventually allow a sequence stratigraphic subdivision of the Blocher Member, onlap of the Blocher onto the Cincinnati Arch and irregular depth of erosion at the top of the Blocher makes lateral correlation of these lags tentative at best in the absence of biostratigraphical constraints (e.g., conodonts). Examination of additional cored intervals and alternative methods of lateral tracing, such as for example truncation of gamma ray log motives (Johri and Schieber, 1999; Schieber, 2000) may allow recognition of consistent subdivisions as our current research proceeds.

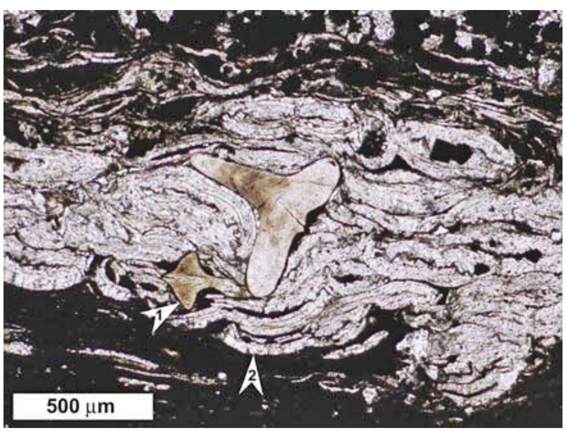


Figure 1.3: Photomicrograph of a conodont (arrow 1; transmitted light) and *Tentaculites* (arrow 2) lag at 0.9 m above the base of the Blocher. A thin lag like this is interpreted to be the product of relatively rare and strong storms (Schieber, 1998a).

The most common fossils observed in the Blocher are inarticulate brachiopods (*Lingula*, on bedding planes), pteropods (*Tentaculites*), and *Tasmanites*. *Tasmanites*, the cyst stage of fossil marine algae, is abundant in the black shale beds of the Blocher as well as in the entire New Albany Shale succession. The exact age of the Blocher is a moving target due to basal onlap and top erosion. Its base most likely gets older as we go westward into the Illinois Basin, and the top should overall get younger in a westward direction (more erosion near the Cincinnati Arch). For the southeastern Illinois Basin, available conodont studies suggest that the base of the Blocher should be no older than uppermost Givetian, and that it may range as high as Middle or even Upper Frasnian (Fig. 1.1) (Sandberg et al., 1994; Over, 2002). Conodonts from the basal lag in western Kentucky are Givetian in age (Ettensohn et al., 1988a), but because of the likelihood of reworking from underlying Middle Devonian carbonates, this does not allow us to define the onset of Blocher deposition.

Selmier Member:

A sharp increase in gamma-ray intensity marks the Blocher/Selmier boundary (Fig. 1.1). Composed of variably bioturbated, organic-rich brownish-black shale intervals that alternate with bioturbated and gray to dark-gray shale intervals, the Selmier Member differs distinctly from the Blocher Member (Figs. 1.1, 1.4). Centimeter to decimeter-thick intervals of black-gray shale cycles have long been interpreted to represent fluctuating anoxic to oxic conditions (e.g., Cluff, 1980; Calvert et al., 1996). Based on examination of comparable black-gray shale cycles within the Dowelltown Member of the Upper Devonian Chattanooga Shale in central Tennessee (Lobza, 1998) this phenomenon may ultimately be reflective of fluctuations in sea level. Settling experiments with clays and fine-grained organic matter (Schieber, 2003b) can also produce black-gray shale cycles, suggesting as an alternative mechanism, that they may also form when strong storms resuspend previously deposited sediment and give rise to post-storm settling segregation. Silty, sandy, pyritic, and shelly lags, as well as knife-sharp contacts at the base of a number of black shale beds are common throughout the Selmier and support the idea of a relatively shallow sea where mud deposition was affected by sea level fluctuations (Johnson et al., 1985), and storm events (Schieber, 1998a).

637.03 m 637.76 m

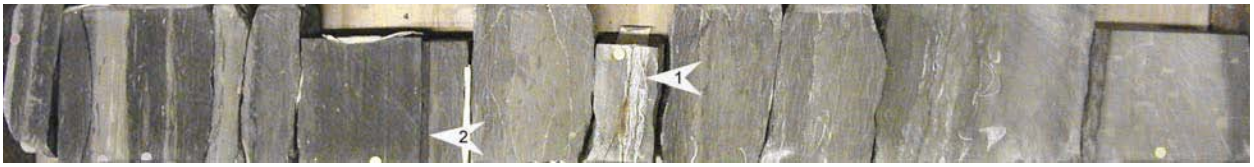


Figure 1.4: Black-gray shale cycles in the Selmier Member. Note the presence of a cm-thick shelly lag (arrow 1) and sharp-based black shale (arrow 2).

Gamma-ray intensity in the Selmier Member is highest in the basal third and considerably lower in the middle and upper portions of the member (Fig. 1.1). This upwards change in gamma-ray intensity corresponds to a change from massive black shale to gray bioturbated shales with interbedded black shales. The upper portion of the Selmier also contains large articulated (calcareous) brachiopods as well as lags composed of brachiopod shells (Fig. 1.4).

633.78 m Morgan Trail Selmier 634.54 m

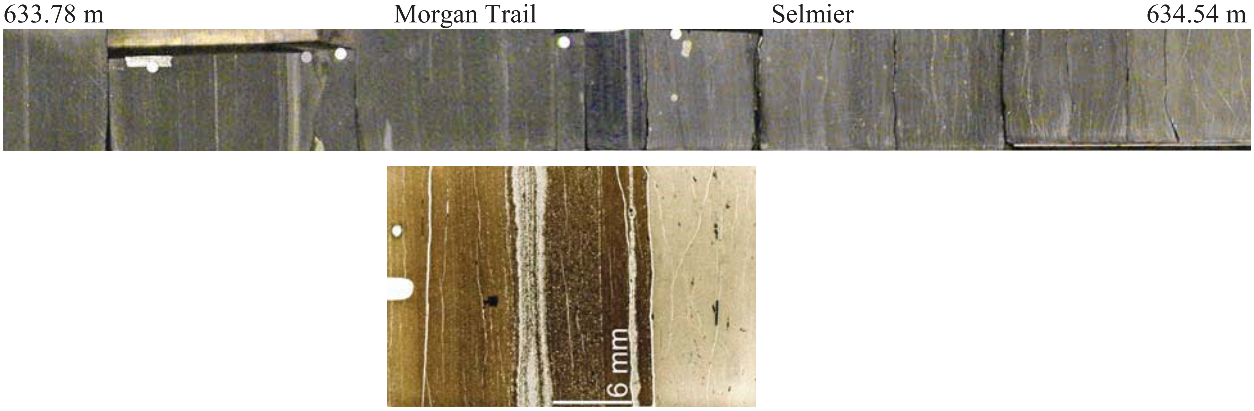


Figure 1.5: At the top of the Selmier occurs an abrupt change from gray bioturbated shale to massive banded black shale. The knife-sharp contact corresponds to a sharp increase in gamma-ray counts (Fig. 1.1) and marks the erosive contact between the Selmier and the overlying Morgan Trail Member. Based on conodont studies on comparable strata, the boundary between the Selmier and Morgan Trail Members coincides with the Frasnian-Famennian boundary (Fig. 1.1) (Sandberg et al., 1994; Over, 2002).

Morgan Trail Member:

The Morgan Trail Member consists mainly of banded black shales with numerous sub-mm- to mm-thick, pyritic and dolomitic-silty laminae (Fig. 1.5). Only a few brownish-black bioturbated shale intervals have been observed (Fig. 1.1). Conodonts indicate an Early Famennian age (Sandberg et al., 1994; Over, 2002). A characteristic feature of the Morgan Trail member are mm- to cm-thick beds of “dirty sandstone” that occur at a spacing of 5 cm to several dm. The latter consist largely of pyritic and chalcedonic infills (Fig. 1.6) of *Tasmanites* cysts within a matrix of clay, organic matter, silt grains, and conodonts and probably represent interludes of extreme sediment starvation and/or reworking (Schieber, 1998a).

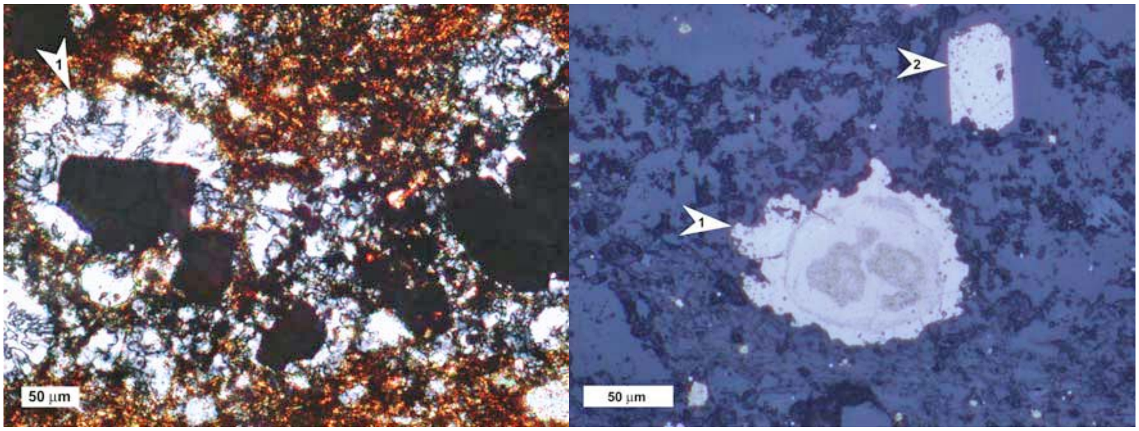


Figure 1.6: Photomicrographs of "dirty sandstone" with spherical to ellipsoidal quartz grains (chalcedony; arrow 1 at left; transmitted light), and pyrite (photo at right, arrows 1 and 2, reflected light), both representing infilled *Tasmanites* cysts. *Right:* Note pyrite replacement of circular "skin" of a *Tasmanites* cyst (preserved in pyrite grain marked with arrow 1), as well as euhedral pyrite overgrowth (arrow 2).

Tasmanites cysts produce a bright yellow fluorescence under UV light, and UV imaging of cored intervals shows distinctly *Tasmanites*-enriched intervals in the Morgan Trail Member. These enriched intervals may reflect winnowing of fines during lowering of sea level or sediment starvation during maximum flooding. The Morgan Trail contains conodonts of lower Famennian age (*triangularis* to middle *crepida* zone; Sandberg et al., 1994), and probably reflects the initial transgression of TR cycle IIe of Johnson et al. (1985). The *Tasmanites*-enriched interval shown in Figure 1.7 is from the Morgan Trail Member in well 1-3 Kavanaugh, coincides with a gamma-ray minimum, and probably reflects sediment starvation during maximum flooding. UV maxima also occur elsewhere in the New Albany succession and work is underway to use them for refined correlations and interpretation of sea level variations.

630.45 m 631.18 m

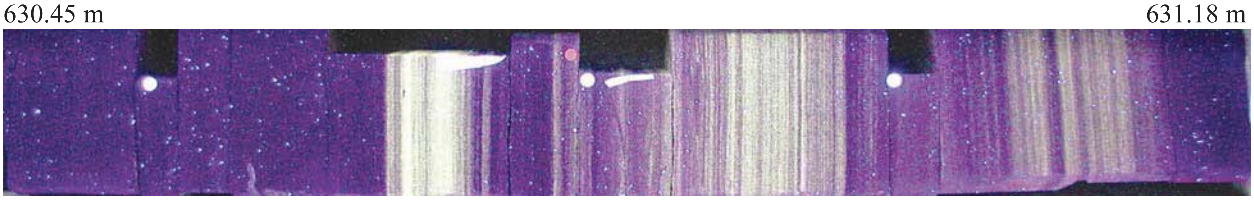


Figure 1.7: UV maxima (yellow) in the Morgan Trail Member. Probably marks maximum flooding for the Morgan Trail.

Camp Run Member:
In contrast to the Selmier, the Camp Run Member is generally composed of thicker beds of black to dark-brown shale (5-150 cm thick), separated by thinner beds (1-10 cm thick) of gray to dark-gray/brown bioturbated shale (see also Figs. 1.1, 1.8). Eastward from well 1-3 Kavanaugh (Daviess Co.), towards the shallower water near the Cincinnati Arch, the number and overall thickness of gray interbeds increases. Conodonts from Camp Run intervals elsewhere in Indiana yielded a Middle-Upper Famennian age (upper *crepida* through lower *marginifera* zone) for the Camp Run Member (Sandberg et al., 1994), corresponding to a regressive interval in the middle of TR cycle IIe of Johnson et al. (1985).

629.72 m 630.45 m

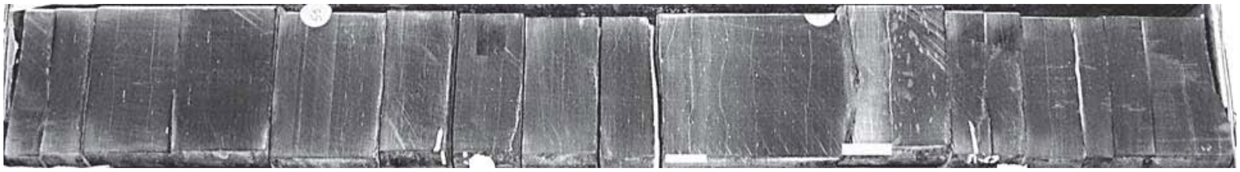


Figure 1.8: Core interval from Camp Run in well 1-3 Kavanaugh. Gray interbeds are marked with white bar at the bottom of the picture. Note burrows filled with gray shale in underlying black shale.

While in many exposures and cores the contact between Camp Run and overlying Clegg Creek Member is a sharp one and indicative of erosion prior to Clegg Creek deposition, in well 1-3 Kavanaugh the contact between the two members has a “transitional” character. An interval of about 1.5-m thickness is characterized by cm-thick sandy and pyritic lags, bioturbated gray and black shales, and by an abundance of reworked *Tasmanites* cysts (Fig. 1.9). This difference may be a reflection of water depth. It appears that on and near the Cincinnati Arch, pre-Clegg Creek erosion is the norm, whereas further away from the arch we see these “transitional” intervals. One could interpret the “transition” intervals as resedimented material that was eroded from arch locations during low-stand of sea level. The closest sequence-speak analog would be a low-stand wedge.

620.05 m Clegg Creek Camp Run 620.78m

Figure 1.9: Cm-thick sandy and pyritic lags in the basal “transitional” interval of the Clegg Creek Member above the underlying Camp Run Member. The “transition” interval is marked with a white bar at the base of the photo. Our pick for the Clegg Creek base is the lag just to the left of the white circle. The base of the lag is probably erosive (see also Fig. 1.10 for details).

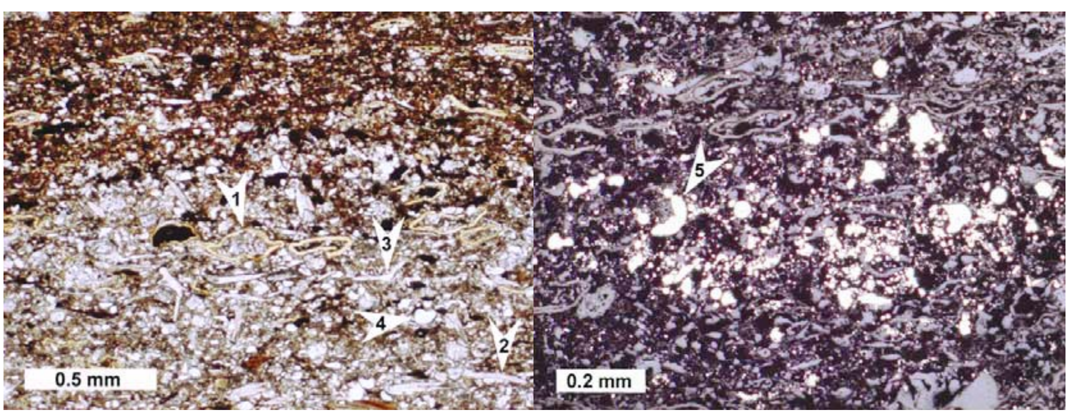


Figure 1.10: Photomicrographs of lag deposit at the boundary between the Camp Run and Clegg Creek Shales. *Left:* transmitted light shows an abundance of reworked *Tasmanites* cysts (arrow 1) and enrichment in coarser particles (*Lingula* shell fragments [arrow 2], conodonts [arrow 3], and rounded quartz grains [arrow 4]). *Right:* reflected light, shows enrichment in pyrite, bright spots. Arrow 5 marks a half-moon-shaped pyritic fill of a *Tasmanites* cyst (Schieber and Baird, 2001).

Clegg Creek Member:

609.90 m 610.64 m

Figure 1.11: Core photo of typical Clegg Creek black shale. It has a massive appearance with faint lamination and scattered sub-mm- to mm-thick silty laminae (quartzose and pyritic).

The Clegg Creek Member consists primarily of banded black shale with numerous sub-mm- to mm-thick silty laminae (quartzose and pyritic) (Fig. 1.11) and abundant disseminated fine crystalline pyrite. The Clegg Creek Shale also contains the highest concentrations of total organic carbon in the New Albany Shale succession (Fig. 1.1). Macroscopically bioturbated, brownish-black shale beds are present in the lower portion of the Clegg Creek. Conodonts from the eastern part of the Illinois Basin indicate that the base of the Clegg Creek is Upper Famennian (upper *marginifera* zone) in age (Sandberg et al., 1994). Judging from its distribution in the eastern U.S., as well as from the basal erosion surface that is observed in many places, the Clegg Creek represents a significant Famennian sea level rise. Given the biostratigraphic age of its base, the Clegg Creek probably coincides with the second transgressive pulse of TR cycle IIe of Johnson et al. (1985). The Clegg Creek Member is unconformably overlain by the Mississippian Rockford Limestone in well 1-3 Kavanaugh (Fig. 1.1).

The biostratigraphic marker *Foerstia* (*Protosalvinia*) (Schopf and Schwietering, 1970) was found in a 1.35-m-thick interval, approximately 7 to 8 m above the base of the Clegg Creek (Fig. 1.1). *Foerstia/Protosalvinia* occurrences coincide with highly pyrite enriched black shales, suggestive of very slow deposition, and probably mark a maximum flooding interval in the upper portion of the Clegg Creek Member. Although conodont data with regard to the age of the *Foerstia* Zone are not as tight as one would like them (Jeff Over, pers. commun., 2004), it seems to fall into the *trachytera* zone and thus may coincide with maximum flooding during the last transgressive pulse of TR cycle IIe (Johnson et al., 1985).

To summarize: Silty, sandy, pyritic, conodont, and shelly lags, as well as sharp-based black shale contacts, are common in the New Albany Shale and are typically indicators of laterally extensive erosion surfaces (Schieber, 1998a). Their recognition, added by the presence of marker beds (e.g., *Foerstia/Protosalvinia* Zone), UV maxima, and comparison of gamma-ray profile, shows that instead of representing a continuous depositional succession, the New Albany Shale consists of stacked shale packages bounded by erosion surfaces. We will identify the most significant of these surfaces during the field trip stops and make them the basis of relating stratigraphic units across the Cincinnati Arch between the Illinois and Appalachian Basins. Ultimately, what will emerge from this effort is a sequence stratigraphic framework for the Upper Devonian black shales of the eastern U.S.

2. Road Log and Stop Descriptions

by
Juergen Schieber and Remus Lazar

with contributions from
Mirela Dumitrescu, Leigh Fall, Mark Harvey, Grzegorz Lis, Andrew Parrish, Thomas Partin, Stephaney Puchalski, Sohini Sur, and William Tackaberry
Department of Geological Sciences, Indiana University,
Bloomington, Indiana 47405

Road Log - Saturday 25, 2004

Total mileage
0.0
Departure from Holiday Inn Express, 411 West Spring Street, New Albany, Indiana.

31.0
Stop 1: I-65, Exit 112, Bernheim Forest, Kentucky (Illinois Basin): Roadcut exposure of the New Albany Shale on the west side of the I-65 South at the intersection with KY-245 (37° 55' 26"N, 85° 41' 22"W (WGS84/NAD83), USGS Shepherdsville Quad; Fig. 2.1.1).

125.0
Stop 2A: KY-52, between Richmond and Irvine, Kentucky (Appalachian Basin): Roadcut exposure of the Ohio Shale on the north side of the road, approximately 6 miles west of Irvine, across from the Emmanuel Baptist Church (37° 42' 12"N, 84° 02' 01"W (WGS84/NAD83), USGS Panola Quad; Fig. 2.2.1).

0.4
Stop 2B: KY-52, between Richmond and Irvine, Kentucky (Appalachian Basin): Convenient roadcut exposure of the upper portions of the Ohio Shale on the north side of the road (37° 42' 04"N, 84° 02' 24"W (WGS84/NAD83), USGS Panola Quad; Fig. 2.2.1).

65.6
Stop 3A: Junction City, Kentucky (Cincinnati Arch): Spectacular roadcut exposure of shales that exhibit a combination of aspects of the Chattanooga, New Albany, and Ohio Shales on the east side of US-127, approximately 3 miles south of Junction City (37° 32' 54"N, 84° 48' 18"W (WGS84/NAD83), USGS Junction City Quad; Fig. 2.3.1).

0.2
Stop 3B: Junction City, Kentucky (Cincinnati Arch): Roadcut exposure of the upper portion of the Devonian black shale succession (37° 33' 23"N, 84° 48' 01"W (WGS84/NAD83), USGS Junction City Quad; Fig. 2.3.1).

97.8
Return to Holiday Inn Express, 411 West Spring Street, New Albany, Indiana.

The location of well 1-3 Kavanaugh and field stops 1-3 is shown in Figure 2.1 and in the overview road map on the back cover of this guidebook.

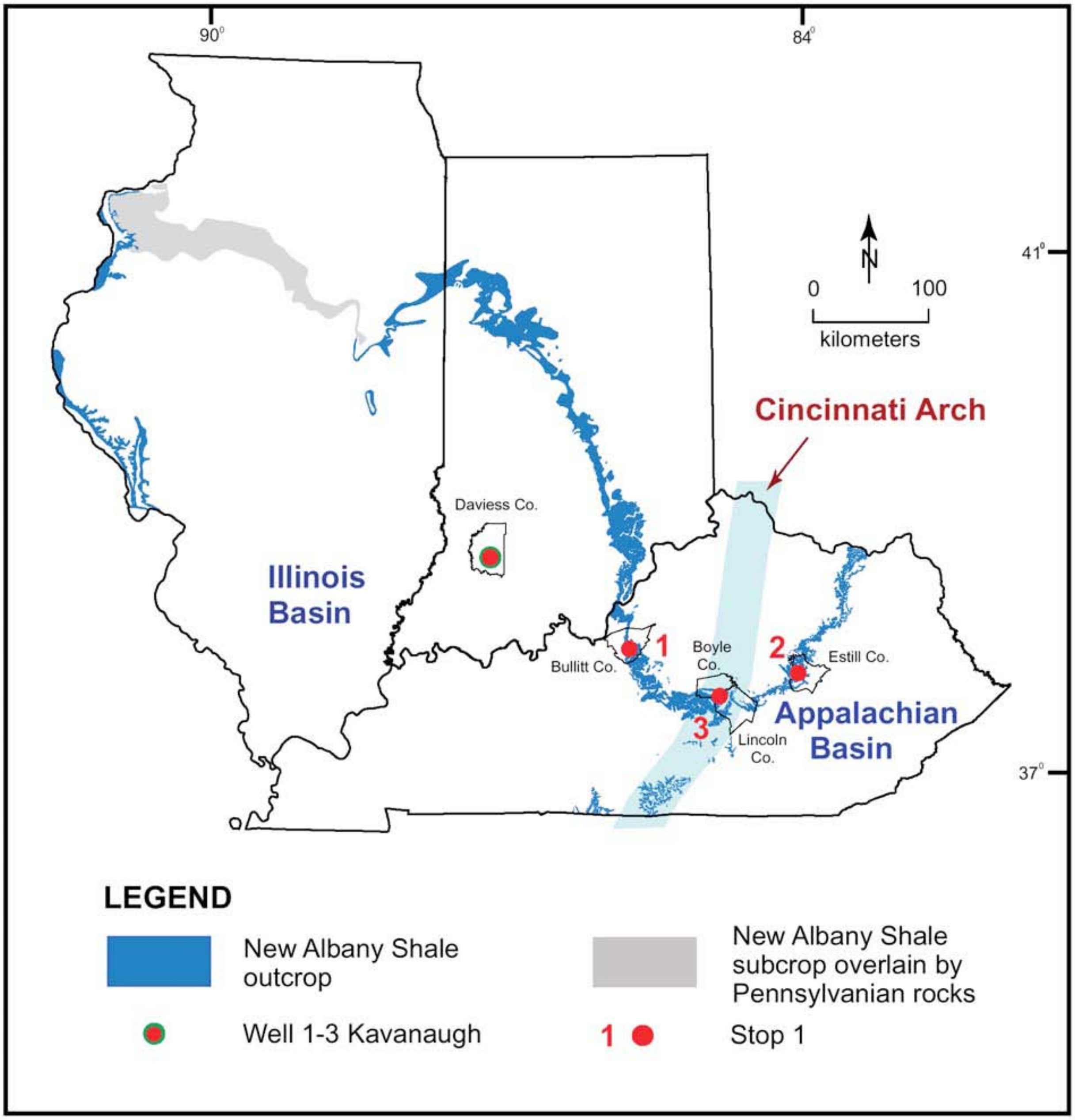


Figure 2.1: Map showing the location of well 1-3 Kavanaugh and field stops 1-3.

2.1: Stop 1, I-65, Exit 112, Bernheim Forest, Kentucky

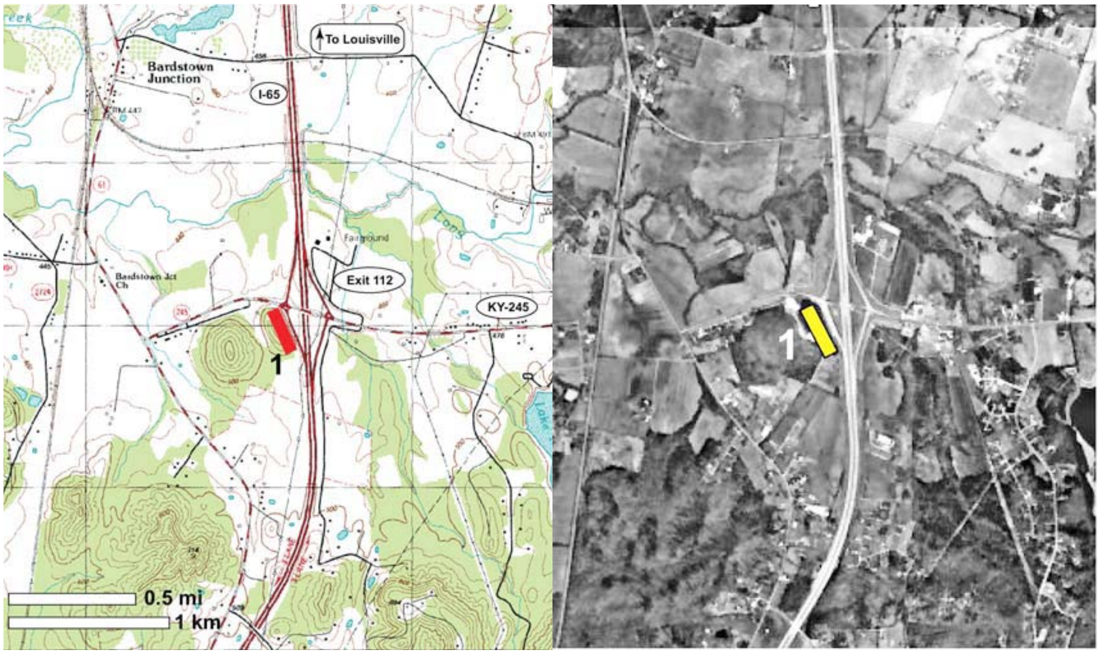


Figure 2.1.1: Stop 1 is a roadcut along the southbound entrance ramp to I-65 at the intersection with KY-245 (Exit 112). The outcrop is marked in red on the topographic map at left and yellow on the air photo at right.

Stop 1: This outcrop exposes a succession of the Devonian New Albany Shale that was deposited in the eastern part of the Illinois Basin (Fig. 2.1). The Middle Devonian Beechwood Limestone outcrops at the base of the exposure (Fig. 2.1.2) and is unconformably overlain by the Middle to Upper Devonian New Albany Shale. The latter is approximately 22 m thick at this location and consists in ascending order of the Blocher, Morgan Trail, Camp Run, and Clegg Creek Members (Fig. 2.1.2). These members were proposed by Lineback (1970) in his classical study of the New Albany and have been in use ever since. Lineback (1970) and subsequent researchers (e.g., Hasenmueller, 1993, Hasenmueller et al., 2000) assumed that black shale deposition in the area commenced sometime during the Middle Devonian and "continued without significant interruptions until the middle of Kinderhookian time" (Lineback, 1970). What is curious in this context is that this supposedly continuous black shale deposition produced members so distinctive that they can be traced over large areas in the subsurface as well as in outcrop. Several boundaries between members are literally knife-sharp and suggest in this day and age of sequence stratigraphy that they in fact represent an erosional break. That this is indeed the case was first demonstrated in the Chattanooga Shale of Tennessee, the southern equivalent of the New Albany Shale (Schieber, 1994, 1998a, 1998b). Tracing erosion surfaces northwards from Tennessee shows that they continue into the New Albany Shale (Johri and Schieber, 1999; Schieber, 2000), and that the most significant ones coincide with the member boundaries established by Lineback (1970) for the New Albany Shale. To illustrate these bounding surfaces in outcrop, and to show how they provide the connection between regionally different stratigraphic and lithological expressions of Late Devonian black shales is one of the focal points of this field conference. In Figure 2.1.2, the erosion surfaces that have been identified with confidence are marked with numbers in white circles (in ascending order). The same numbering scheme is also used in stratigraphic overviews for Stops 2 and 3. In earlier work on the Chattanooga Shale of Tennessee and southern Kentucky (Schieber, 1998b), additional erosion surfaces were recognized, probably because of closer proximity to the Cincinnati Arch. In stratigraphic overviews for this field guide, approximate positions of some of these additional erosion surfaces are marked with numbers in grey circles. Future research may in some cases confirm these surfaces, and in other cases identify their correlative conformities.

Starting at the south end of the exposure we see, at the base, the Beechwood Member of the Middle Devonian North Vernon Limestone (Sandberg et al., 1994), a lateral equivalent of the Boyle Formation of eastern Kentucky (see Stop 2). The Beechwood is a light to dark-gray crinoidal limestone that weathers tan to medium brown (Fig. 2.1.3). A thin pyritic lag marks the unconformable contact between the Beechwood Limestone and the overlying Blocher Shale (Fig. 2.1.3).

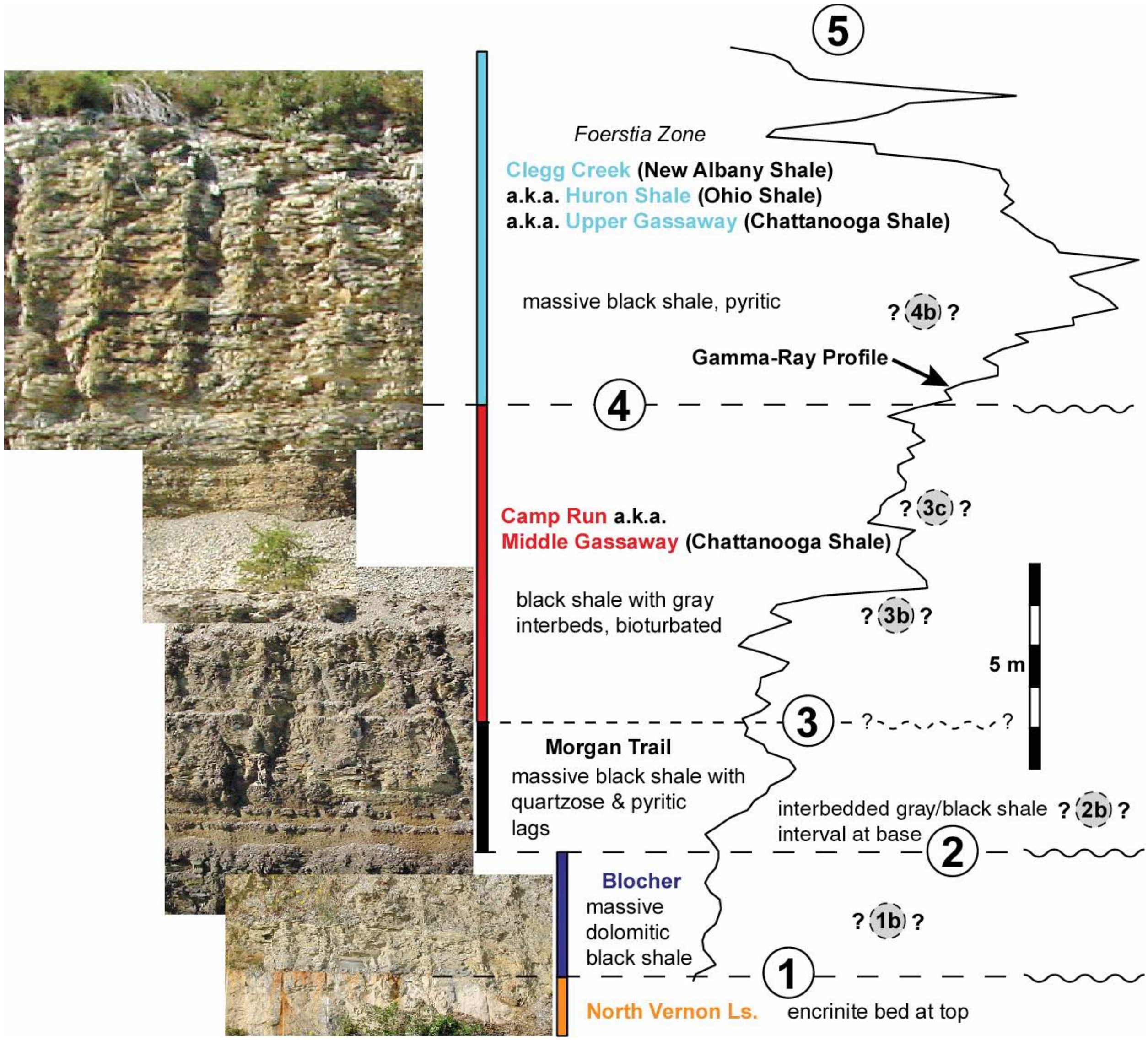


Figure 2.1.2: Stratigraphic overview of Stop 1. Wavy lines are known or suspected erosion surfaces (sequence boundaries). The numbers in white circles serve to match these surfaces to those observed in other stops. The numbers in gray circles mark the approximate location of erosion surfaces that are suggested from studies in other areas but have not yet been positively identified.

Figure 2.1.3: *Left*: Outcrop detail photograph of encrinite at the top of the Beechwood Limestone (crinoid stems pointed out be yellow arrows). *Right*: Irregular-undulose nature of Beechwood paleotopography. Red arrow points at cm-thick pyritic lag at the base of the Blocher.

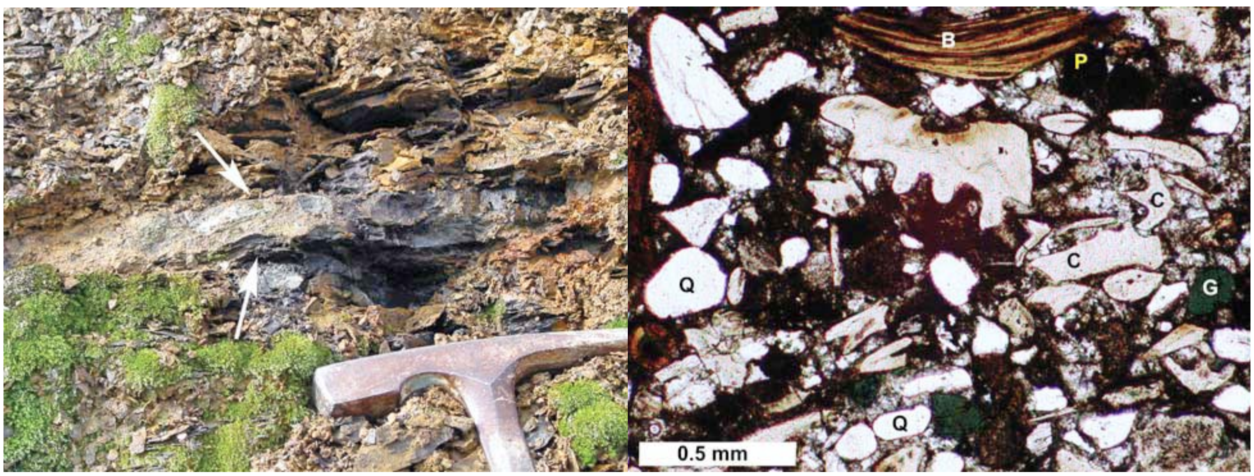


Figure 2.1.4: *Left*: The lag deposit (white arrows) at the Blocher-Morgan Trail contact. *Right*: Photomicrograph (transmitted light) of lag deposit. Shows rounded quartz (Q), pyrite (P), glauconite (G), conodonts (C), and shell fragments of linguloid brachiopods (B).

Figure 2.1.5: Interbedded gray and black shale (ledge-forming) in basal portion of Morgan Trail. Shows sharp base of black shale bed in center.

Blocher Member: In this exposure, the Blocher Member, a massive dolomitic black shale with mm- to cm-thick lenticular-wavy beds of dolosiltite is visibly draped over the North Vernon paleotopography (Fig. 2.1.3). Brownish-black when freshly exposed or examined in cores, it weathers into cm-thick blocky slabs having a brownish-bluish tint (Fig. 2.1.3). According to Over (2002), the top of the Blocher at this location is of mid-upper Frasnian age, and the top may be of uppermost Givetian or early Frasnian age, based on the presence of the encrinite bed (Fig. 2.1.3) at the top of the Beechwood (Sandberg at al., 1994).

The next unit above the Blocher would typically be the *Selmier Member*, a unit of alternating gray and black shales (Lineback, 1970). At this locality, however, the Selmier is missing (most likely due to erosion), and the Blocher is directly overlain by the Morgan Trail Member.

Morgan Trail Member: A 1- to 2-cm thick pyritic lag with rounded quartz grains, glauconite, *Lingula* shells, and abundant conodonts (Fig. 2.1.4) separates the Blocher from the shale unit that overlies it. The conodonts indicate a lower Famennian (lower *crepida* zone) age for the base of the next shale package (Over, 2002). This age assignment indicates that this black shale unit should be assigned to the Morgan Trail Member of the New Albany Shale (Sandberg et al., 1994; Over, 2002). Depending on how one calibrates the Late Devonian conodont record (Sandberg et al., 1994; Klapper, 1997; Tucker et al., 1998) there may be 3 to 7 million years of rock record missing between the Blocher and the base of the Morgan Trail at this location. Thus, although the erosion surface between Blocher and Morgan Trail is subtle and superficially conformable at the outcrop scale, it is nonetheless a very significant break in the stratigraphic record.

The basal meter of the Morgan Trail in this exposure is atypical in that it consists of interbedded black and gray shales, thus inviting mistaken identification as Selmier or Camp Run. These black-gray cycles may reflect a "shallow" water Morgan Trail facies that has been eroded (or never been deposited) elsewhere. Examined more closely, the black shale beds have sharp and potentially erosive bases (Fig. 2.1.5), and have gradational contacts with overlying gray shales. These decimeter-scale black-gray cycles may reflect minor sea level variations during Morgan Trail deposition and could represent parasequences. Above this basal interval the remainder (±2m) of the Morgan Trail Member is massive and variably pyritic due to thin lags enriched in pyrite-filled *Tasmanites* cysts.

Camp Run Member: The Camp Run consists of interbedded black (a few cm's to several m's thick) and gray shale (a few cm's to 30-cm-thick) beds. The gray beds are fully bioturbated, and the black beds are visibly bioturbated from the top (burrows filled with gray shale) and have in addition very subtle indications of early depositional bioturbation (Schieber, 2003a). The presence of less-resistant gray shale beds is a basic field criterion for distinguishing the Camp Run from the underlying and overlying shales (Morgan Trail and Clegg Creek, respectively), and as we can see from the base of the Morgan Trail in this exposure, it is not a failsafe criterion. Elsewhere, for example in central Tennessee, the Camp Run equivalent (Middle Gassaway) is in erosive contact with underlying black shales. Although we can see here a sharp contact in form of the first gray shale bed above the Morgan Trail, whether this contact is indeed erosive at this location has not yet been established with certainty. It is likely that as we go further westward away from the Cincinnati Arch, erosive contacts found on and in vicinity of the arch will turn into their "correlative conformities" (sensu Vail). The upper boundary of the Camp Run, its contact with the overlying Clegg Creek Member, is knife-sharp (Fig. 2.1.6) in this exposure (and in many others as well) and represents an erosion surface. Although the Camp Run and Clegg Creek appear conformable on the outcrop scale, the erosion surface is visible regionally through progressive truncation of the Camp Run gamma-ray log motive (Schieber, 2000; Barrett, 2002). The black-gray shale cycles in the Camp Run are suggestive of intermittent improvement of bottom water oxygenation and, depending which brand of magic one prefers, may be a byproduct of sea level variations, change in basin circulation patterns, drop in surface productivity, or climate variations.

Clegg Creek Member: Massive in appearance and pyritic, the Clegg Creek Member has a sharply contrasting outcrop expression than the underlying Camp Run Member (Fig. 2.1.6). The presence of a pyrite-enriched interval with *Foestia/Protosalvinia* in the top portion of the Clegg Creek is significant because it facilitates correlation with the other two stops of this field trip, as well as with well 1-3 Kavanaugh (introduced yesterday). *Foerstia* is a useful biostratigraphic marker for correlations with other portions of the Devonian black shale succession (Kepferle, 1981; Hasenmueller et al., 1983; Roen, 1993). The Clegg Creek itself is truncated on top and overlain in places by a bed with reworked phosphate nodules, the so-called Falling Run Bed (Campbell, 1946).

Cross-cutting Veins: At the northern end of this outcrop occur more or less vertical veins, filled with quartz, dolomite, and locally some bitumen (Fig. 2.1.7). These veins may extend for up to 5 meters vertically through the outcrop, are from a few cm's to 15 cm wide, and have been contorted and telescoped because of the compaction of the surrounding shale after vein emplacement. These features indicate that vein emplacement took place while their shale host was still not fully compacted. "Backstripping" the contortion and telescoping of these veins suggests that they were emplaced when their shale host still had between 20 to 30 percent porosity. Judging from shale compaction models, this would imply at a minimum a burial depth of several hundred meters when the veins were emplaced. Although, the very slow accumulation of these black shales could have allowed the package to reach the indicated porosities at somewhat shallower depth. In any case, injection of fluids to force open these veins would have required overpressured fluids and may well be related to the trapping of deeper formation waters beneath the Devonian shale seal. These veins are oriented in NW-SE direction, the same as other comparable veins in Devonian black shales of the region, and coincident with the preferred orientation of lineaments mapped at the surface and fracture orientations in the New Albany Shale (Carr, 1981).

Figure 2.1.6: Knife-sharp erosional contact (white arrows) between Camp Run and Clegg Creek Members. Red arrows at the top of the exposure mark a soft weathering interval (due to abundant pyrite) that coincides with the *Foerstia/Protosalvinia* Zone.

Figure 2.1.7: Vertical vein filled with quartz and dolomite, cutting essentially vertical through the Camp Run Member (north end of exposure). Vein is contorted and telescoped because of shale compaction after vein emplacement.

2.2: Stop 2: On Route 52 between Richmond and Irvine, Kentucky, ~3.5 miles east of Estill County line

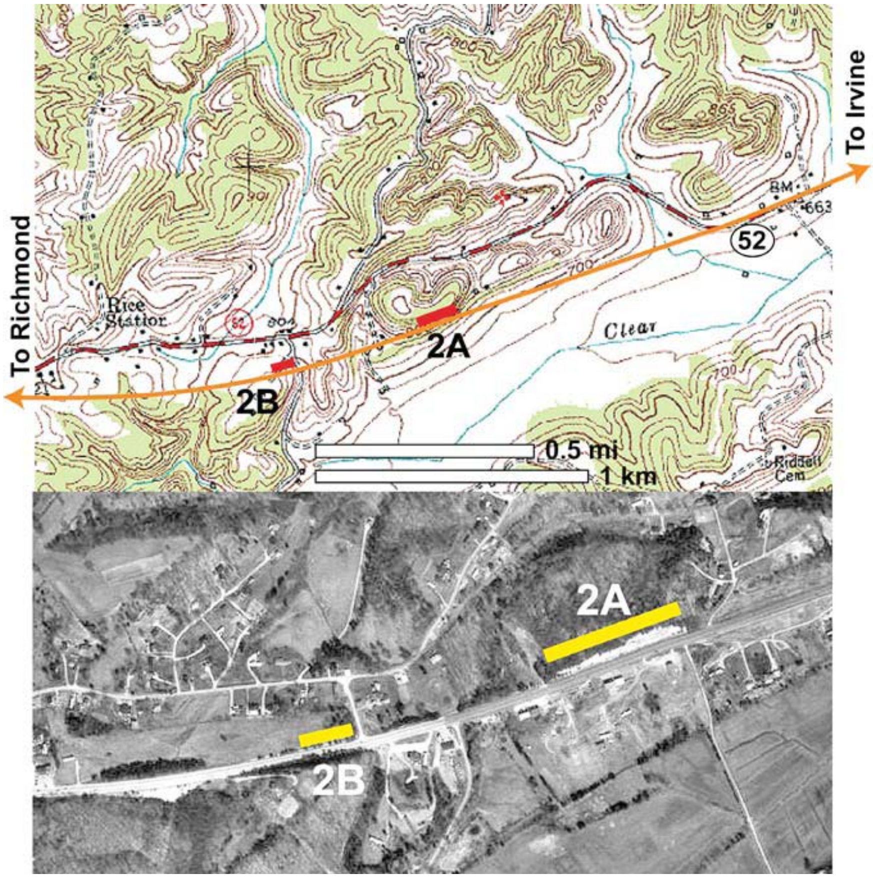


Figure 2.2.1: The exposures we will visit at Stop 3 are in roadcuts along KY-52, approximately 6 miles west of Irvine. They are marked in red on the above topographic map and in yellow on the air photo below.

This exposure differs from Stop 1 in that we are now to the east of the Cincinnati Arch and thus have moved from the Illinois into the Appalachian Basin (Fig. 2.1). Consequently, we can not expect the rocks to look exactly the same as at Stop 1, and we also have to be prepared to encounter stratigraphic units that we did not see previously. Nonetheless, our rocks of interest still are of the same comforting black color as previously. The total thickness of black shales exposed here is about 36 meters, almost twice as much as in the previous exposure.

Although the entire section is exposed at Stop 2A, the portions in the upper part of the cut are difficult to reach and will be examined at Stop 2B instead. In combination, the two cuts show a section of Devonian black shales that begins in the Middle Devonian and essentially reaches to the top of the Devonian. Whereas the lowermost black shale at Stop 1, the Blocher, is quite possibly mostly Frasnian (Sandberg et al., 1994; Over, 2002), here we will see Middle Devonian black shales that predate the Blocher and have not been found (yet) in the Illinois Basin.

Stop 2A: Stratigraphic units in this exposure are discussed from the bottom upwards (Fig. 2.2.2). For the lowermost units (Boyle and Portwood), the paper by Brett et al. (this guidebook) should be consulted for details.

Boyle Dolomite: At the very base of the exposure, we see nicely exposed the Middle Devonian Boyle Dolomite (Fig. 2.2.2), a medium-gray, orange-buff weathering dolostone and dolomitic limestone, with layers of irregular pale cream-colored chert nodules. Its age is Middle Devonian, probably Givetian. It has an unconformable (low-angle) contact with the overlying Portwood. The angular contact is best seen in large Boyle outcrops several miles to the west (towards Richmond) along KY-52.

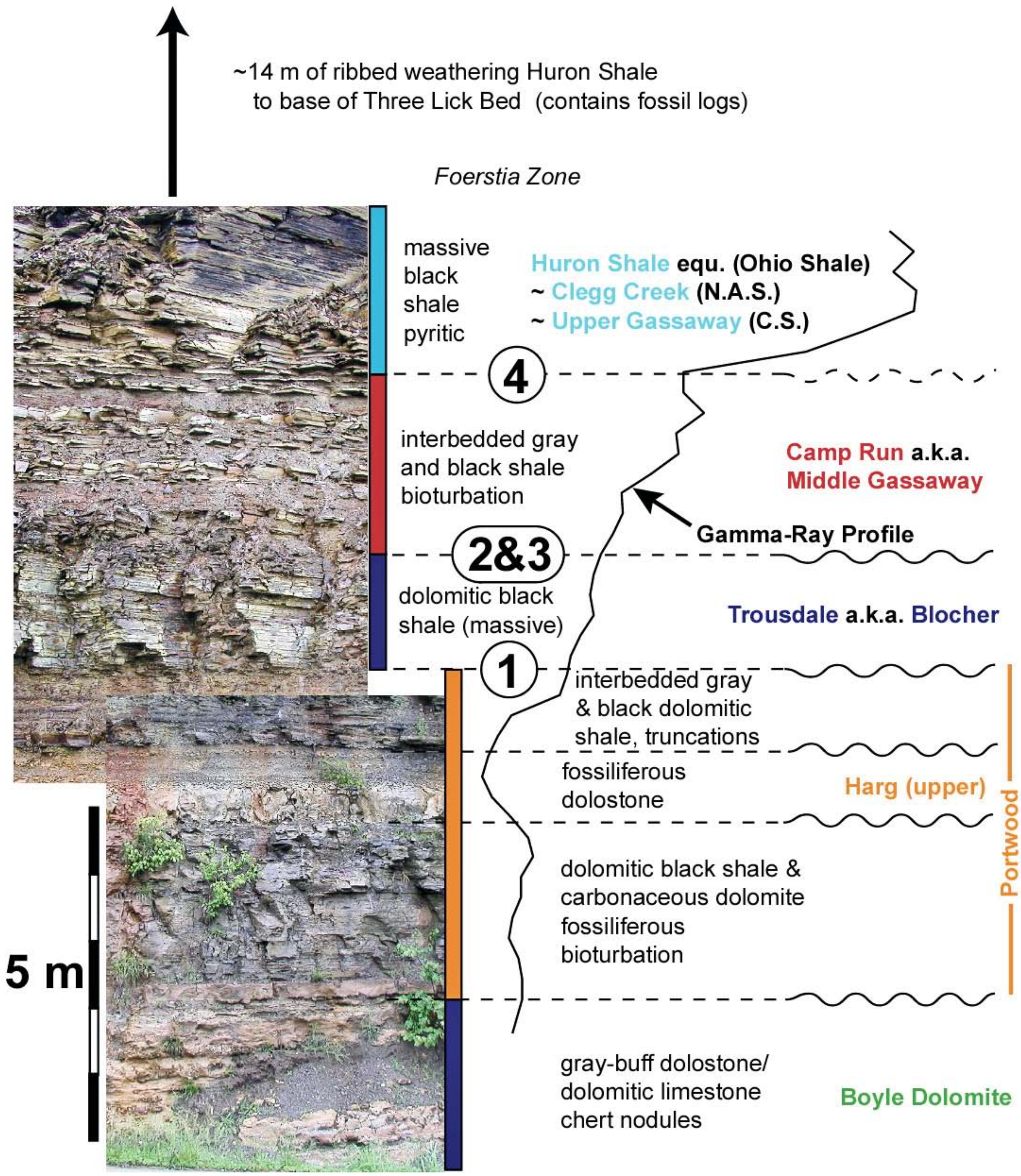


Figure 2.2.2: Stratigraphic overview of Stop 2A. Wavy lines are known or suspected erosion surfaces (sequence boundaries). The numbers in circles serve to match these surfaces to those observed at other stops.

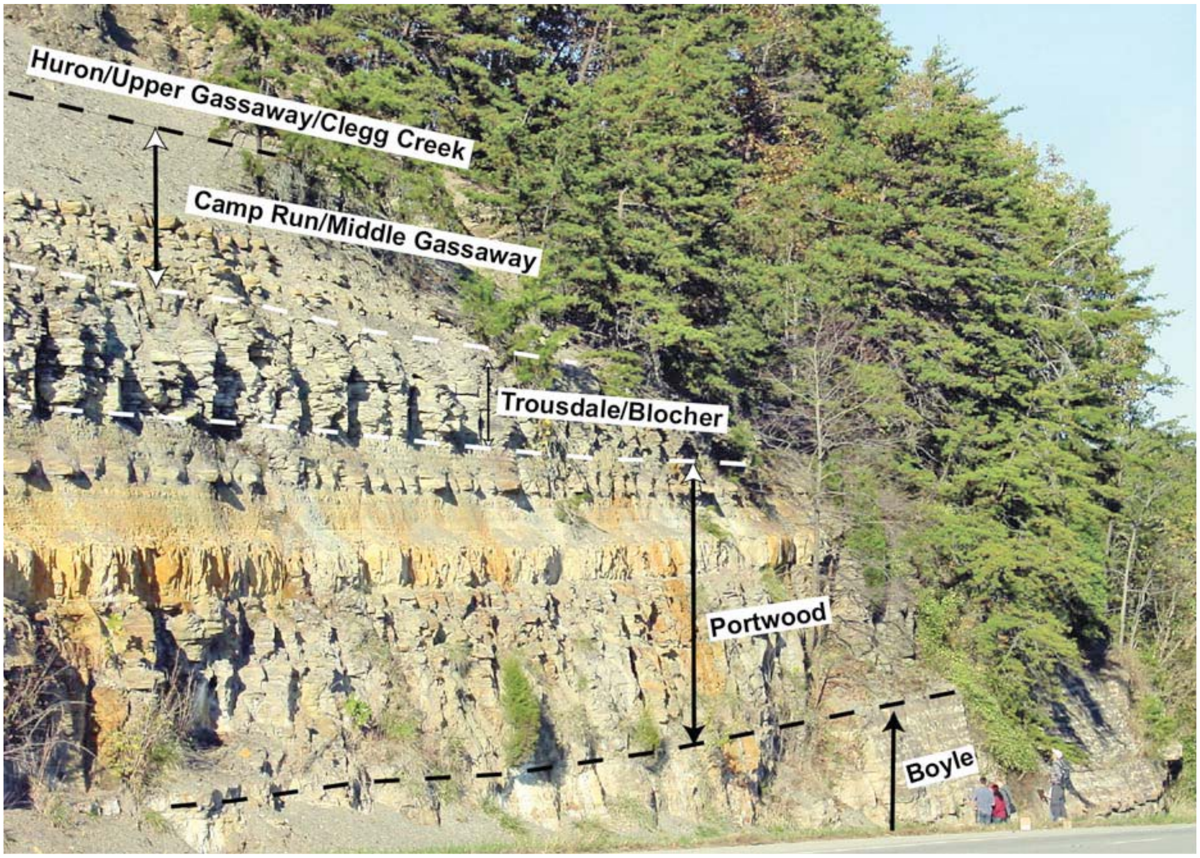


Figure 2.2.3: East end of exposure at Stop 2A. Shown are the major subdivisions discussed at this stop, marked with arrows (thickness) and dashed lines (contacts).

Portwood: The Boyle is separated by a thick lag horizon (up to 50 cm thick) from the overlying Portwood Formation (Figs. 2.2.3, 2.2.4). The lag is a fine to medium sandstone that is dominated by detrital dolomite grains overgrown by interlocking clear dolomite cement. In addition to dolomite the lag also contains well-rounded quartz grains, well-rounded glauconite grains, and bone debris. The Portwood is a unit that is characterized by strong lateral variability and has long defied attempts at lateral correlation of subdivisions visible in given outcrops. At first glance it seems to vary so strongly from outcrop to outcrop that correlations seem all but impossible. At the base of this Portwood section (see also Fig. 2.2.2) we see an interval of strongly dolomitic black shales that is quite fossiliferous in thin section, contains glauconite grains, and shows bioturbation (Fig. 2.2.4). It is considered a lateral equivalent of the Tully Formation (Givetian) in New York (Brett et al., this volume). This carbonaceous interval is overlain by a buff colored dolomite bed (10 to 50 cm thick) with an undulose erosive base, probably a sequence boundary (Carl Brett considers it the middle/upper Tully sequence boundary). Above this dolomite bed follow about 1.6 meters of interbedded black and gray dolomitic shales to the top of the

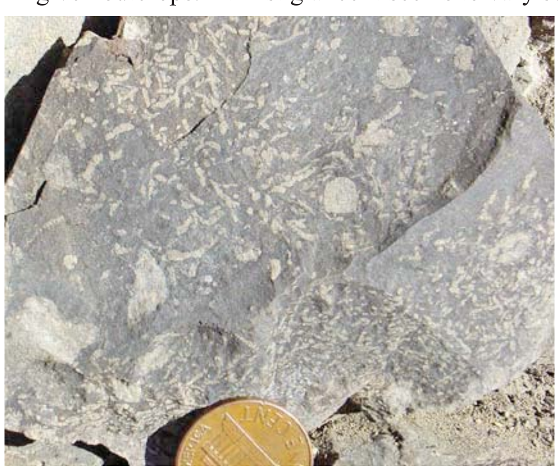


Figure 2.2.4: *Left:* Boyle-Portwood contact, boundary lag marked with white arrows. *Above:* Bioturbation in Portwood dolomitic black shale unit. Larger tubes (light circles) as well as *Chondrites*.

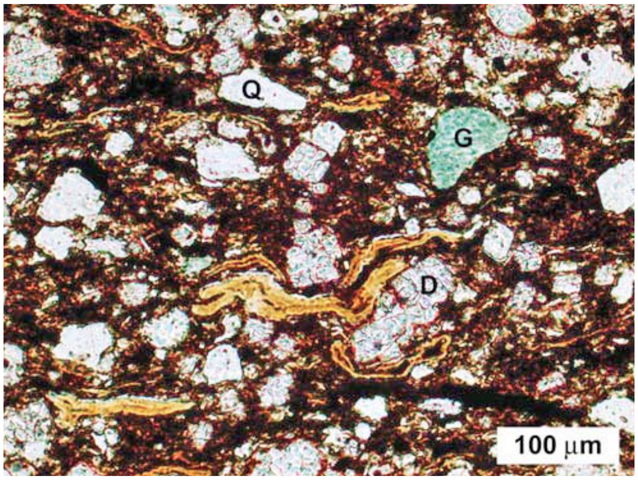


Figure 2.2.5: Photomicrograph from the dark dolomitic shale interval in the striped interval at top of Portwood. Yellow deformed streaks are *Tasmanites*, dolomite marked D, quartz marked Q, glauconite marked G.

Portwood. In the middle of this 1.6-m interval, a more resistant black shale bed seems to overlie yet another truncation (erosion) surface. Thin sections from the upper half of this 1.6-m interval show that these shales are still strongly dolomitic, contain glauconite pellets, and are mottled due to bioturbation (Fig. 2.2.5).

Trousdale/Blocher: The next higher unit is a dolomitic black shale that contains phosphatic shells of inarticulate brachiopods and abundant *Tasmanites*. It is significantly less dolomitic than the black shales in the underlying Portwood (Fig. 2.2.6), and very similar petrographically to the Blocher and Trousdale examined elsewhere in the region. Campbell (1946) reported Geneseo style fauna from this unit, and Brett et al. (2003) report conodonts that suggest an uppermost Givetian age, further suggesting that it overlaps in age with the Blocher in Indiana.

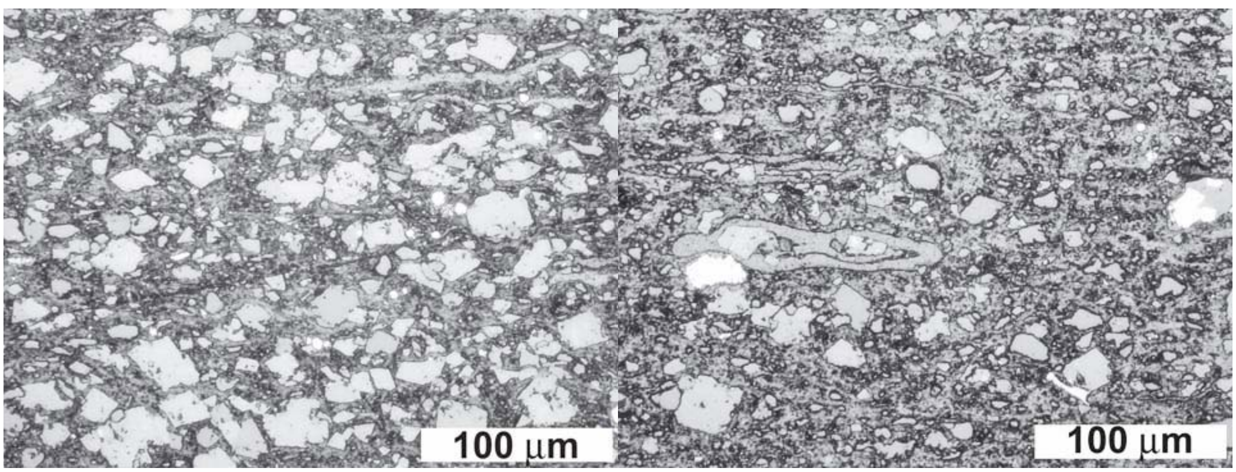


Figure 2.2.6: *Left:* Photomicrograph (reflected light) of Portwood black shale (above Boyle). *Right:* Photomicrograph of Trousdale black shale. The light-gray euhedral grains are dolomite, elongate horizontal features are *Tasmanites*; the remainder consists of clay, quartz silt, organic matter, and some pyrite (bright spots).

Middle Gassaway/Camp Run: The next interval above the Trousdale/Blocher consists of interbedded black (resistant ledges) and gray shales (soft, recessive) that vary in thickness from 4 to 20 cm (Fig. 2.2.7). The black shale beds show nice burrows (*Chondrites, Planolites, Zoophycos*) filled with gray shale from above (Fig. 2.2.7). This interval bears close resemblance to the Middle Gassaway as observed in central Tennessee, and also the Camp Run in Indiana in exposures/cores along the eastern outcrop belt.

We currently have no conodont data from this interval, but by comparison with sections further east (Morehead, I-64) that place comparable strata into the Camp Run bracket (Over, 2002), and by sheer lithologic similarity, we assume that these beds are correlative to the Camp Run in Indiana/western Kentucky and the Middle Gassaway in central Tennessee. We should also note that there is a lag deposit at the base of this interval, as well as a low-angle truncation of underlying Trousdale/Blocher beds.

Figure 2.2.7: *Left:* Outcrop of interbedded black and gray shale of the Middle Gassaway/Camp Run interval. *Right:* Macroscopically visible bioturbation in black shale beds. Shows mainly *Chondrites* and *Planolites*.

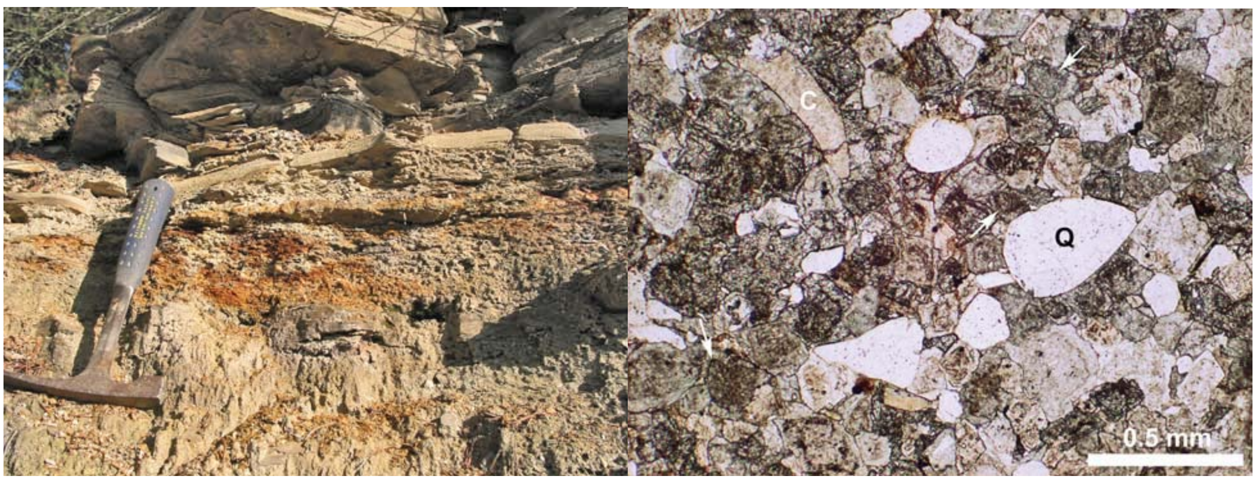


Figure 2.2.8: *Left:* Rusty-colored resistant lag at base of the Camp Run interval. *Right:* Photomicrograph of the lag that shows rounded quartz (Q), conodont fragments (C), and rounded detrital dolomite grains (white arrows) with overgrowth cement.

Figure 2.2.9: Disturbed zone in Portwood. To the left and right, we see the Harg dolomite bed at the same elevation (vertical arrows), and in between there is an area with deformed beds, jumbled stratification, and pods of dolomite (inclined arrows) that are deformed (Fig. 2.2.10) and clearly at a lower elevation.

In detail, the lag in Figure 2.2.8 is separated from the underlying Trousdale by a 15-cm-thick, poorly exposed interval of interbedded black (1- to 2-cm beds) and gray shales (2- to 4-cm beds). This kind of lithology is atypical for the Trousdale and whether it is in erosive contact with the Trousdale is presently not known. There is a possibility that those 15 cm are all that is left of what once might have been a Selmier/Dowelltown equivalent in this area. Careful evaluation of photomosaics showed that the Trousdale thins about 15 percent over that portion of the outcrop where both top and base are exposed, and that the thinning is due to erosion on top.

Upper Gassaway/Clegg Creek/Huron: Following above this interbedded interval is a massive weathering shale unit that, together with the remainder of the outcrop above, has the look and feel of the Huron Shale Member of the Ohio Shale as seen further to the northeast (Morehead, I-64), but is about half as thick. This correlation is supported by the strong gamma-ray signature of the basal massive black shale of this unit (characteristic also of Clegg Creek and Upper Gassaway) and confirmed by the fact that this unit contains the *Foerstia* Zone, as do Upper Gassaway and Clegg Creek. These shales were deposited more slowly than other black shales in the succession, and contain abundant diagenetic pyrite, in part, possibly because of bottom current reworking of the black shale substrate and consequent pyrite enrichment (as observed in the Upper Gassaway) in thin (sub-mm) lag deposits. The abundant pyrite causes these shales to produce efflorescences of variably hydrated ferrous/ferric sulfates associated with pyrite oxidation--melanterite, szomolnokite, copiapite, coquimbite, and jarosite. These efflorescences can form whitish to yellowish crusts on the outcrop and may wax and wane in response to precipitation. The base of this shale interval is marked by a knife-sharp contact with the underlying black/gray interbedded unit, and may well be erosive. We have not yet located a lag at this location, but this may in part be due to the inaccessibility of this contact at this location. There is evidence of erosion prior to deposition of this black shale unit at the base of the Upper Gassaway (in Tennessee) and the Clegg Creek (in Indiana), and it is also observed at Stop 3, located on the Cincinnati Arch (and thus more likely affected by sea level drops). The transgression marked by this massive black shale unit could be the second transgressive pulse of TR cycle IIe of Johnson et al. (1985), a transgression which led to the most extensive flooding recorded by the Late Devonian black shale succession of the eastern U.S. The remainder of the section will be examined at Stop 2B.

It should be pointed out here that the base of the Huron Shale, as found in Ohio, is approximately at the base of the Famennian (*triangularis* zone). In northeastern Kentucky, however, earlier deposited Famennian strata (approximately the lower third) were completely removed by erosion (Over, 2002), and the first Famennian black shale unit that is preserved is several conodont zones younger (*rhomboidea* zone) than its lithostratigraphic equivalent in Ohio. Thus, although we use the term “Huron Shale” in reference to this unit during our field trip, we must keep the biostratigraphic difference between Ohio and Kentucky in mind. This variable age of the Huron base, due to progressive onlap of black shales onto the Cincinnati Arch as sea level rose, has been the cause for considerable confusion and head-scratching in the past. Technically speaking, the underlying interval of black/gray interbedded shales could also be called Huron because if we are correct with our Gassaway/Camp Run assignment, then these shales are also Famennian and thus of (type) Huron age (Such are the joys of stratigraphy).

Deformed Beds in the Portwood: Just about in the middle of the roadcut at Stop 2A, there is a zone where the prominent dolomite bed (Harg) in the Portwood is displaced downward (Fig. 2.2.9), separated into deformed pods, and surrounded by deformed shale (Fig. 2.2.10). These pods can resemble ball and pillow structures and suggest that the dolomite bed sank into the underlying shale unit, implying liquefaction of the shale. The overlying stratigraphic units are not affected, pointing to soft sediment deformation during Portwood time. Because the shale liquefaction affected only a narrow area, the suggestion is of a localized energy release, such as one would expect from movement of deeper seated faults. Had the energy source been an earthquake that affected a large surface area, or perhaps a tsunami, we should expect a correspondingly larger lateral extent of the liquefaction zone as well. The paper by Brett et al. (this guidebook) contains additional information on deformed beds in the Portwood, some thoughts about possible causes, and also argues for fault movements as a possible cause.

Stop 2B: To have a more convenient look at the upper portion of the Devonian section we drive westward (uphill) on KY-52 for approximately 0.4 miles. A nice exposure of Devonian black shales on the north side of the road (Fig. 2.2.11) shows the top portion of the Huron Shale, the Three Lick Bed, and an overlying more massive and weathering-resistant black shale that correlates with the Cleveland Shale of Ohio (Kepferle and Roen, 1981).
Both the Huron Shale and the Cleveland Shale are members of the Ohio Shale, and the Three Lick Bed (TLB) is a convenient marker to separate them (Provo et al., 1978). The TLB extends as a marker over large portions of the Appalachian Basin, but its origin is a bit of a mystery. We can see that the black shale beds between the three gray shale beds that define the TLB have a well-defined sharp base, suggesting that we actually have black-gray couplets that mark depositional events or cycles. The TLB has been interpreted as a distal tongue of the Chagrin Shale, a more proximal deltaic succession, but that does not explain the triplet nature of this bed that stays so constant over such a large area.

Figure 2.2.10: Closeup of a pod of dolomite in the disturbed zone in the Portwood. Note shale wrapping around pod at left.

The Huron Shale shows "ribbed" weathering on the dm scale in this exposure, related to rhythmically varying contents of clay and organic matter (Jaminski et al., 1998) that lead to resistant ledges of carbonaceous shale and softer portions that are enriched in clay (but still carbonaceous). Of interest here are thin discontinuous beds of cone in cone calcite that are probably testament to a (time) increment of very slow sediment accumulation. Measuring up from the base of the Huron as defined at Stop 2A, we have here a total of 17 m of Huron Shale. Going just 70 km to the NE (Morehead, Kentucky) we would find that this portion of the section has more than doubled (36 m) in thickness.

The overlying Cleveland Shale is more massive and resistant looking because of an overall higher TOC content. It still shows cycles of resistant versus softer beds, but the cycle thickness is now on the sub-dm scale. If we assume that the cycles reflect some kind of periodic forcing mechanism (e.g., climate, Milankovitch, etc.), we have two options to interpret the difference in cycle thickness between the Huron and Cleveland Shale:

1) Sedimentation rates dropped drastically from Huron to Cleveland.
2) The periodicity of the forcing mechanism or the forcing mechanism itself changed.

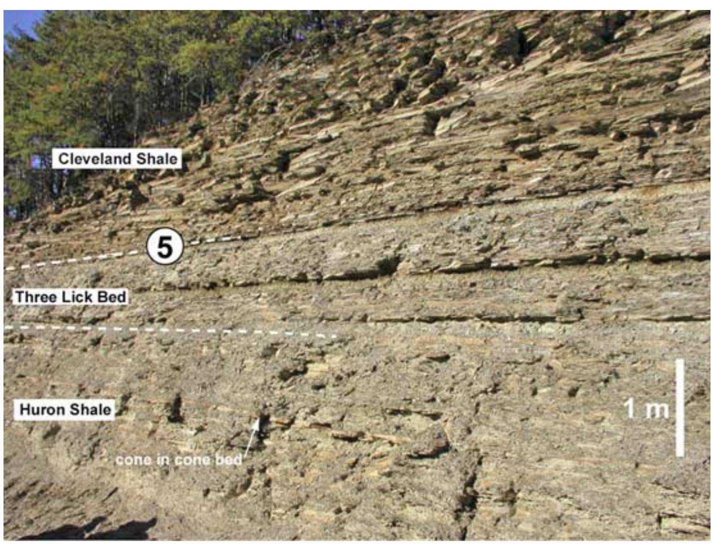


Figure 2.2.11: Stratigraphic units at Stop 2B. Three Lick Bed separates Huron and Cleveland Shale. Arrow points to cone in cone calcite bed. The circled number 5 serves to match this surface to its equivalent at Stop 3.

Option 1 seems more likely for the reason that, at this particular horizon (Cleveland base), there is evidence for an erosive interlude prior to Cleveland deposition, with localities ranging from southern Tennessee to northeastern Ohio. In that sense, the knife-sharp Cleveland base is clearly representative of a sequence boundary, possibly corresponding to the transgression associated with TR cycle IIf of Johnson et al. (1985). This boundary is marked as a circled number 5 in the stratigraphic overview for Stop 3 (Fig. 2.3.2). Even where we do not find direct evidence for erosion in the form of lags and scours, the sharp basal contact of the Cleveland and its high TOC content are suggestive of its deposition during a transgression and sea level rise. In that case, clastics would have been held back in estuaries and on coastal plains, leading to smaller clastic input and (all else staying the same) thinner cycles.

We will see the Huron-Three Lick Bed-Cleveland interval again at Stop 3, another 70 km to the west, where it will be thinner still because of greater distance from the clastic source (the Huron will be ~10 m thick, versus 17 m at Stop 2).

2.3: Stop 3, ~3 miles south of Junction City, Kentucky

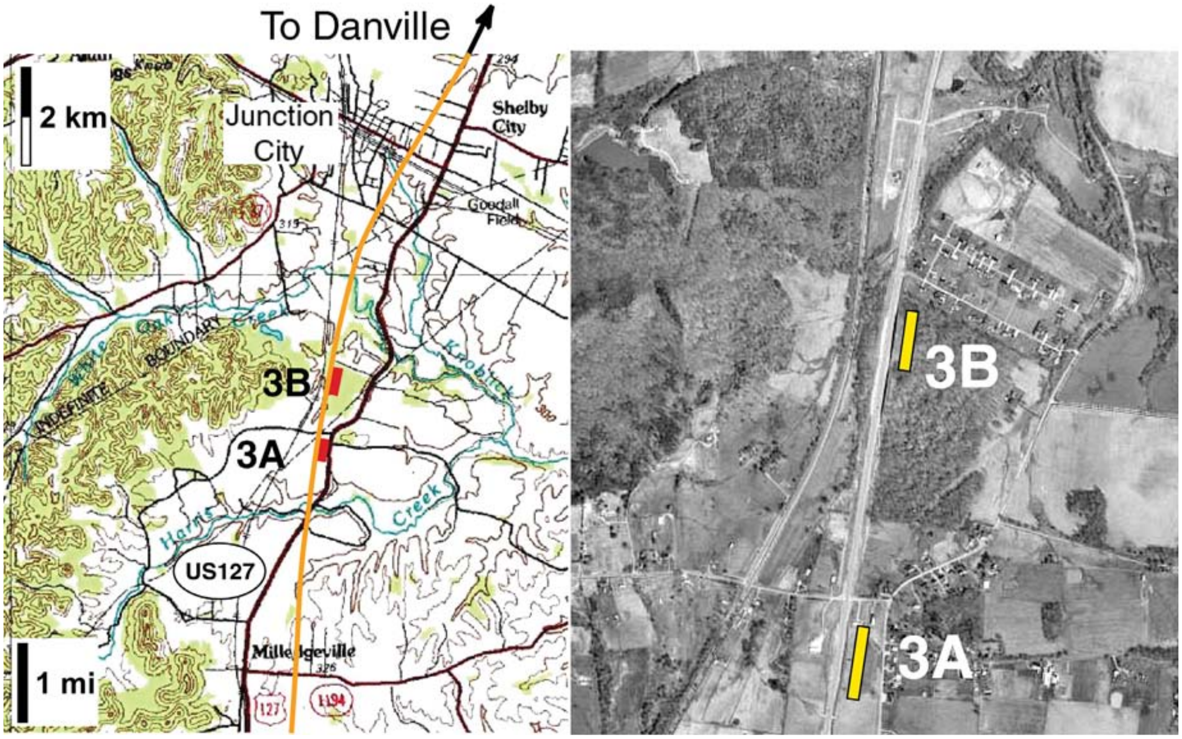


Figure 2.3.1: The exposures we will visit are in roadcuts along US-127, approximately 3 miles south of Junction City. They are marked in red on the topographic map at left, and in yellow on the air photo at right.

The two marked roadcuts show, in combination, a fairly complete section of Devonian black shales. Stop 3A shows the lower part of the section, and Stop 3B shows the upper part. The strata exposed here were deposited near the crest of the Cincinnati Arch (Fig. 2.1), and as such, constitute the connection between the Appalachian and the Illinois Basins. The total thickness of Devonian black shales is about 17 meters, less than in the previous two exposures. We will again see the erosion surfaces that we already inspected in the previous two stops. The exposed strata, although in "legal" terms belonging to the Chattanooga Shale (de Witt, 1981), show a combination of aspects of the Chattanooga Shale, the New Albany Shale, and the Ohio Shale.

Stop 3A: Stratigraphic units in this exposure are discussed from the bottom upwards (Fig. 2.3.2).

Boyle and Duffin: The Middle Devonian Boyle (a foot or less) and Duffin carbonates (60 to 80 cm thick) occur at the base (south end) of this exposure. Similar to Stop 2A, the Boyle consists of medium-gray, orange-buff weathering dolostone and dolomitic limestone with layers of irregular pale cream-colored chert nodules. Conodonts suggest that it is Middle Devonian, probably Givetian in age (see paper by Brett et al., this volume). The Duffin carbonates are a facies of the Middle Devonian Portwood Formation, a unit that is characterized by strong lateral variability. Recent work by Carl Brett and Gordon Baird suggests that it will finally be possible to unravel its complex facies patterns and to see stratigraphic order in this unit (see paper by Brett et al., this guidebook).

Although in places sufficiently coarse to have earned the name "breccia", at this locality the Duffin is a crudely bedded calcareous/dolomitic sandstone (Fig. 2.3.3) with variable amounts of silicified fossil debris and large vugs that can contain nice clusters of calcite crystals. The origin of these vugs is problematic. Comparable vugs occur elsewhere (e.g. around Nashville, Tennessee) in carbonates beneath the Devonian black shale succession, and in really fresh outcrops they are actually filled with gypsum. They probably formed when acidic formation waters were squeezed out of the sedimentary stack that accumulated in the Appalachian and Illinois Basins, migrated through the carbonates beneath the seal of Devonian shales, and dissolved part of the carbonate matrix. Quartz-dolomite-bitumen veins similar to those seen at Stop 1, also occur in the Trousdale Shale of this outcrop (Fig. 2.3.4), and may well be related to the movement of overpressured fluids underneath the Devonian shale seal.

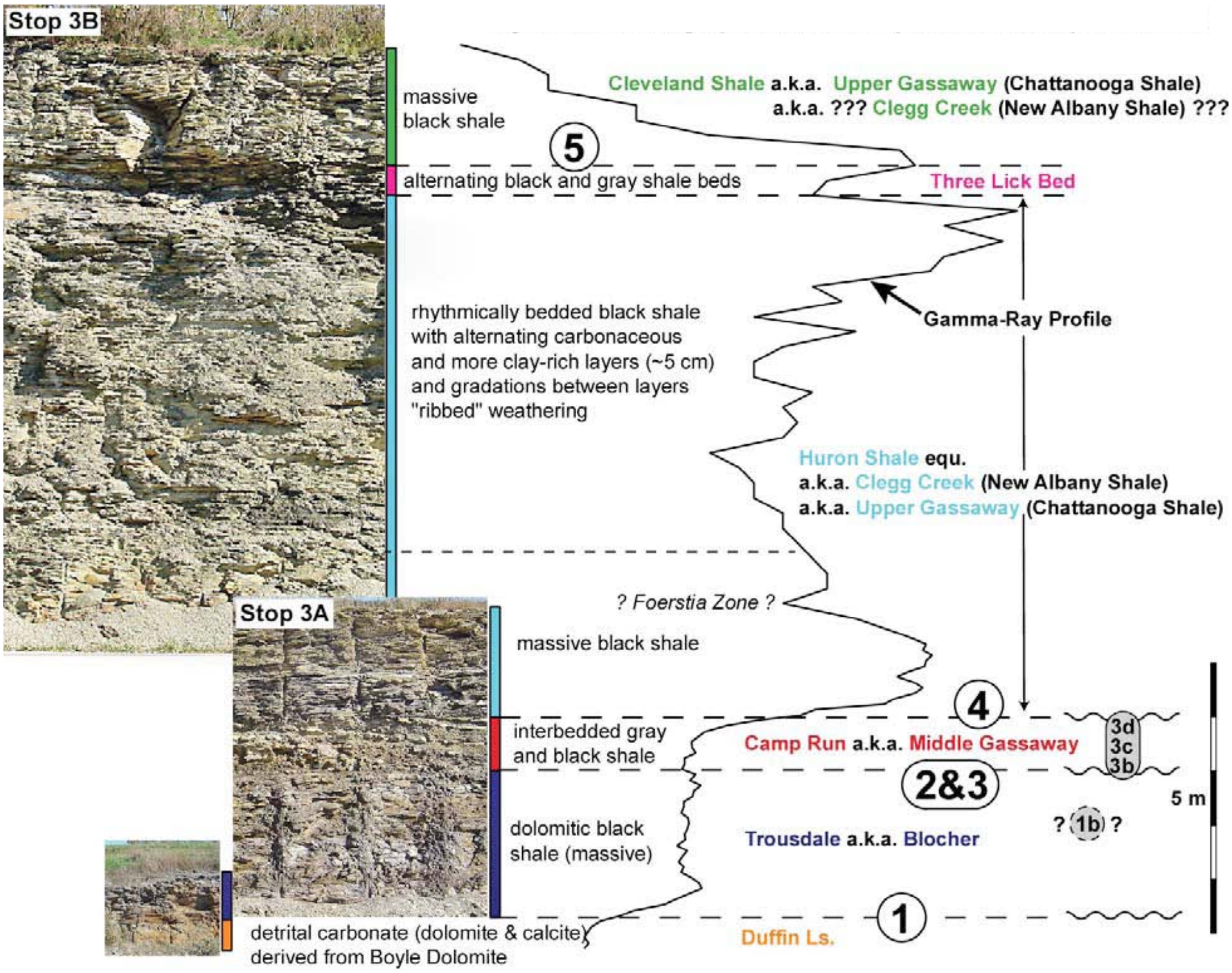


Figure 2.3.2: Stratigraphic overview of Stop 3. Wavy lines are known or suspected erosion surfaces (sequence boundaries, numbers in circles match surfaces to those seen at other stops). Gray circled numbers mark approximate location of erosion surfaces that are suggested from studies in other areas but have not yet been positively identified.

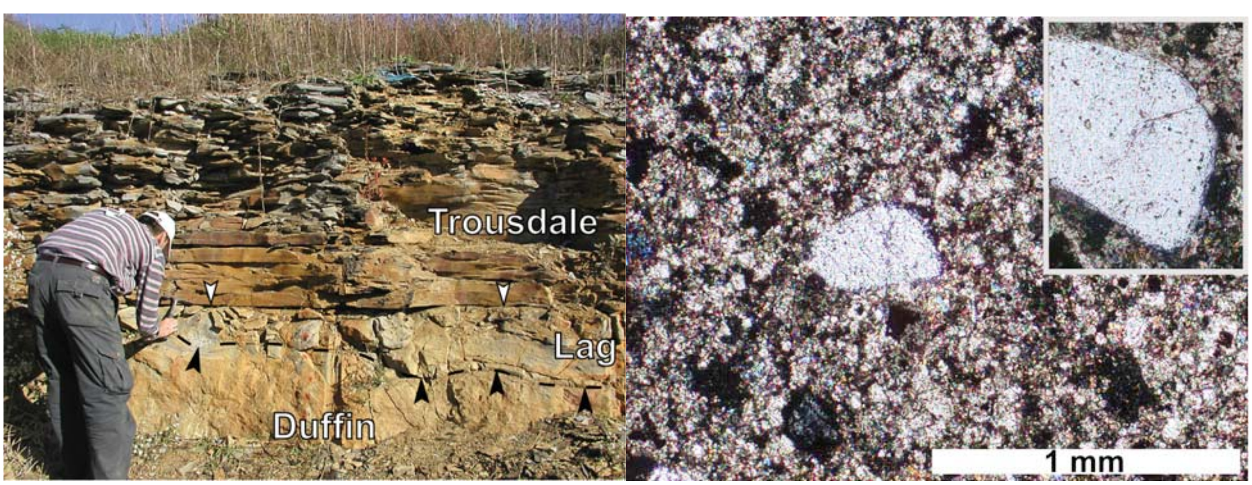


Figure 2.3.3: *Left:* Base of succession at stop 3A (south end), with buff weathering Duffin overlain by platy rusty weathering Trousdale Shale. A lag deposit (up to 40 cm thick) separates the two units. Base of lag (black arrows, dashed line) is undulose and fills in surface irregularities on the Duffin. Upper surface of lag is even and forms a sharp contact (white arrows) with overlying Trousdale. *Right:* Lag consists of abundant dolomite grains with interlocking overgrowth cement and scattered grains of chert (from silicified fossils) and well-rounded quartz sand.

Figure 2.3.4: At left, quartz-dolomite-bitumen vein (white arrow) in Trousdale contorted because of compaction.

Trousdale/Blocher: Dolomitic black shales assigned to the Trousdale/Blocher interval overlie the Duffin carbonates and are separated from them by a thick lag deposit (Fig. 2.3.3). The stark contrast between the probably shallow water (within wave base) Duffin deposits and the overlying and the deeper (but not too deep) deposited Trousdale Shale (Campbell, 1946) probably reflects sea level rise and flooding in association with the Taghanic onlap (Late Givetian, Johnson et al., 1985), a time of maximum highstand that prompted widespread dysoxic/anoxic (?) conditions and correlates with the Geneseo black shales in New York (Kirchgasser et al., 1997). The black, platy Trousdale contains phosphatic shells of inarticulate brachiopods, *Tasmanites* cysts, scattered dolomite grains, and scattered pyrite framboids and small pyrite concretions (Fig. 2.3.5). It also contains discontinuous-lenticular dolomitic laminae (a few mm thick) that consist of cemented detrital dolomite grains (silt to sand size). Bioturbation is not obvious, but subtle traces and lamina disruptions have been observed. The total thickness of Trousdale in this outcrop is approximately 2 m (varies along outcrop). The similarity between the Trousdale and the Blocher as seen at Stop 1 is readily apparent. Although the names differ between eastern and western Kentucky, it seems fairly certain that it is a contiguous unit that reaches across the Cincinnati Arch. Latest Givetian conodonts (*disparalis* Zone) have been reported from the Trousdale near Clay City, Kentucky, also supporting a Blocher-Trousdale equivalency (Brett et al., 2003) and association with Taghanic flooding.

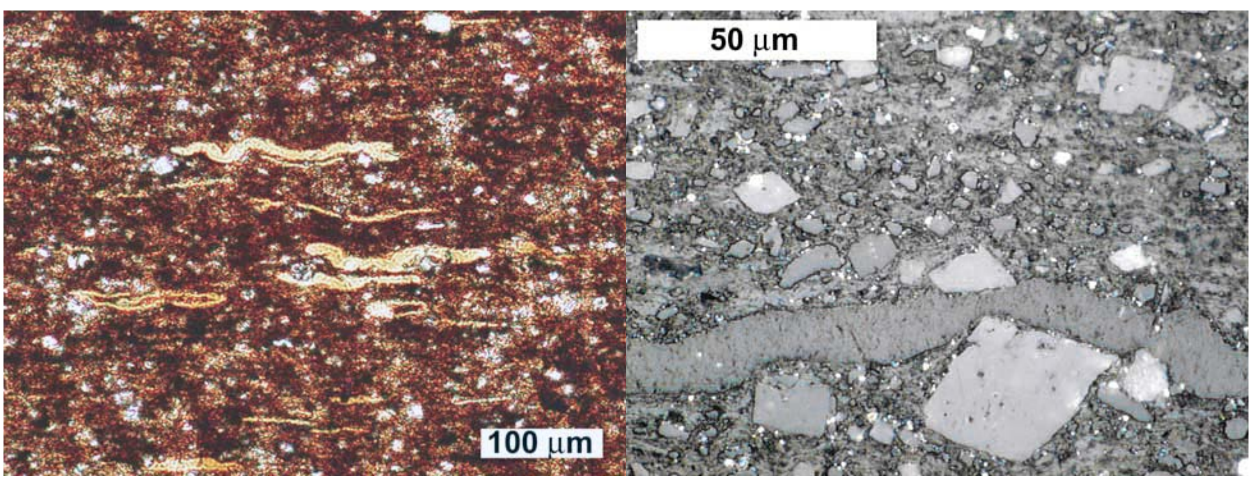


Figure 2.3.5: Photomicrographs of Trousdale carbonaceous shale. *Left:* transmitted light, shows brownish matrix of clay minerals and organic matter (kerogen). Horizontal-wavy yellowish streaks are compacted *Tasmanites* cysts, light (white) spots are dolomite grains. *Right:* reflected light, shows fine quartz silt (dark-gray irregular grains, a few microns in size), dolomite rhombs (light-gray, euhedral and tens of microns in size), and deformed *Tasmanites* in lower half. Although there is horizontal alignment of *Tasmanites*, there is no clear lamination. This suggests disruptions of initial surface stratification of the probably quite soupy sediment by surface and shallow infauna (polychaete worms, nematodes, meiofauna, etc.) that was able to tolerate low benthic oxygen levels and disrupted the sediment sufficiently to prevent preservation of “nice” primary laminae.

Although dolomite can form during diagenesis in carbonaceous shales, there is probably too much dolomite to be accounted for by extraction from overlying seawater. It is more likely that dolomite was derived from distant outcrops of underlying Middle Devonian carbonates, forming islands in the Trousdale-Blocher sea. Because the underlying relief of the pre-Trousdale erosion surface seems quite muted (judging from large exposures), one would have to conclude that the water between "islands" could not have been excessively deep. Although difficult to pin down without more detailed information, the water depth during Trousdale deposition was probably on the order of tens of meters at best. That, in essence, the same black shale facies is found from Indiana (Blocher) to eastern Kentucky (Trousdale) during the Late Givetian-Middle Frasnian time interval suggests that the later differentiation into discrete basins (Illinois versus Appalachian) was not well developed (if at all) at that time.

Middle Gassaway/Camp Run - **The highlight of this outcrop** is the next interval above the Trousdale. It consists of interbedded black shales (resistant ledges, 5 to 15 cm thick) and gray shales (soft weathering, 5 to 15 cm thick), and varies in thickness across the exposure (1.1 m at the north end, 0.6 m at the south end). In terms of facies, these shales are a very good match for the middle Gassaway (Chattanooga Shale) in Tennessee and also show considerable resemblance to the Camp Run (New Albany Shale) in cores and exposures along the outcrop belt in Indiana. Comparable shales near Liberty (20 miles south along US-127) have been examined for conodonts by Over (2002), and yielded an age that is compatible with the middle Gassaway and Camp Run intervals.

Although this interval is quite thin, it shows a most interesting feature --inclined truncation surfaces (Fig. 2.3.6) that attest to intermittent sea level drop that brought previously deposited shales within the reach of wave erosion, followed by again rising sea level and renewed shale deposition (Schieber, 1998a,b). There are at least four transgressive-regressive (TR) episodes recorded here and four prominent lag deposits that are associated with them (Fig. 2.3.7). What is curious here is that these lags sit somewhat above the actual truncation surface that marks the regressions. A possible explanation could be that these lags represent the maximum flooding surfaces of the associated TR cycles. This is somewhat counterintuitive, but has been observed elsewhere (e.g., Swift et al., 1987). It could mean that during maximum flooding, extreme sediment starved conditions allowed occasional strong storms to still leave a preservable imprint in the rock record. In this sense, these lags probably record multiple reworking episodes (amalgamation lags), a viewpoint that is supported by the observation of discontinuous shale drapes and shale streaks within samples from these lags.

Thin sections of lags show that euhedral dolomite grains that form an interlocking fabric with adjacent grains are their main component (Fig. 2.3.8). In addition to dolomite, we find glauconite pellets, abraded phosphatic bone debris, *Lingula* shells, and well-rounded quartz grains (sand size). The dolomite grains, although typically euhedral in outline, contain rounded cores of detrital dolomite (cloudy, sand to silt size) that have a clear rim of overgrowth cement (Fig. 2.3.8). Although one might at first think that the dolomite is derived from erosion of the underlying Trousdale, the grains are generally too large to be of that source. It is more likely that they were derived from "knobs" or islands of Middle Devonian carbonates (Boyle, Portwood) that projected above the Middle Gassaway/Camp Run surface and were subject to wave erosion during low stands of sea level. This particular question will probably require some careful geochemical fingerprinting for its resolution. *Lingula* shells in these lags may have been derived from the underlying Trousdale. The source of the well-rounded quartz grains is probably more distal and will, as well, require more investigation.

The observed thinning of this unit towards the south end of the outcrop is due to yet another episode of sea level drop followed by a major transgression, probably the second transgressive pulse of the IIe TR cycle of Johnson et al. (1985) (see Stop 2).

Upper Gassaway/Clegg Creek/Huron: The black shales that result from this transgressive pulse are highly enriched in organic matter and are variably known as Upper Gassaway (Tennessee/southern Kentucky), Clegg Creek (Indiana/western Kentucky), and upper Huron Shale (Ohio/northeastern Kentucky). This is also the most prolific gas-producing interval in the Devonian black shale succession. Extreme sediment starvation during maximum flooding (coincident with the *Foerstia/Protosalvinia* Zone) has locally led to highly pyritic shales that may contain up to 40 wt. percent sulfur. The erosion surface that is associated with this TR cycle is distinct and clearly visible in cores, gamma-ray profiles, and outcrops of the New Albany and Chattanooga Shales, and is a very valuable marker for sequence stratigraphic purposes. Statements made at Stop 2 with regard to the age of the Huron base apply here as well.

Figure 2.3.6: Outcrop photo of truncation surfaces in the interbedded black/gray shale interval above the Trousdale. Figure 2.3.7 (below) shows a tracing of truncation surfaces and bedding planes from a photo

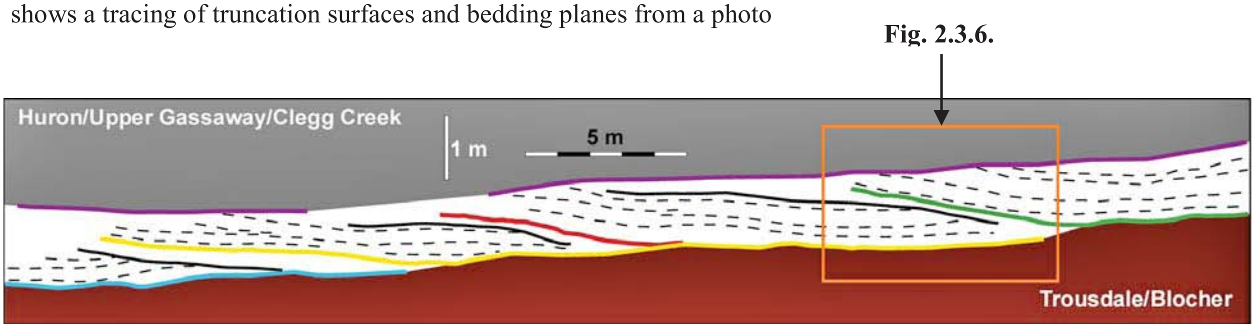


Figure 2.3.7: Truncation surfaces in the Middle Gassaway/Camp Run equivalent (vertical exaggeration by a factor of 2). Lag deposits are marked with solid colored lines, and traced beds are marked with dashed black lines. Erosion surfaces within the interval are marked with solid black lines. The basal lag is marked in blue and separates the underlying Trousdale/Blocher from the overlying Middle Gassaway/Camp Run. Three additional lags are associated with the following three TR cycles (marked in yellow, red, and green).

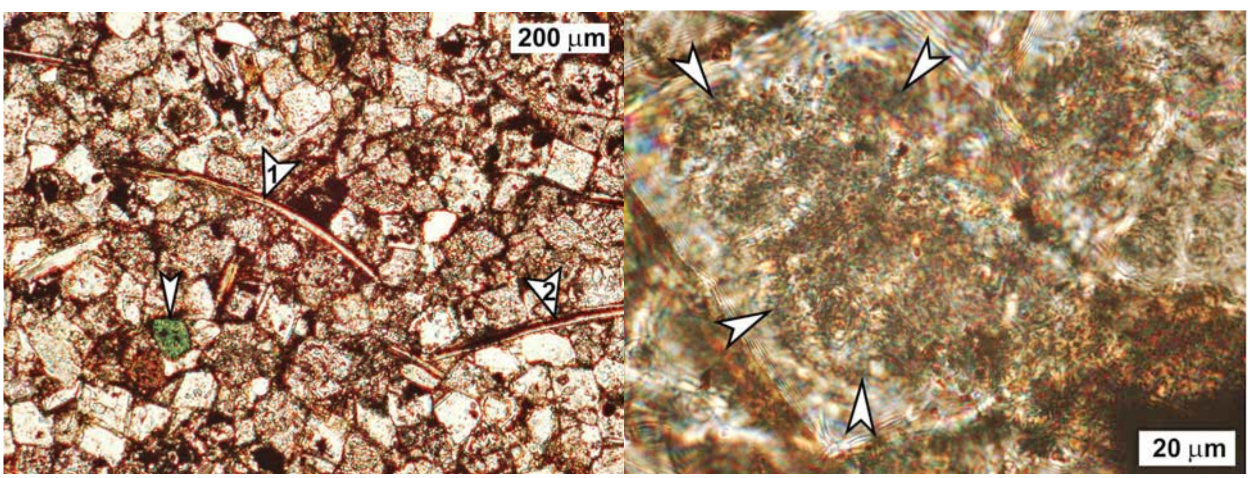


Figure 2.3.8: Photomicrographs from lag deposits in the Middle Gassaway/Camp Run interval. *Left:* Fabric overview with interlocking euhedral dolomite grains, rounded quartz grains, *Lingula* shells (arrows 1 and 2), glauconite pellets (narrow white arrow), and brownish phosphatic grains (bone debris). *Right:* Closeup of dolomite crystal that shows a cloudy detrital core (arrows) and a clear overgrowth rim with rhombohedral margins.

More than any of the other exposures that we have seen today, this one vividly and unmistakably drives home these messages:

1) Intermittent erosion does occur in Devonian black shale successions.
2) This is due to lowering of sea level.
3) These erosion surfaces can be the basis for sequence stratigraphic subdivision.
4) Sequences in black shales do not have to be very thick.

As a case in point, in the Camp Run/Middle Gassway interval of this outcrop, we have four sequences over a vertical distance of about one meter, indicating that only detailed analysis of cores and outcrops will be able to resolve these important stratigraphic markers. In the context of this outcrop (Fig. 2.3.2), the associated parasequences may well be the black/gray couplets that make up the succession between erosion surfaces.

It is also worth noting that at some distance from the Cincinnati Arch, in western Indiana, the Camp Run is quite a bit thicker (measures on the order of 10 meters or more as compared to barely a meter at Stop 3A) and lacks obvious erosion surfaces. This is evidently a reflection of deeper water conditions in Indiana that reduced the likelihood that shales suffered serious wave erosion during sea level drops. One can, however, (with some imagination) see multiple depositional cycles (at least three) in the Camp Run of Indiana, probably a distal reflection of the sea level changes that caused erosion in Cincinnati Arch locations.

Stop 3B: We already passed this exposure on our way down from Junction City (Fig. 2.3.1). It represents the upper portion of the Devonian black shale section at this location. The outcrop is a continuation of the succession seen at Stop 3A and slightly overlaps with it at road level (the match-up was done with gamma-ray profiles).

Huron Shale: What we see here at the base are a few more feet of massive Huron (high radioactive interval) that pass upwards into less resistant shales that weather in a characteristic ribbed fashion. This "ribbing" is due to periodic changes in clay and organic matter content (high clay = softer weathering; high TOC = harder weathering) that probably reflects climatic cycles (Jaminski et al., 1998). The resulting couplets of softer and harder shale are in this location a decimeter or less in thickness, but further east (for example in exposures on I-64 west of Morehead, Kentucky) they measure in decimeters and the respective interval can be hundreds of meters thick. The difference is a reflection of higher sedimentation rates in the Appalachian Basin and smaller sedimentation rates on the Cincinnati Arch.

Three Lick Bed: This outcrop also shows the Three Lick Bed that we saw at Stop 2B in the upper third of the exposure. The Three Lick Bed is thinner now and the gray shale beds are less pronounced, again a reflection of smaller sedimentation rates on the Cincinnati Arch. Like elsewhere in Kentucky and Ohio (Walker Hellstrom and Babcock, 2000), the Three Lick Bed is also marked by a sharp drop in gamma-ray activity (Fig. 2.3.2).

Cleveland Shale equ.: Above the Three Lick Bed follows again a more massive weathering black shale interval that we consider correlative with the Cleveland Shale of Ohio. It is the uppermost Devonian black shale unit in the Appalachian Basin and partial laterally equivalents occur in the Upper Gassaway Member of the Chattanooga Shale in Tennessee and southern Kentucky. Whether its lateral equivalents are also preserved at the top of the New Albany Shale is presently not known.

3. Accompanying Papers

3.1. New Albany and Ohio Shales: An Introduction

by
Remus Lazar and Juergen Schieber

The Middle to Upper Devonian black shales of the eastern U.S. are part of an epicontinental succession that was deposited over vast areas of the North American craton (de Witt et al., 1993) during a time characterized by a general rise in sea level (Johnson et al., 1985), atmospheric decline in pCO_2 (Berner, 1990), and major diversity change and extinction in biota. In particular, the Frasnian-Famennian mass extinction event is considered one of the five greatest biotic crises of the Phanerozoic (Sepkoski, 1986; Scotese and McKerrow, 1990; Jablonski, 1991; McGhee, 1996; Hallam and Wignall, 1999; House, 2002). During this time, eastern portions of North America were located approximately between 15^0 and 30^0 south latitude (Scotese and McKerrow, 1990; Ettensohn, 1992a; Day et al., 1996). As relative sea level rose, flooded continental areas of the eastern U.S. became parts of shallow seas where muds accumulated and became shales such as the New Albany Shale of the Illinois Basin and the Ohio Shale of the Appalachian Basin.

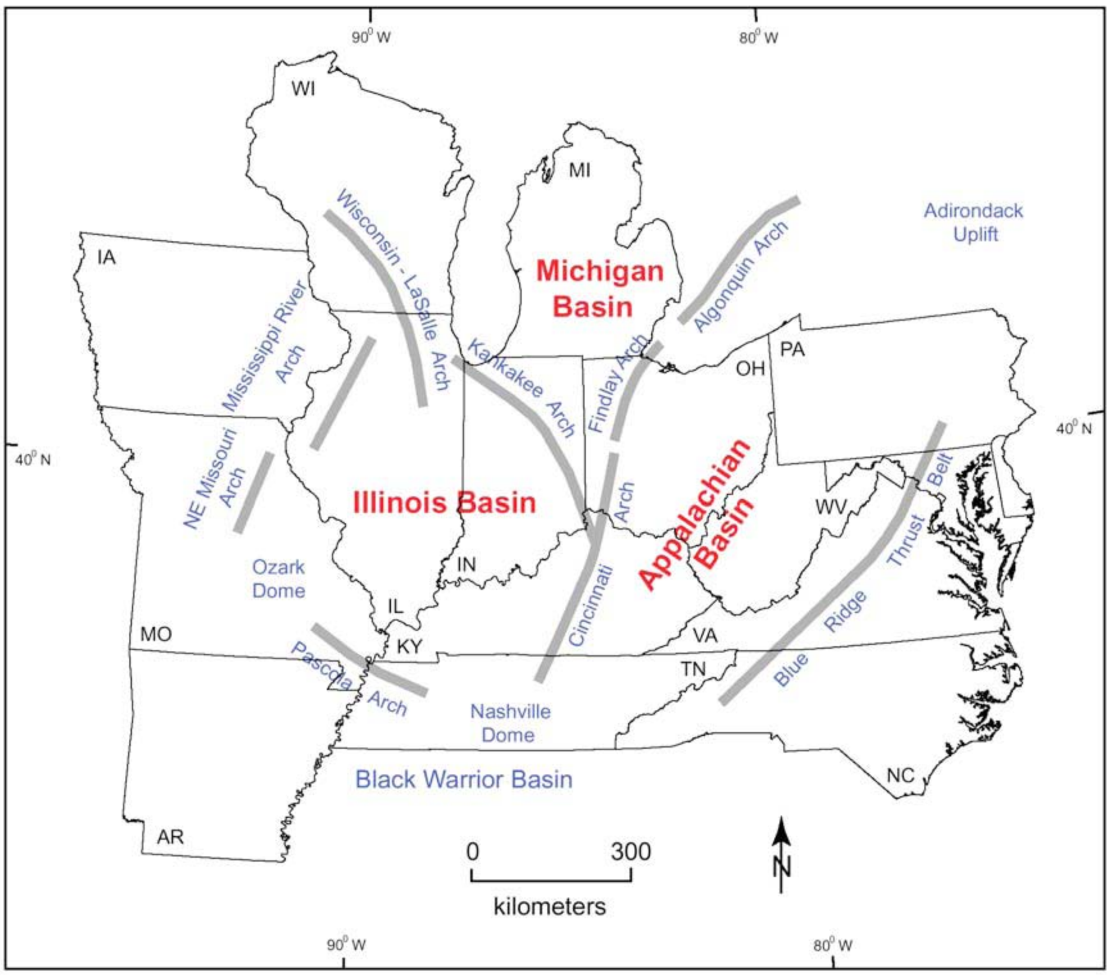


Figure 3.1.1: Major structural features outlining the Illinois and Appalachian Basins (modified after Kepferle and Roen, 1981; Buschbach and Kolata, 1991; Ettensohn, 1992a; de Witt et al., 1993; Mathews, 1993; Lumm et al., 2000).

The New Albany Shale
The Middle to Upper Devonian New Albany Shale occurs in outcrops and in the subsurface throughout much of the Illinois Basin (Lineback, 1968, 1970; Hasenmueller and Comer, 2000). The Illinois Basin formed primarily during

the Paleozoic Era (Buschbach and Kolata, 1991; Kolata and Nelson, 1991) and began as a rift complex that gradually evolved into a cratonic embayment (Buschbach and Kolata, 1991). Subsequent modification by major tectonic events led to structural closure and to the present geometry of the basin (Buschbach and Kolata, 1991). Today, the Illinois Basin covers approximately 60,000 mi^2, mostly in parts of Illinois, Indiana, and Kentucky (Fig. 3.1.1) (Barrows and Cluff, 1984; Lumm et al., 2000). It is bounded by the Cincinnati Arch in the east, the Kankakee Arch in the northeast, the Wisconsin-LaSalle Arch in the north, the Mississippi River Arch in the northwest, the NE Missouri Arch and the Ozark Dome in the west, and the Pascola Arch in the south (Fig. 3.1.1). The southern part of the Illinois Basin covers the northeastern tip of the New Madrid Rift Complex (Lumm et al., 2000).

The name New Albany was proposed by Borden (1874) for the shale exposures along the Ohio River at New Albany, Floyd County, Indiana (cf. Lineback, 1968). Huddle (1933, 1934) and Cross and Hoskins (1951) were among the earliest authors to describe the fauna and flora present in the New Albany Shale. Based on a combination of fossil content, lithology, and joint patterns, Campbell (1946) proposed the first detailed stratigraphic subdivisions of the New Albany Shale. Campbell's stratigraphy was significantly revised by Lineback (1964, 1968, and 1970). The New Albany Shale has received increasing attention after 1970 with studies addressing questions regarding shale stratigraphy (e.g., Ettenson 1992a; Roen, 1993; Sandberg et al., 1994; Over, 2002), geochemistry (e.g., Beier and Hayes, 1989; Hatch et al., 1991; Ingall et al., 1993; Calvert et al., 1996; Frost and Shaffer, 2000), environment of deposition (e.g., Cluff, 1980; Ettensohn and Barron, 1981; Schieber and Riciputi, 2004), and hydrocarbon potential (e.g., Cluff and Byrnes, 1991; Seyler and Cluff, 1991; Hamilton-Smith et al., 2000).

Considerable stratigraphic variability characterizes the New Albany Shale throughout the Illinois Basin. In southeastern Indiana, for example, the New Albany Shale unconformably overlies the Middle Devonian North Vernon Limestone (Fig. 3.1.2) and is subdivided into five members (Blocher, Selmier, Morgan Trail, Camp Run, and Clegg Creek in ascending order). A phosphatic lag, usually less than 10 cm thick (the Falling Run Bed; Campbell, 1946), occurs at the top of the Clegg Creek Member. Early Mississippian, fossiliferous, gray, and brownish-black shales (the Underwood, Henryville, and Jacobs Chapel Beds; Campbell, 1946), less than 1 m thick, overly the Falling Run Bed (Fig. 3.1.2). Locally, these beds are absent and the Clegg Creek Member is directly overlain by the Mississippian Rockford Limestone. Where the Rockford Limestone is absent, the Clegg Creek Member is overlain unconformably by the Mississippian New Providence Shale (Fig. 3.1.2) (Lineback, 1970). The lag deposit at the top of the Clegg Creek Member (Falling Run Bed), followed by Mississippian strata, marks a regional truncation surface that is recognized in Indiana, Kentucky, and Tennessee and separates Upper Devonian from Early Mississippian strata. Although the Early Mississippian package of Falling Run through Jacobs Chapel Beds has traditionally been included in the New Albany Shale, from a genetic (sequence stratigraphic) perspective the top of the New Albany Shale should be redefined to coincide with the top of the Clegg Creek.

The New Albany Shale reaches more than 90 m in thickness in parts of southeastern Illinois, western Kentucky, and southwestern Indiana, as well as in west-central Illinois (Lineback, 1970; Barrows and Cluff, 1984; Hasenmueller et al., 2000). The shale thins towards the basin margins where it can be less than 30 m in thickness (Lineback, 1970).

Generally speaking, the New Albany Shale consists of dark-colored, organic-rich (up to 20 percent TOC; Type II kerogen), laminated, banded, or bioturbated shales, and lighter-colored and rather organic-poor (less than 2 percent TOC; Type III kerogen) bioturbated shale (e.g., Lineback, 1968, 1970; Barrows and Cluff, 1984; Ingall et al., 1993; Calvert et al., 1996; Frost and Shaffer, 2000; Lazar and Schieber, 2003). Beds of siltstone, sandstone, limestone, and dolostone are also present, but they are limited in extent and thickness (Lineback, 1968). Analyses of the isotopic composition of organic matter in the shales of the Camp Run Member show that, on average, $\delta^{13}C_{org}$ values are 1.9‰ lighter in the laminated intervals (-29.17‰) than in the bioturbated intervals (-27.30‰; Calvert et al., 1996). This suggests either a larger input of terrestrial organic matter in the latter intervals (Calvert et al., 1996), or (more likely) a difference in diagenetic alteration of organic matter between laminated and bioturbated intervals (preferential loss of ^{13}C from laminated intervals, enrichment of ^{13}C in bioturbated intervals; Calvert et al., 1996). Increasing carbon content in the laminated shales is traditionally considered to indicate increasingly anoxic depositional environments (e.g., Barrows and Cluff, 1984; Calvert et al., 1996; Frost, 1996). The New Albany Shale is enriched in trace metals, especially towards the top of the formation (Shaffer et al., 1983; Ripley et al., 1990; Calvert et al., 1996; Frost and Shaffer, 2000; Lazar and Schieber, 2003).

Illite is the dominant clay mineral, and chlorite and expandable clays are present in varying but smaller proportions (Lineback, 1968; Frost and Shaffer, 2000). Illite was found more abundant relative to chlorite in the bioturbated shale compared with the laminated intervals of the Camp Run Member (Calvert et al., 1996). Quartz, calcite, dolomite, and pyrite are other main components of the mineral fraction (Lineback, 1968; Frost and Shaffer, 2000). Pyrite occurs in several different forms including framboids and very fine and closely spaced pyritic laminae (Frost and Shaffer, 2000; Lazar and Schieber, 2003).

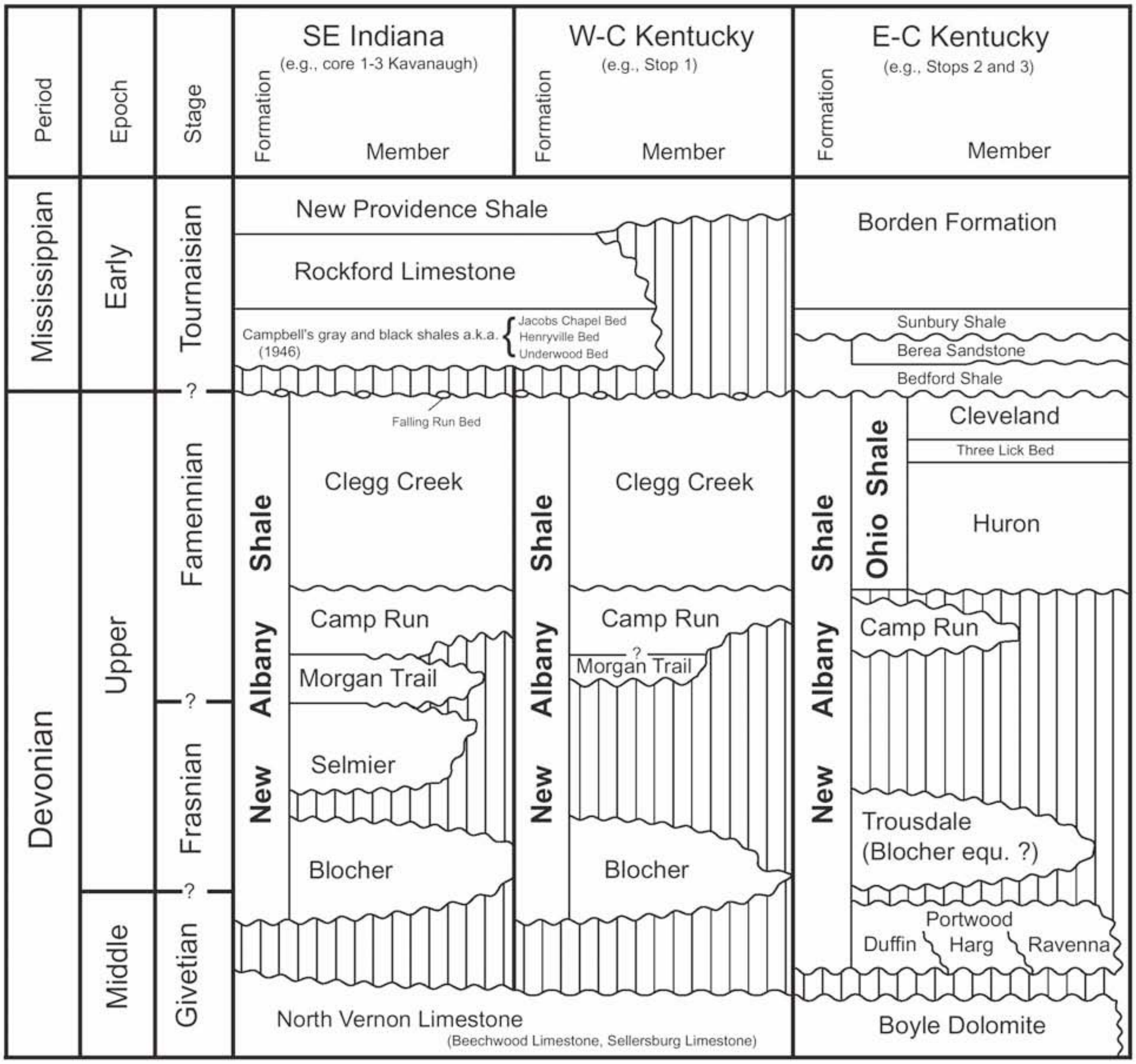


Figure 3.1.2.: Middle Devonian-Early Mississippian stratigraphy in southeastern Indiana, west-central Kentucky, and east-central Kentucky. Thickness not to scale (modified after Campbell, 1946; Lineback, 1970; Provo et al., 1978; Kepferle and Roen, 1981; Ettensohn et al., 1988b; Ettensohn, 1992a; Hamilton-Smith, 1993; Brett et al., 2003).

Tasmanites, *Foerstia (Protosalvinia*), logs of *Callixylon*, conodonts, brachiopods, pteropods, arthropods, and fish fossils have been found in the New Albany Shale (e.g., Huddle, 1933, 1934; Lineback, 1968, 1970; Niklas, 1976; Cluff, 1980; Sandberg et al., 1994; Over, 2002; Lazar and Schieber, 2004). *Foerstia (Protosalvinia*) occurs in the Clegg Creek Member of the New Albany Shale and is a useful biostratigraphic marker for correlation of the New Albany Shale with laterally equivalent Devonian black shales of the Appalachian and Michigan Basins (e.g., Kepferle, 1981; Hasenmueller et al., 1983; Roen, 1993). Trace fossils, including *Zoophycus*, *Chondrites*, and *Planolites*, have been identified in or just below the light-colored shale intervals (e.g., Lineback, 1968, 1970; Cluff, 1980).

Ohio Shale

The Upper Devonian Ohio Shale occurs in outcrops and in the subsurface in the western portion of the Appalachian Basin (Ettensohn et al., 1988a,b; Ettensohn, 1992a; de Witt et al., 1993). The Appalachian Basin is a foreland basin that developed during the late Proterozoic and Paleozoic (Ettensohn, 1992a; Roen, 1993). Northeast-trending, the basin is elongate and asymmetrical, approximately 1,500 km in length, and less than 150 km (Tennessee) to about 500 km (southeastward across Ohio to Virginia) in width (Fig. 3.1.1) (Roen, 1993). It extends from the Adirondack Uplift in the north to the Black Warrior Basin in the south. Along the northwestern border, the Appalachian Basin is separated from the Michigan Basin by the Findlay and Algonquin Arches (Ettensohn, 1992a; Roen, 1993) (Fig. 3.1.1). To the west, the Cincinnati Arch separates the Appalachian Basin from the Illinois Basin, whereas to the east, the Appalachian Basin is bordered by a belt of metamorphic and igneous rocks of the Blue Ridge Thrust Belt (Fig. 3.1.1) (Ettensohn, 1992a; Roen, 1993).

The Middle Devonian-Early Mississippian shales of the Appalachian Basin in Kentucky have been studied since the middle of the nineteenth century (cf., Pollock et al., 1981). East of the Cincinnati Arch, in the east central part of Kentucky, the name “Ohio Shale” is commonly used for the shale interval of Upper Devonian age (e.g., Provo et al.,1978; Pollock et al., 1981; Ettensohn, 1992a; de Witt et al., 1993). The Ohio Shale comprises the bulk of the Middle Devonian-Early Mississippian shale succession and is the only one that occurs over a large area (Kepferle et al., 1982; Ettensohn, 1992a; Hamilton-Smith; 1993). It consists of the Huron Member, the Three Lick Bed, and the Cleveland Member (Fig. 3.1.2) (Provo et al., 1978; Ettensohn et al., 1988a; Ettensohn, 1992a; de Witt et al., 1993), and overlies various locally occurring Middle Devonian to early Upper Devonian units (e.g., Boyle, Portwood, Dowelltown) (Pollock et al., 1981; Ettensohn et al., 1988a; Ettensohn, 1992a; de Witt et al., 1993) (Fig. 3.1.2). The complexity of the lower part of the black shale succession is a result of multiple erosive interludes that removed some units partially or entirely, and its correlation to units in the Illinois Basin is still tenuous and in flux. The Ohio Shale is overlain by the Early Mississippian Bedford Shale, Berea Sandstone, and Sunbury Shale (Fig. 3.1.2) (Hamilton-Smith, 1993). In south central Kentucky and in Tennessee the entire sequence is called the Chattanooga Shale (Jordan, 1985; Hamilton-Smith, 1993; Schieber, 1998b). The entire black shale sequence thins from nearly 560 m in the eastern part of Kentucky to less than 10 m on the crest of the Cincinnati Arch in south central Kentucky (Ettensohn et al., 1988a).

Generally, the Ohio Shale consists of grayish-black, brownish-black, and black shale; beds of gray shale are more commonly cited in the lower Huron Member and the Three Lick Bed of the Ohio Shale. A few beds of limestone, up to 10 cm in thickness, may also be present (Provo et al., 1978; Pollock et al., 1981; Ettensohn et al., 1988a; de Witt et al., 1993). Organic-carbon content, concentration in heavy elements, and abundance in phosphate and pyrite nodules increase towards the top of the Ohio Shale (Ettensohn and Barron, 1981; Pollock et al., 1981; Ettensohn et al., 1988a; Moody et al, 1988; Rimmer, 2004).

Although it contains the same range of lithologies as the New Albany Shale, overall organic-carbon contents are lower in the Ohio Shale (Maynard, 1981; Curtis, 2002). The average organic-carbon content and the amount of Type II kerogen of the black shale sequence increases westward, whereas the amount of Type III kerogen, presumably derived from organic matter of terrestrial plants of the Appalachian source area, increases eastward (Maynard, 1981; Roen, 1984; Hamilton-Smith, 1993). Analyses of the isotopic composition of organic matter show that, on average, $\delta^{13}C_{org}$ values are lighter in the Three Lick Bed (-27.4‰) when compared to the Huron Member (-29.3‰) and the and Cleveland Member (-28.9‰) (Maynard, 1981). The Ohio Shale contains a higher proportion of clays than the New Albany Shale (Hosterman and Whitlow, 1983; Frost and Shaffer, 2000). Quartz, calcite, dolomite, and pyrite are the most common authigenic minerals (Ettensohn et al., 1988a). Pyrite most commonly occurs as framboids, nodules, and lenses (Ettensohn et al., 1988a).

Tasmanites, *Foerstia (Protosalvinia*), logs of *Callixylon*, conodonts, brachiopods, fish fossils, as well as trace fossils (*Zoophycus*, *Chondrites*, *Planolites*, *Cruziana*, *Teichichnus,* and *Rhizocoralium)* have been described from the Ohio Shale (e.g., Cross and Hoskins, 1951; Schopf and Schwietering, 1970; Niklas, 1976; Barron and Ettensohn, 1981; Jordan, 1985; Ettensohn et al., 1988a; Savrda, 1991; Ettensohn, 1992a; Roen, 1993; Over, 2002; Brett et al., 2003).

3.2. Sequence Stratigraphy of Highly Variable Middle Devonian Strata in Central Kentucky: Implications for Regional Correlations and Depositional Environments

by
Carlton E. Brett[1], Gordon C. Baird[2] and Alexander J. Bartholomew[1]
[1] Department of Geology, University of Cincinnati, Cincinnati, Ohio 45221-0013
[2] Department of Geosciences, SUNY College at Fredonia, Fredonia, New York 14063

INTRODUCTION

A central issue in stratigraphy is the explanation of rapid lateral changes in strata. Abrupt lateral changes in strata are commonly interpreted as recording somewhat chaotic internal mosaics of facies. While this is a part of the explanation, especially in nearshore or paralic facies, rapid changes in thickness and facies are more problematic in offshore to basinal facies, for which spatially widespread conditions are generally to be expected. Such patterns seemingly imply that through-going depositional sequences are absent in these units and suggest an overriding effect of local, tectonic, or autocyclic effects. However, additional factors may be at play: lateral changes may also result from complex patterns of truncation of originally more continuous successions. Such is the case in the offshore carbonates and dark shale facies, such as those represented in the Middle Devonian strata considered herein.

Middle Devonian rocks exposed in central Kentucky have a long history of study. Early workers including Linney (1882), Girty (1898), and Foerste (1906), documented the faunas and stratigraphy of these rocks in considerable detail. Seminal work of Guy Campbell (1946) laid the groundwork for a detailed synthesis of the New Albany black shale succession in southern Indiana, Kentucky, and elsewhere. More recent work on these rocks includes studies of stratigraphy and bone beds (Conkin et al., 1973, 1976), diagenesis (Johnson, 1980), depositional environments (Stephenson, 1979), syntectonic sedimentation (Ettensohn, 1987, 1992a,b, 2004; Barnett and Ettensohn, 1992), trace fossils (Jordan, 1979), and conodonts (Runge, 1959; Pieracacos, 1983; Pieracacos and Helfrich, 1984).

One of the key problematic issues in the Middle Devonian succession of central Kentucky that has been acknowledged for many years is the extreme variability of the units. Seemingly, no two outcrops of the Middle Devonian Boyle Formation and Portwood Member (basal New Albany or Ohio Formation) in central Kentucky are alike and this has frustrated correlation and sequence stratigraphic interpretation. We have recently attempted to resolve some of these issues by detailed comparative study of numerous excellent outcrops including newly modified roadcuts in central Kentucky. A new picture of these strata is emerging that involves substantial local erosional truncation of units at no less than five distinct surfaces. These beds also show evidence of disturbance probably as a result of seismic activity on nearby faults and/or slumping of shales and thin carbonates of the Portwood Member into sinkholes on the underlying Boyle Formation.

STUDY AREA

The present study is confined to the region of exposure of Middle Devonian rocks in central Kentucky east of the Cincinnati Arch (Fig. 3.2.1), in Madison, Estill, Powell, and Clark Counties (Fig. 3.2.2). This succession is particularly well exposed in a series of recently improved roadcuts along Kentucky Rte. 52 between Waco and Irvine, Kentucky, in sections along Kentucky Rte. 89 from Irvine north to Mina, and again on Kentucky Rte. 15 and the adjacent Mountain Parkway (Bert Combs Highway) north of Clay City.

GENERAL STRATIGRAPHY OF THE MIDDLE DEVONIAN

This report deals primarily with two major units of the Middle Devonian in Kentucky, the Boyle Formation a sandy skeletal limestone and cherty dolostone, and the Portwood Member of the New Albany (or Ohio) Shale (Figs. 3.2.3, 3.2.4). The Boyle rests with profound unconformity on beds of Early Silurian to Late Ordovician age; this is a local manifestation of the Wallbridge Unconformity (Sloss, 1963). Both the Boyle and Portwood are Givetian age on the basis of conodont biostratigraphy, although they are separated by an erosional unconformity, probably equating with the Taghanic unconformity of the Appalachian Basin. In the following sections, various aspects of this unusual succession and its unconformities are explored.

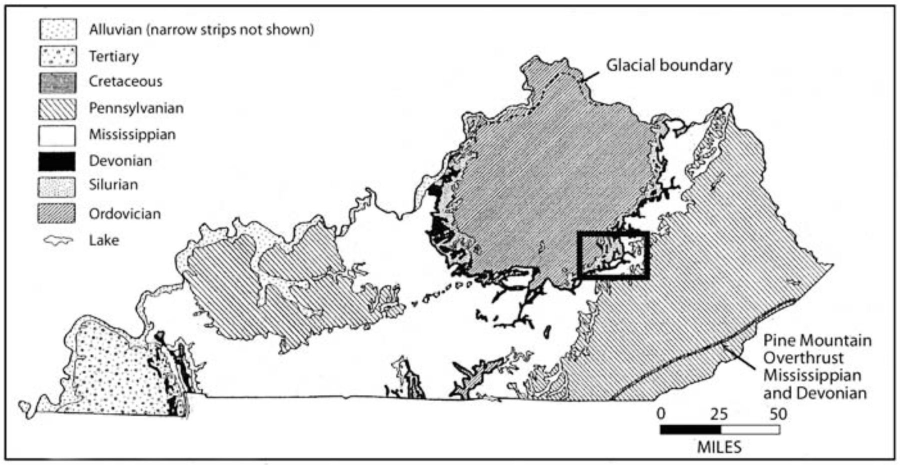


Figure 3.2.1: Simplified geologic map of Kentucky showing the Devonian outcrop belt around the south end of Cincinnati Arch (Jessamine Dome). Box shows study area of this report. After McGrain (1975).

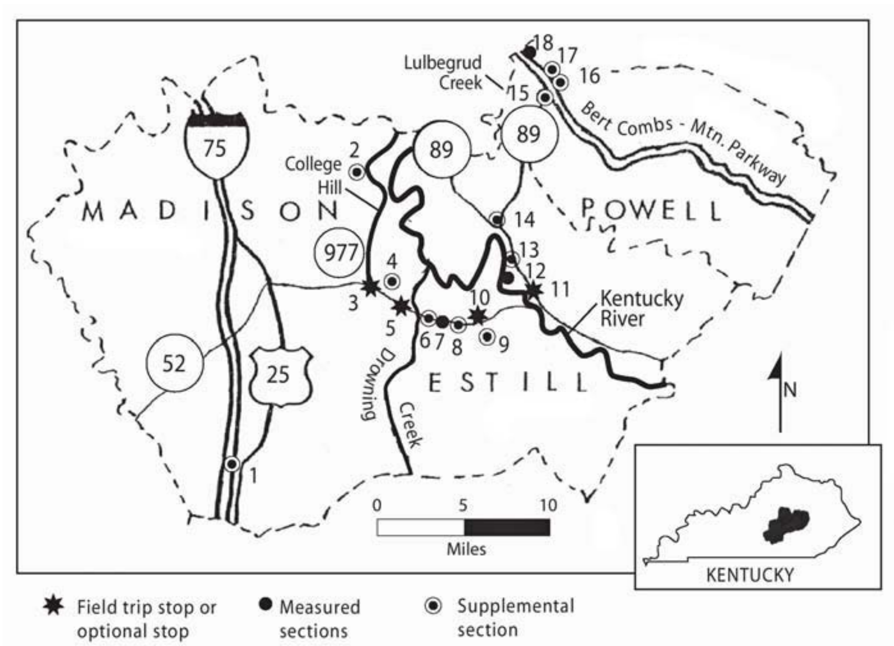


Figure 3.2.2: Location map for studied Middle Devonian Boyle and Portwood (lower Ohio-New Albany Formation) sections in Madison, Estill, and Powell Counties, central Kentucky. Localities listed by number include: 1) I-75 exit ramp cuts at Berea, Kentucky (now covered); 2) section at the junction of Rte. 977 and Cain Springs Road, ~5 miles north of College Hill; 3) cuts along both sides of KY Rte. 52, 0.2 miles east of Rte. 977 at Waco; 4) Bybee (type Portwood; former McLaughlin farm); 5) newly enlarged cut on north side of Rte. 52, 1.2 miles west of Drowning Creek (Madison-Estill County line); 6) cuts on both sides of Rte. 52, 0.9 miles east of Drowning Creek, near Winston Road; 7) weathered cut on north side of Rte. 52, 1.3 miles east of Drowning Creek; 8) cut on south side of Rte. 52 1.5 miles east of Drowning Creek; 9) cut on abandoned county road near Rice Station; 10) cut on north side of Rte. 52 opposite Emmanuel Baptist Church, 3.9 miles west of Kentucky River bridge in Irvine; 11) railroad cut along north bank of Kentucky River immediately west of bridge/overpass of Rte. 52/89; 12) new cut on Rte. 499, 0.5 miles west of junction with Rte. 89; 12) cuts behind Estill County Middle School and on Rte. 89 immediately to the north; 13) cut on west side of Rte. 89, 0.4 miles north of Calloway Creek and 4 miles north of bridge in Irvine; 14) cut along railroad track just NE of junction of Rtes 89 and 82, Hargett (type Harg); 15) cut on Rte. 15 north of junction with Rte. 82; 16, 17) cuts along N side of Bert Combs Mountain Parkway, northwest of entrance ramp off Rte. 82 near Clay City; 18) cut along Mountain Parkway just SE of bridge over Lulbegrud Creek, Powell/ County line. Modified from Pieracacos (1983).

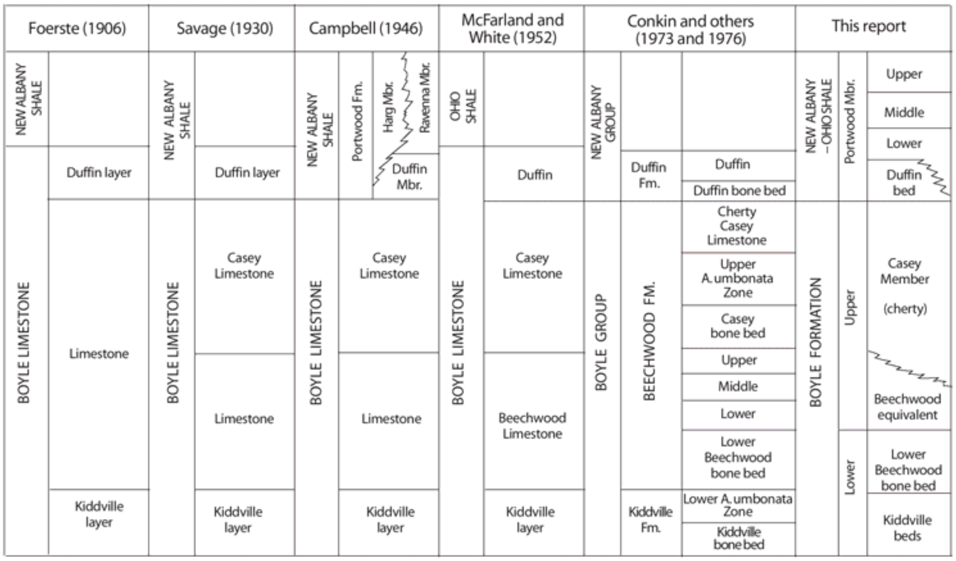


Figure 3.2.3: Summary of terminology used in this paper in relation to that of previous authors.

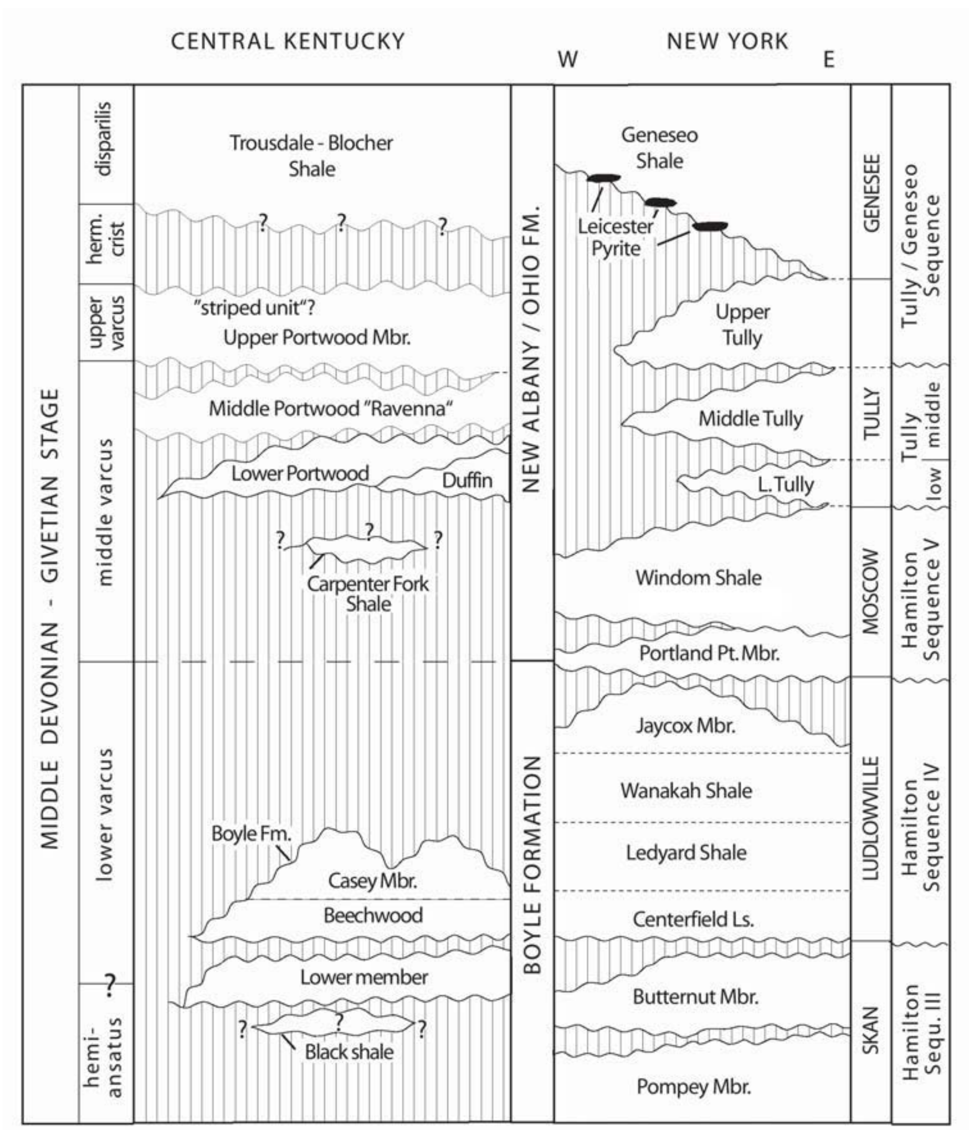


Figure 3.2.4: General stratigraphy and age relations of the Middle Devonian Boyle and Portwood Formations in central Kentucky and correlative succession in type Hamilton-Tully area in New York State. Abbreviations: *herm. crist*. =*hermanni-cristatus* Zone; vertical bars indicate unconformities.

Basal Devonian Unconformity

The basal contact of the Devonian is sharp and unconformable, and rather complex, representing the confluence of the Wallbridge unconformity (base of Sloss's (1963) Kaskaskia megasequence), as well as several lesser, but still significant disconformities. In outcrops this contact generally appears nearly planar with little relief (Fig. 3.2.5). However, in a few locations, near Irvine, Estill County, Kentucky (loc. 11), remnant mounds or "hills" of middle Silurian strata, and blocks of crinoidal grainstone, previously identified as Silurian Bisher Formation, extend upward several meters into the New Albany (Fig. 3.2.6) (McFarlan et al., 1944). The Bisher is otherwise absent in this area, having been cut out by the Wallbridge Unconformity and how these erosional remnants could have persisted for nearly 40 million years is unknown. Hoge et al. (1976) expressed some reservations as to the identity of these grainstones and we are also uncertain that these blocks and remnants belong to the Bisher Formation. The cherty Casey Member of the Boyle Formation was observed to drape and/or lap out against these bedrock highs (McFarlan et al., 1944), but we note that the lithologies of these remnants also resemble the crinoidal grainstone facies of the Boyle itself and that the mounds may be Middle Devonian facies internal to the Boyle (Fig. 3.2.6).

Varied units occur above the Silurian Estill Shale contact in the study area. In most cases, sandy dolostones or dolomitic shales, assigned to the Kiddville Bed (or submember) of the Boyle, rest sharply on soft green claystones of the Silurian Estill Formation, although in the area near Waco and Bybee, the Boyle and all subjacent Devonian units are absent and the younger Portwood Formation directly overlies the unconformity (Figs. 3.2.5, 3.2.10, 3.2.16).

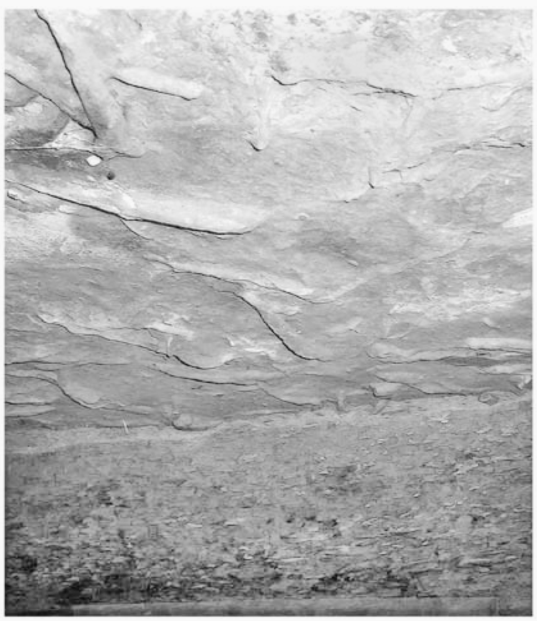
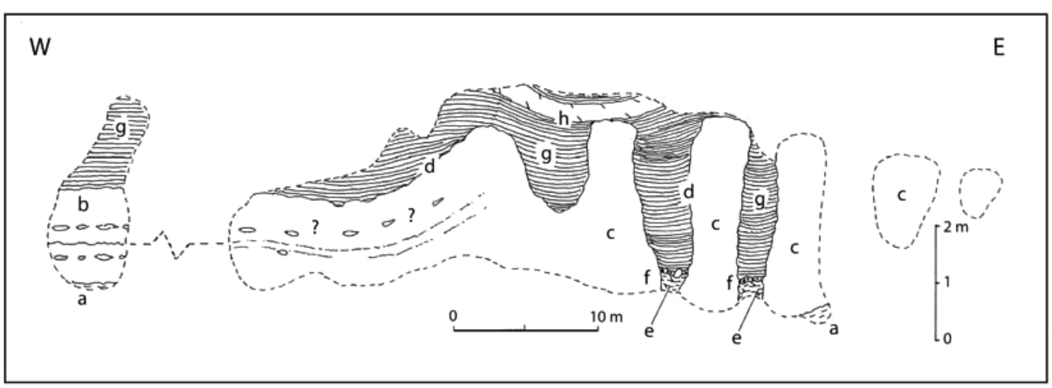


Figure 3.2.5: Hypichnial burrow casts along basal bed of lower Portwood unit in sharp, but planar unconformity on fossiliferous Silurian Estill Shale. Note that the Boyle is entirely missing at this locality, although it is nearly 8 m thick less than a mile to the east. The burrows were made into a mud 40 million years older than the sediment that fills them; type Portwood section on unnamed creek near entrance to former McLaughlin farm off Waco loop Road; Bybee (Portwood; loc. 4).

Figure 3.2.6 (below): Diagrammatic interpretation of black shales and dolostones of Portwood Member, New Albany Shale, draped over irregular contact on blocks of karstified crinoidal grainstone. From railroad cut along north bank of Kentucky River, Irvine (loc. 11), lettered units include: a) Silurian Estill (Crab Orchard) Shale; b) normal cherty facies of the Boyle Formation, Casey Member; c) karstified crinoidal grainstone (here interpreted as crinoidal shoal facies of the Boyle, but previously referred to as the Silurian Bisher Formation); note that this unit forms columns and blocks that are surrounded by black shales of the Portwood Member; limestone also appears to be draped by cherty Casey Member; d) sharp karstified surface of limestone in contact with black shale; e) silty dolomitic shale at bottom of pockets; possible lower Portwood division; thin, sandy bone bed with pebbles of carbonates; g) black laminated shale ("Ravenna facies") of middle Portwood which is draped in hollows between blocks and pillars of limestone; note near pinchout of this unit over highs; h) buff, dolomicrite of upper Portwood division.



Lower Boyle: Kiddville Beds

A series of thin carbonate and shale units can be recognized in most outcrops below the main massive, cherty to crinoidal portion (= "Casey Member") of the Boyle Formation, discussed below (Figs. 3.2.7, 3.2.8). As yet, these beds are not biostratigraphically well dated, although macrofossils, including placoderm fish plates, indicate that they are Middle Devonian. Previous authors have assigned these units to the Boyle, although they are lithologically distinct. The section immediately underlying the main Boyle Formation is the most consistent and provides a frame of reference for tracking changes in under- and overlying strata (Figs. 3.2.7, 3.2.8).

In northeastern outcrops of the Boyle near Kiddville (Indian Fields), Clay City, and Irvine areas, the massive, cherty upper Boyle dolostone ("Casey Member") is everywhere underlain by 7 to 15 cm of dark-brownish-gray silty shale with phosphatic nodules. This shale shows a sharp, irregularly burrowed contact with the overlying Boyle dolostone and is gradationally underlain by a massive, sandy glauconitic dolostone bed, about 30 to 40 cm thick, that contains rather common silicified fossils in its upper third and a flaser-like laminae in the lower portion. Phosphatic nodules and placoderm fish bones are common in this bed, which was termed the "Kiddville Bed" or "bone bed" by Linney (1882; see also Conkin et al., 1973, 1976).

The Kiddville Bed commonly forms the base of the Boyle Formation and the lowest unit of the Devonian (Conkin et al., 1973, 1976). However, in sections near Irvine, Estill County, Kentucky, additional units intervene between the Silurian and the Kiddville Bed (Figs. 3.2.7, 3.2.8). Here, the Kiddville layer sharply overlies a lower shaly zone, which, near Irvine, carries lenses of chertified brachiopods belonging to the Middle Devonian species *Ambocoelia* cf. *A. umbonata* (Fig. 3.2.9A). In locations north of Irvine, a thicker interval of black shale up to 15 cm thick, is preserved at this position (Fig. 3.2.7). This shale is underlain, in turn, by a 20- to 25-cm bed of burrowed, glauconitic sandy dolostone. In the roadcut on Rte. 52 opposite Emmanuel Baptist Church (loc. 10; Fig. 3.2.8), this bed shows prominent hypichnial burrow casts on its base, where it rests on about 37 to 40 cm of black, sandy shale that overlies Silurian Estill Shale at a sharp contact. The age of this shale is unknown at present, but it may be allied with other thin tongues or partings of dark shale within the lower Boyle. Finally, in roadcuts on Rte. 89, 3.5 to 10 miles north of Irvine, still lower (older), cherty dolomitic carbonates occur below a thinner remnant of this shale (Fig. 3.2.7). This complex of units is poorly understood and is under study. At least the upper shale, with *Ambocoelia*, is Middle Devonian, but lower units are not dated, although the presence of placoderm armor fragments indicates a Devonian rather than Silurian age.

In sections to the west of Rice Station (loc. 9), the basal Boyle stratigraphy is less well understood. Immediately to the west of the Drowning Creek Valley (Madison-Estill County line), massive, crinoidal to cherty upper Boyle rests on a glauconitic, bioturbated, sandy dolostone bed, about 60 to 70 cm thick, that carries a few poorly preserved rugose and tabulate corals, small athyrid brachiopods, and minor bone (Fig. 3.2.10). We interpret this bed as the Kiddville Bed. As in other localities in the northern Kentucky region, the base of this bed is sharp and carries distinctive hypichnial trace fossils (*Rusophycus* and *Cruziana*). The upper surface of the bed is corroded and impregnated by phosphatic mineralization. This unit is separated from the basal upper Boyle grainstone by a 0.5- to 1-cm parting of dark-brownish-gray shale that carries abundant dendroid graptolites.

In an outcrop along Rte. 52, about 0.9 miles east of the Drowning Creek Valley (loc. 7), the glauconitic dolostone is similar and lies directly beneath the upper Boyle (Casey Member). However, in the very next outcrop, only 0.15 miles further east, a very similar--and probably the same--glauconitic, sandy bed is separated from the upper Boyle, by an intervening greenish-gray shale, 145 to 150 cm thick, containing abundant fenestrate bryozoans, atrypids and small rugose corals (Fig. 3.2.10). This unit has not been observed at any other localities, although it may be the equivalent of the dendroid graptolite-bearing shale parting in sections to the west and the brownish-gray, phosphatic shale above the Kiddville Bed to the east.

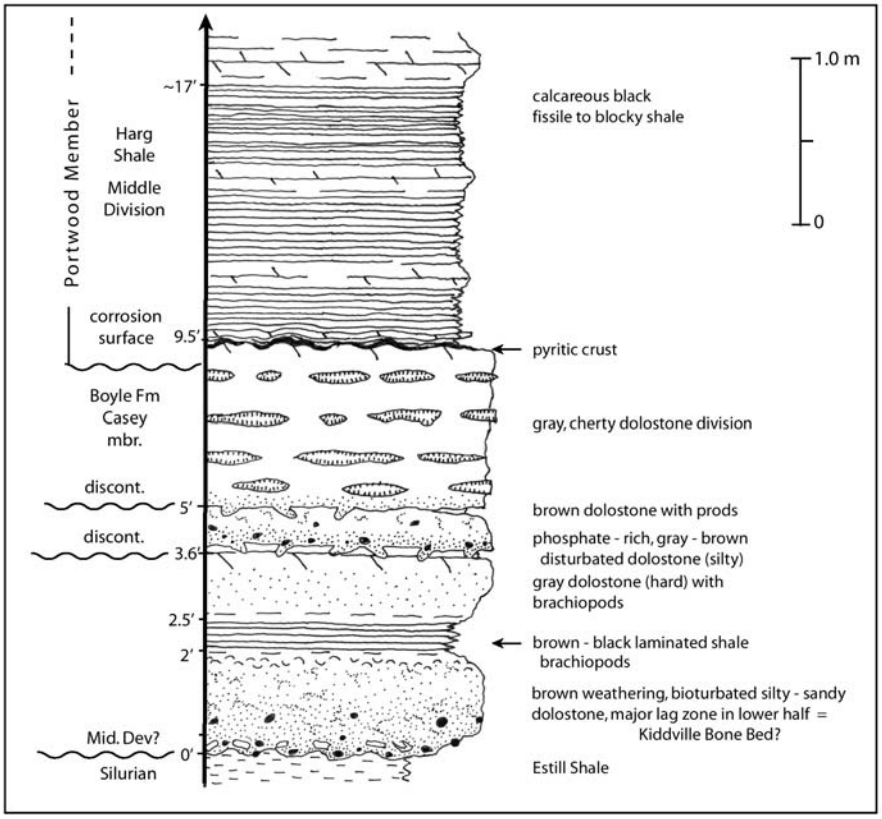


Figure 3.2.7: Diagrammatic section of the Boyle Formation and Portwood Member of New Albany (Ohio) Shale, showing details of lower Boyle, including two bone beds separated by black shale in approximate position of lower *Ambocoelia* beds, roadcut on west side of Rte. 89, about 3.5 miles north of Irvine, Estill County, Kentucky (loc.13).

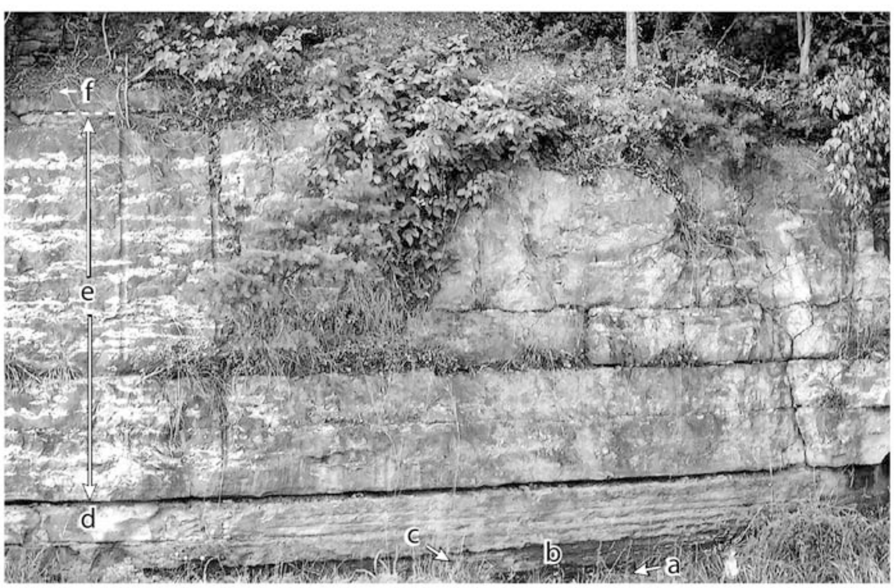


Figure 3.2.8: Boyle Formation outcrop along Rte. 52 opposite Emmanuel Baptist Church (loc. 10). Units discussed include: (a) lowest shaly unit, (b) lower Kiddville Bed; (c) lower *Ambocoelia* pod beds (d) lower Beechwood bone bed of Conkin et al. (1973, 1976); (e) Casey Member (cherty limestone, ~3 m thick); (f) base of Portwood Member, New Albany/Ohio Shale.

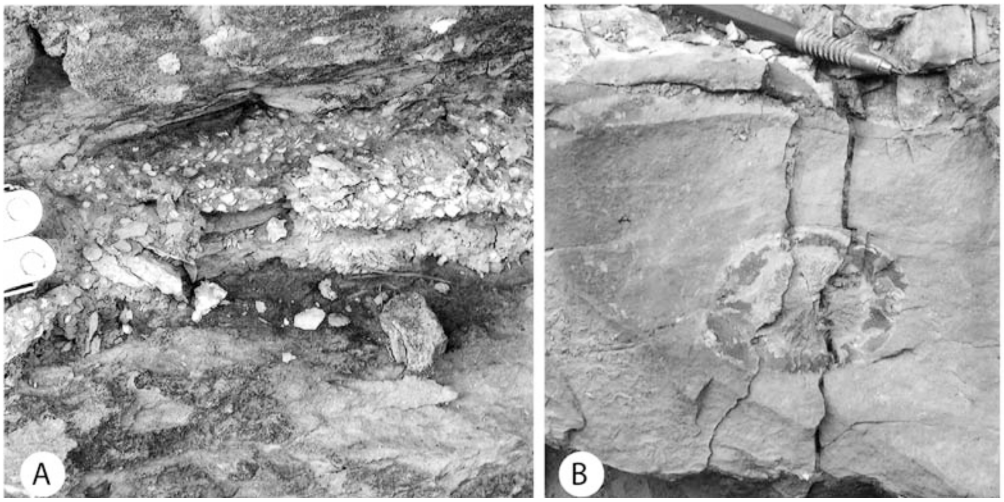


Figure 3.2.9: Details of Boyle Formation. A) Close-up of *Ambocoelia* pod bed in lower Boyle Formation (loc.10). B) Chert nodule in Casey Member of Boyle Formation nucleated on a spheroidal sponge (*Hindia*); Rte. 89 cut north of Irvine (loc. 13).

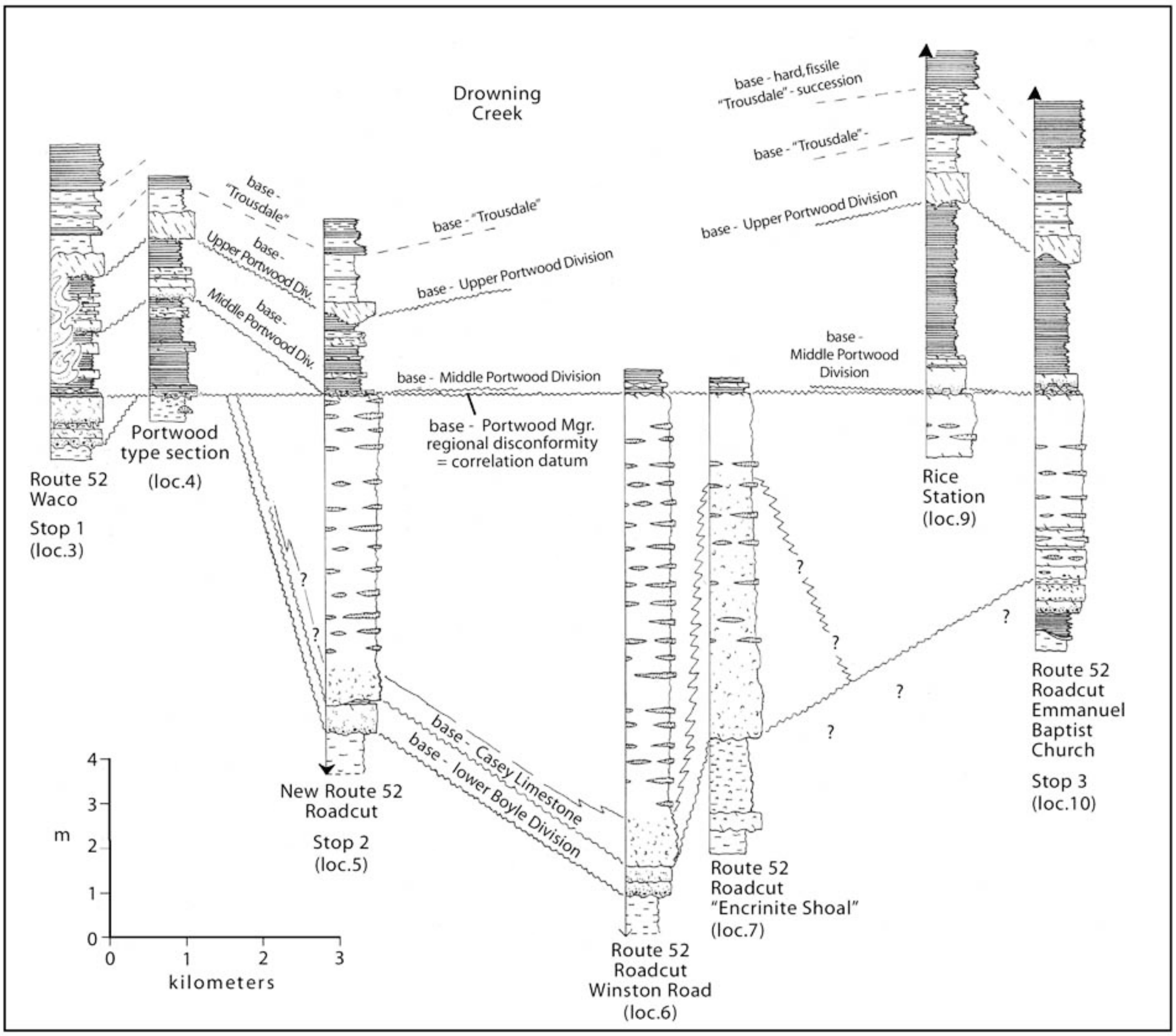


Figure 3.2.10: Correlation of Boyle and Portwood sections along and near Rte. 52 between Waco (loc. 3) and the Emmanuel Baptist Church (loc. 10), Madison and Estill County, Kentucky. Note extreme variation in thickness of Boyle Formation; also note erosional removal of lower Portwood division beneath a megaburrow-based bed.

Upper Boyle Formation
The main, upper part of the Boyle Formation is highly variable in thickness, ranging from 0 to 10 m (Figs. 3.2.8, 3.2.10). This interval is medium-gray, orange-buff weathering dolostone and dolomitic limestone, typically having numerous layers of irregular, ellipsoidal, pale cream-colored chert nodules. The age of the formation based on conodonts is Middle Devonian. The presence of *Icriodus l. latericrescens* and *Polygnathus l. linguiformis* in samples from near Irvine indicates a Givetian age (D.J. Over, pers. com., 2004). Pieracacos and Helfrich (1984) report conodonts of the lower *varcus* Zone in central Kentucky (see below).

In localities near the Drowning Creek Valley, the basal unit of the upper Boyle comprises 0.5 to 1.5 m of echinoderm grainstone to silty packstone, containing fenestrate bryozoans, the trilobite *Phacops* cf. *P. rana*, a few atrypid and cyrtinid brachiopods, and a unique echinoderm fauna, including undescribed diploporan and rhombiferan “cystoids” and blastoids (Dexter et al., 2004). This interval is planar to cross-bedded and shows a basal limestone breccia at Drowning Creek area localities; Stephenson (1979) reported a small mound of breccia about 40 cm high and about 1 m across from the Rte. 52 about 1.2 mi east of Drowning Creek (loc. 6). This basal unit grades upward into laminated, fine-grained grainstone/calcisiltite, with bands of light-gray to cream-colored chert nodules (cherty dolowackestone or dolomicstone facies of Stephenson, 1979). Rare fossils, including the sponge *Hindia*, commonly as nuclei of chert nodules (Fig. 3.2.9B), and a few small brachiopods (*Ambocoelia, Pseudoatrypa*), favositids, and solitary rugose corals occur within this facies.

Upper Contact of Boyle Formation
The Boyle-Portwood contact has been interpreted as conformable (Conkin et al., 1976). However, we argue that the upper Boyle is bounded by a major erosion surface at its top that separates this unit from the overlying Portwood Member. The cherty upper or main part of the Boyle is particularly variable in thickness, even though, as noted above, lower stratigraphic units are traceable through most outcrops with only moderate change in lithology and thickness (Fig. 3.2.10). For example, the Boyle ranges from 0 to 10 m in thickness in successive outcrops separated by less than 2 miles, between Bybee and the Drowning Creek Valley (Fig. 3.2.10), with variation of more than 5 meters in outcrops separated by only 0.1 mile. This initially suggested that the upper contact of the Boyle might be irregular.

Although in most sections the upper Boyle contact appears to be nearly planar, the extraordinary outcrop at Irvine, Kentucky, shows a relief of over 2 meters, including narrow (1- to 2-m wide) pillars of pelmatozoan grainstone facies that project upward into the overlying Portwood Formation (Fig. 3.2.6). As noted above, these were considered to be erosional remnants of the Silurian Bisher Formation (McFarlan et al., 1944), but, based on relationships with surrounding Boyle and distinctive cystoid fossils, we suggest, as did Savage (1930), that these may be remnants of a thickened crinoidal grainstone facies locally developed in the Boyle. Regardless, they have obviously been subject to erosion and dissolution and individual blocks lie loose on the Silurian unconformity. At least one such block was surrounded by bone-rich lag sediment. Blocks of the grainstone have been detached from the main mass of the pillars and are surrounded by the Portwood dark shales.

Savage (1930) and McFarlan and White (1952) documented apparent cavity fillings of black shale and breccia, termed Duffin breccia (see Fig. 3.2.12), within the Boyle in southern Boyle County. These outcrops included a lens of black shale, apparently within the Boyle at Carpenter Fork of Rolling Fork Creek; this outcrop was interpreted by McFarlan and White (1952) as deposition of black New Albany (Portwood) muds in a cavern within the Boyle. Barnett and Ettensohn (1992) reinterpreted the black shale as a graben filling and the overlying strata as a subsequent deposit of Duffin breccia (see below). However, there appears to be a bed of normal Boyle Dolostone between the black shale (Carpenter Fork) and the Duffin breccia, such that the original interpretation may be supported.

McFarlan and White (1952) also illustrated a remarkable outcrop on Rte. 21, 4 miles west of Berea, Kentucky, in which the cherty Casey Member of the Boyle appears to interfinger with Duffin chert-rich breccia (Fig. 3.2.6B). They concluded that this indicated penecontemporaneous formation of the breccia and normal cherty carbonates of the Boyle. We do not agree; the chert and dolostone fragments appear to be derived from the Casey facies of Boyle, thus they must postdate these deposits (as also suggested by conodont studies of the Duffin; see below). Instead, we suggest that the breccia represents infilling of a karstified surface of Boyle with debris resulting from partial dissolution of the rock, possibly a collapse of breccia into a sinkhole. Because the breccia also interfingers with a tongue of normal Boyle, we further suggest that it was either formed in situ or infiltrated into crevices, both above and below a projecting ledge (similar features were documented by Brett et al., 2000, along the Wallbridge unconformity in New York state). This further indicates a period of karstification prior to deposition of the Portwood. We interpret some occurrences of the Duffin as nontransported karstic breccia; other occurrences richer in mud and locally graded appear to represent secondarily mobilized flow bodies correlative with Portwood deposition (see below).

In addition to dissolution effects, Stephenson (1979) interpreted the dolomitization of the Boyle to have resulted from mixing of fresh and salt water during subaerial exposure; if so, it is likely that dolomitization occurred prior to dissolution. Indeed, the presence of dolostone as well as chert fragments in the Duffin breccia indicates that both of these diagenetic phases developed prior to karsting. The chertification was apparently early and preceded dolomitization, as chert nodules preserve the original carbonate fabric, including delicate fossils such as uncompacted sponges. Thus, features that were obliterated by dolomitization were protected by silicification.

The presence of conodonts of mixed zones, including reworked Ordovician elements in the Duffin mixed with lower *varcus* Zone forms in the Duffin breccia (Pieracacos and Helfrich, 1984), indicates that its deposition was preceded by erosion, in places completely through to the Ordovician. The admixture of elements as young as the early Famennian *A. triangularis* Zone in the Duffin, also reported by Pieracacos and Helfrich, is enigmatic, but may indicate a second period of dissolution and reworking of material into unconsolidated breccia, possibly associated with formation of basal Famennian bone bed 16 (see Brett et al., 2003).

A bed of fossiliferous chamositic iron ore up to 2 to 5 m thick, the Preston Ore, appears in the position of the Boyle near Owingsville, Kentucky (Kindle, 1906; Bucher, 1918; Lewis, 1949). This ironstone is lenticular and is inferred to represent a channel-filling succession. It is notable that chamositic ooids are found at a number of localities in the late Givetian Tully Formation in New York and Pennsylvania (Heckel, 1973).

Portwood Member (of the Ohio Shale or New Albany Formation)

Campbell (1946) designated the term "Portwood Formation" for a calcareous, commonly soft-sediment deformed interval at the base of his New Albany Shale east of the Cincinnati Arch, typically exposed in a creek near the hamlet of Portwood (now called Bybee), just east of Waco, Kentucky (Fig. 3.2.11). Although numerous subsequent authors have abandoned this term, we argue that this has led to an imprecise and sometime ambiguous terminology. For example, Jordan (1979) referred to this interval as a facies of the lower part of the lower Huron Member (Fig. 3.2.3). The interval may correspond, in part, to the Blocher Member of the New Albany Shale (also proposed by Campbell, although the latter contains less dolostone and is largely of a different, slightly younger, age based on conodonts. We have found that the interval designated as Portwood in fact, has a consistent and mappable internal stratigraphy, lithology, and fauna. We, therefore, resurrect this term, in much the sense used by Campbell (1946), as a member of the New Albany or Ohio Shale, as distinct from the Huron Member.

This interval had been recognized for some time as the *Hypothyridina* Zone, based on the presence of distinctive suite of brachiopods, including *Hypothyridina venustula* (now *Tullypothyridina venustula*)**,** *Lingulipora williamsiana*, *Leiorhynchus mesacostale*, and *Emmanuella* sp., which also occur uniquely in the upper Givetian (middle *varcus* zone) lower Tully Formation throughout the Appalachian Basin. Thus, Savage (1930) correlated the Portwood interval (then called *Hypothyridina* Zone) with the Tully, and subsequently Cooper (1942) corroborated this correlation and assigned the Portwood to his late Middle Devonian Taghanic Stage (Fig. 3.2.4).

Campbell recognized three local and perhaps intertonguing facies of the Portwood: the Duffin, Harg, and Ravenna "members" of the Portwood (Fig. 3.2.4). A basal brecciated dolostone and dolomitic shale zone locally as much as 15 ft thick was referred to as the Duffin bed (Fig. 3.2.12), a term originally used to designate a peculiar breccia at Duffin along the south side of the Cincinnati Arch (Jessamine Dome) near Junction City, Kentucky (Linney, 1882); the Duffin was extensively traced by Foerste (1906). Unfortunately, the term "Duffin" has been applied more broadly to the entire dolomitic interval, herein termed "Portwood"; this usage prompted some authors to abandon the term Duffin, but we see no problem in retaining this term, provided it is restricted, as per the original definition, to the brecciated carbonate unit. Recently, Barnett and Ettensohn (1992) and Barnett et al. (1993) reconsidered this unit and interpreted it as a seismite or tsunamite deposit.

Locally, the Duffin "bed" may directly overlie or even fill pockets in the upper surface of the Boyle Formation. However, in some localities the Duffin is separated from the Boyle by black, laminated shale and argillaceous, burrowed dolostone (Foerste, 1906). In the vicinity of Junction City, the Duffin breccia overlies a thicker black shale of Givetian age (middle to upper *varcus* conodont zone), the Carpenter Fork Shale. Barnett et al. (1993) pointed out that the breccia locally contains black shale clasts, apparently derived from this underlying shale.

Remarkably, McFarlan and White (1952) suggested that the Duffin could be included either as a unit of the underlying Boyle, or as a unit in the basal New Albany Shale in different areas of Kentucky. It is clear the Duffin contains clasts derived from the Boyle and an intervening shale, even in cases where it extends down into the Boyle. It is clearly separated from that unit by a major unconformity that we infer to be a sequence boundary. However, in-situ, karstic Duffin would be a facies functionally and chronologically separate from marine-resedimented Portwood Duffin; one represents a post-Boyle, pre-Taghanic onlap terrestrial domain, and the other, a later synsedimentary marine facies. This was a key source of McFarlan and White's confusion. The resedimented Duffin is genetically related to and interbedded with the New Albany (Portwood Member). We consider it to be a bed of the Portwood.

A second, commonly overlying, facies, the Harg "member" consists of dark-gray to black calcareous shale and dolomitic lutite and calcisiltite typically exposed at the railroad cut at Harg Station (now called Hargett) north of Irvine, Kentucky. The Harg facies is prominent between Waco and Irvine, and again near Clay City. The Harg facies will be considered in greater detail below. The third facies, named "Ravenna" for railroad cuts near Ravenna Station, southeast of Irvine, consists of dark-gray to black platy shale with rare *Lingulipora*. The Ravenna appears to laterally replace the middle unit Harg Shale, while an upper carbonate unit grades laterally northeastward into calcareous Ravenna facies. As the Ravenna seems simply to be a slightly more shaly facies of the middle Portwood (or Harg "member"), we see no need to retain either "Harg" or "Ravenna" as formal stratigraphic units; rather they are useful only as general facies designations.

The Harg or Ravenna facies are everywhere overlain by black, platy shales assigned by Campbell (1946) to the "Trousdale Formation"; this is clearly a tongue of the Blocher Member, and that term probably should be used to replace the name "Trousdale". This dark shale yields abundant black, phosphatic shells of the inarticulate (lingulacean) brachiopods *Schizobolus* and *Orbiculoidea*. This interval is correlative with the Blocher Member of the New Albany shale to the west of the Cincinnati Arch. Recently, D. J. Over obtained conodonts of the latest Givetian *disparalis* Zone in this shale south of Clay City (Brett et al., 2003).

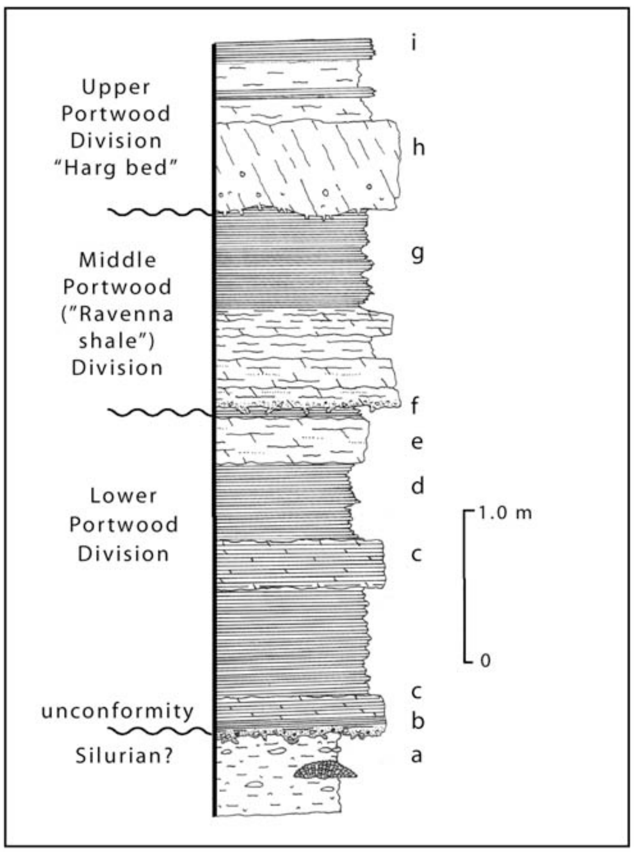


Figure 3.2.11: Details of Portwood Member at type section at former Andrew McLaughlin farm south of Road near Bybee (formerly Portwood), Madison Co., Kentucky (loc. 4). Lettered units include: a) Silurian Estill Shale containing fossiliferous ("Ribolt") facies with bryozoan-rich limestones and some larger corals; b) basal bed of Portwood, note lag of erosional clasts and phosphatic pebbles; the Boyle Formation is absent at this unconformity; c) dark shale of lower unit of Portwood; c) argillaceous dolostone bed; d) black shale; e) bioturbated, light weathering argillaceous dolostone; f) basal bed of middle Portwood division showing irregular burrowed base ("megaburrow bed" of Jordan, 1979); contains small phosphatic pebbles and small brachiopods; g) black "Ravenna" shale of middle division; h) thick "Harg facies" dolomicrite bed of upper Portwood Member; contains sparse brachiopods, nautiloids and burrows; i) hard band of dark shale near top of Portwood.

Detailed Stratigraphy of the Portwood Member

In the study area, the Duffin breccia bed is developed only at a few localities both in the northwest, along Rte. 977 near College Hill (loc. 2) and the northwest, near Indian Fields. It is up to 1.5 m thick and consists of small, angular clasts of dolostone, chert, and rare black shale "floating" in a dolomudstone matrix (Fig. 3.2.12). As noted, the Duffin breccia may be amalgamated to the Boyle Dolostone (e.g., in exposures at loc.18, along the Mountain Parkway, near Indian Fields) (Fig. 3.2.12), or separated from it by nonbrecciated black shale and dolostone, here interpreted as the basal Portwood, or a tongue of the "Carpenter Fork Shale" of Barnett and Ettensohn (1992), for example at Berea and College Hill (locs. 1, 2). Fossils, including crinoid ossicles, are common in some Duffin samples, and Savage (1930) reported a mixed Tully-upper Hamilton fauna from the Duffin, including *Tullypothyridina*, *Emmanuella subumbona*, “*Leiorhynchus*”, and *Mucrospirifer mucronatus* var. *tullius*. These fossils may be in part reworked from older shales.

Figure 3.2.12: Duffin breccia bed at base of Portwood Member, resting on corroded top of Boyle Dolostone; cut along north side of Bert Combs Mountain Parkway SE of Powell County line (loc. 18).

The Harg facies of the Portwood was further subdivided by Campbell (1946) into three successive units (Figs. 3.2.11, 3.2.15). The lower Portwood is well developed near Waco and consists of 2 to 3 m of dark-gray to black shale. However, in most localities it consists of a thin, (a few centimeters) medium, dark-gray shale, locally with a basal lag of phosphatic debris. At the large roadcut along Rte. 52 opposite Emmanuel Baptist Church (Figs. 3.2.8, 3.2.10), just 25 cm of shale and thin dolostones is capped by a silty dolostone having a distinctive sole surface covered with sharply defined, large hypichnial burrow casts termed “megaburrows” by Jordan (1979), who first recognized this bed. At Hargett, a greenish-gray mudstone with dark blotches about 80 cm thick intervenes between the top of the Boyle and the sharp base of a comparable bed.

The lower Portwood interval is about 3 m thick at the Portwood type section, where it rests directly on fossiliferous Silurian shale, the Boyle having been completely removed (Figs. 3.2.10, 3.2.11, 3.2.15). Similar thicknesses are observed in northeastern localities, such as along the Mountain Parkway north of Clay City. In the area of Indian Fields, this interval contains or is replaced by the Duffin breccia bed, which rests sharply and unconformably on the underlying Boyle Dolostone (Fig. 3.2.12). The Duffin is apparently a lenticular unit within the lower Portwood. In some localities, especially near Waco, Kentucky, the lower Portwood interval contains irregular, ball-and-pillow masses, as well as rotated blocks and tightly overturned folds developed in cream to buff weathering silty, argillaceous dolostone (see Figs. 3.2.15, 3.2.16).

The middle Portwood interval is variably 1.6 to 4.4 m (5 to 14 ft) thick and consists of fissile, dark-gray, calcareous shale with a few thin limestone layers. Soft-sediment deformation is noted in this interval at Waco, the Emmanuel (Good Shepherd) Baptist Church locality, and the Mountain Parkway cut just south of Lulbegrud Creek (see Figs. 3.2.19, 3.2.20). The basal bed of this interval is a 25- to 30-cm thick buff to orange weathering, sandy dolomicstone bed (Fig. 3.2.13); this bed contains rare phosphatic nodules and small brachiopods and may be the source of much of the “Tully fauna” of the Portwood. The bed shows sharp and very irregularly prodded base as a result of large hypichnial casts of firmground burrows (Fig. 3.2.13), identified as *Cruziana*-like megaburrows (Jordan, 1979). This “megaburrow bed” is locally caught up in deformation at Waco, where the bed is isoclinally folded. The bed was found to overlie an unconformity at which the lower Portwood is variably eroded. In places nearly the entire lower Portwood interval is missing and the “megaburrow bed” may come to rest on the upper Boyle, as at the Rte. 52 cut west of Drowning Creek.

The main fauna of the “*Hypothyridina* Zone” has been obtained from shales of the middle Portwood. Campbell (1946) reports abundant *Lingulipora williamsiana* and uncommon *Tullypothyridina venustula*, *Camarotoechia mesacostale*, and *Emmanuella* sp. from this interval at the Portwood type section (loc. 4), Rice Station (loc. 9), and elsewhere in the region between Waco and Irvine.

The upper Portwood forms a distinctive interval of thick- to medium-bedded, somewhat contorted, argillaceous dolostone (dolomicstone) that weathers pale buff (Figs. 3.2.14, 3.2.15). The basal bed, which we informally term the “upper Harg lenticular bed” of this interval is lenticular, generally exceeding 30 cm, but ranges from 0 to as much as

88 cm thick and shows substantial lateral variation even at the scale of an outcrop. Individual lenses may be up to 50 m wide. Careful examination of this bed indicates that it overlies a channeled surface on the middle Portwood shale, and thus occurs at variable distances above the base of the Portwood, as was first pointed out by Stephenson (1979) and Jordan (1979). Jordan (1979) documented a dramatic channel in the (then) new roadcut on Rt. 52 at Waco. At the cut on Rte. 52, 1.2 miles west of the Drowning Creek valley, the bed ranges from 100 to 150 cm above the top of the Boyle. In the cut opposite Emmanuel (Good Shepherd) Baptist Church (loc. 10), the bed ranges from 280 to 320 cm above the Boyle contact. Overlying beds consist of pale, olive-gray dolostone and dolomitic shale having limonitic thread-like burrows (*Trichichnus*) and in places *Zoophycos*. The channeled dolostone bed also displays distinctive vertical fractures of probable far-field tectonic origin.

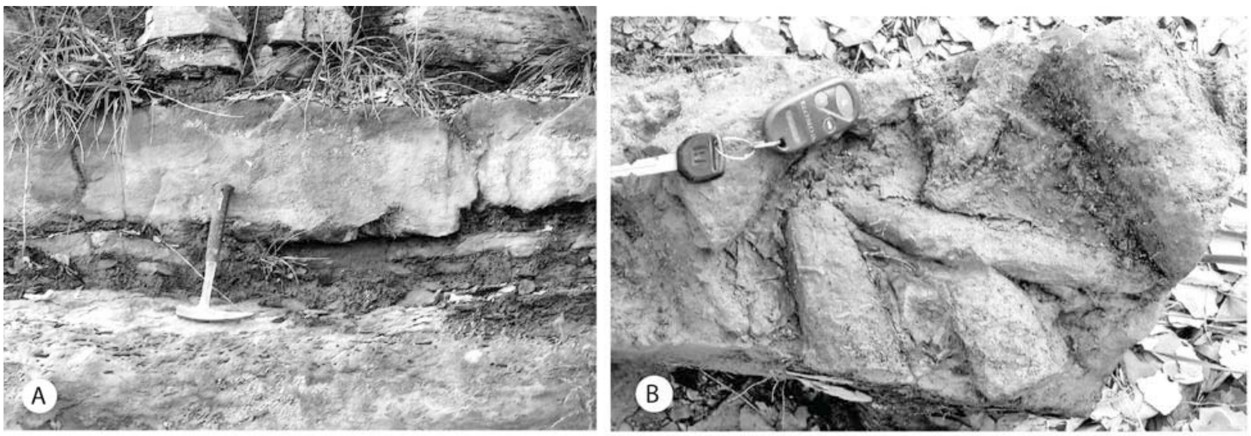


Figure 3.2.13: Basal prodded or "megaburrowed" bed of middle Portwood (Harg facies); Rte. 52 roadcut opposite Emmanuel Baptist Church (loc. 10). A) Lateral view of bed; hammer is resting on sharp top of Boyle Formation; note about 20 cm of shale and shaly dolostone of lower Portwood division. B) Lower surface of bed showing large prods or megaburrow casts with smaller *Planolites* internal to fillings.

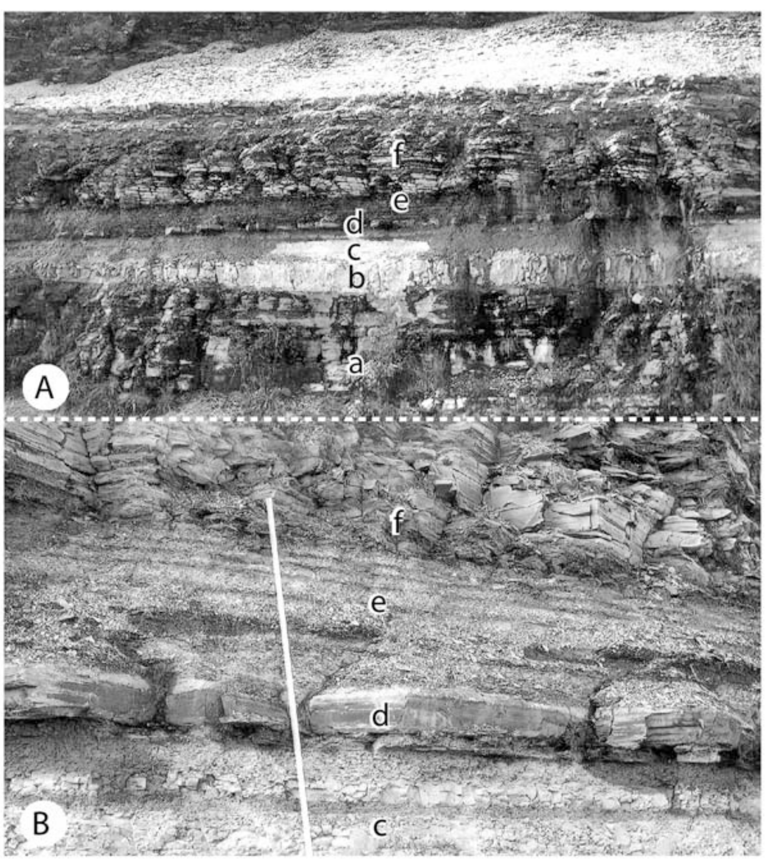


Figure 3.2.14: Details of lower New Albany (Ohio) Shale at Rte. 52 roadcut opposite Emmanuel Baptist Church (loc. 10). A) Overview showing the following units: (a) middle Portwood division ("Ravenna black shale facies); (b) light colored dolomicrite bed ("upper Harg bed") filling broad channel (arrows); (c) rust stained shaly dolomicrite beds of upper Portwood; (d) black shale bed of upper Portwood; (e) "striped" unit at top of Portwood, (f) "Trousdale" or Blocher shale. B) Close-up of upper Portwood units including top of units b to f, as listed above. Note particularly the prominent black shale unit and overlying "striped beds" showing decimeter-scale cyclicity of dark shale and light dolomitic mudstone beds.

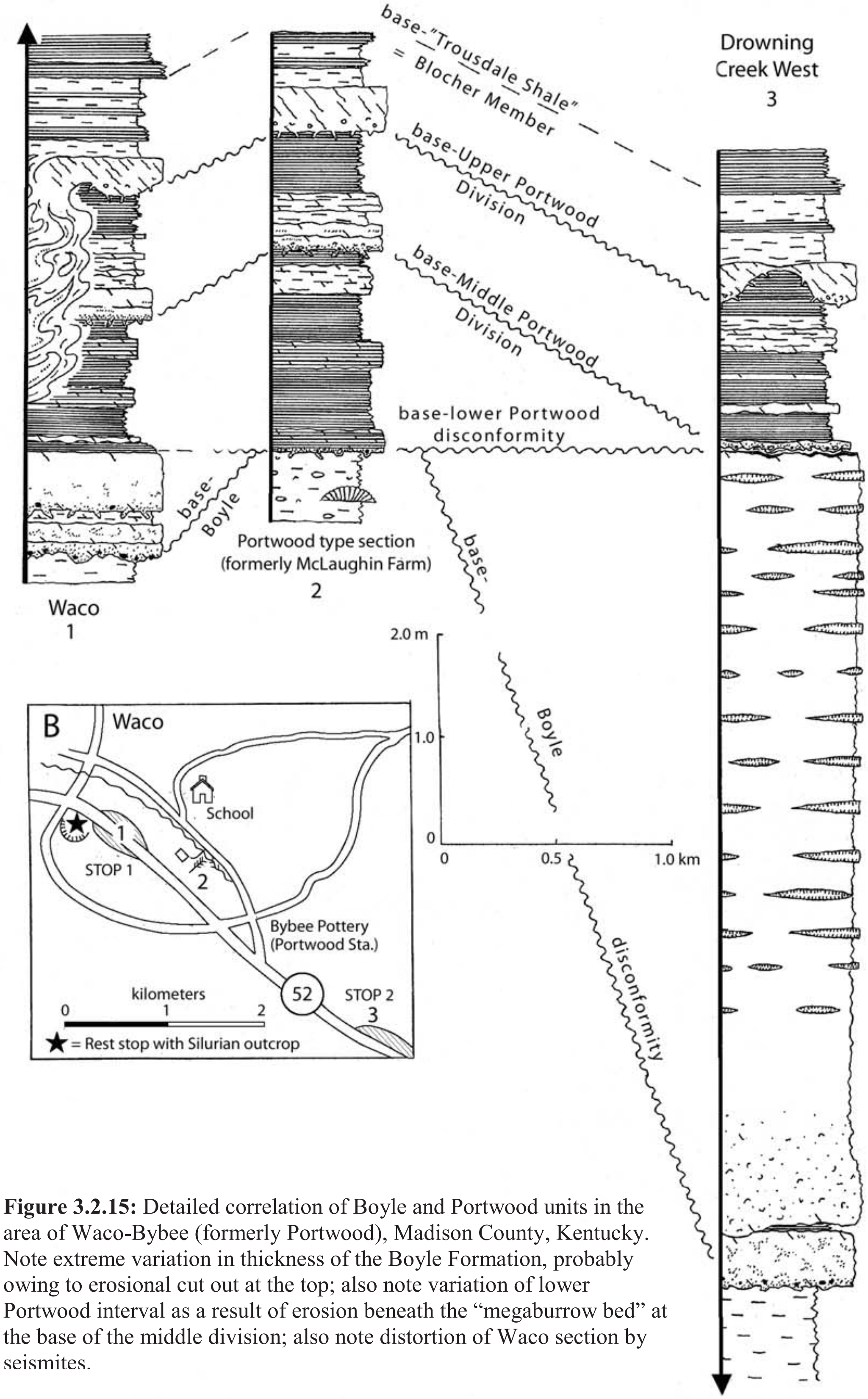


Figure 3.2.15: Detailed correlation of Boyle and Portwood units in the area of Waco-Bybee (formerly Portwood), Madison County, Kentucky. Note extreme variation in thickness of the Boyle Formation, probably owing to erosional cut out at the top; also note variation of lower Portwood interval as a result of erosion beneath the "megaburrow bed" at the base of the middle division; also note distortion of Waco section by seismites.

Locally, we observed rare fossils within this upper Harg channeled bed, including very poorly preserved *Camarotoetoechia*, and *Emmanuella* , as well as *Phacops* at Waco. Foerste (1906, p. 106) reported a more diverse fauna from this level, including “Devonian cyathophylloid corals, *Atrypa reticularis* and other shells” at the railroad cut SW of Rice Station. Very rare specimens of chonetid and atrypid brachiopods, crinoid columnals, and rugose and tabulate corals occur at this horizon in the roadcuts west of Drowning Creek (Stephenson, 1979; personal observations). These fossils do not represent a typical lower Tully faunal assemblage, but apparently represent a recurrence of a more diverse, Hamilton (Boyle)-like assemblage.

It must be herein stated that the present authors did find some of the taxa reported by previous authors, but the fauna of the Portwood interval overall is striking for its general sparseness and low diversity. Most disappointing is the fact that no *Tullypothyridina* were found in any section, though great effort was expended to find this particular taxon. However, it must be noted that, within the Tully Formation in New York, *Tullypothyridina* often occurs in dense clusters within hypichnial burrow prods and may be absent or scarce outside of the prods (Heckel, 1973; Baird et al., 2003), hence, earlier Portwood workers may have found these brachiopods in rare clusters. Dolomitization of many Portwood beds contributed to the difficulty of finding any fossils.

The thickness of the Portwood Formation varies substantially and seemingly without pattern in the study area (Fig. 3.2.15). This may be attributable to irregularities of the unconformity on the underlying Boyle Formation. Thick areas of the Portwood show some correlation with thin Boyle successions. However, there also appears to be erosion below the upper Harg lenticular unit, which may contribute to variations in thickness.

As a whole, the carbonates of the upper Portwood (Harg facies) appear to be thicker and more fossiliferous in western exposures, while the middle unit passes laterally to the southeast into dark shales of the Ravenna facies.

DEFORMED BEDS OF THE PORTWOOD: PROBABLE SEISMITES

Recently, synsedimentary deformed strata have attracted a good deal of interest and many have been reinterpreted as products of seismic shocking or seismites *sensu* Seilacher (1982); see Pope et al. (1997) Ettensohn et al. (2002); McLaughlin and Brett (2004). Key aspects in recognition of probable seismites include a) evidence for liquefaction of muds; b) involvement of several beds; c) association of varied styles of deformation; d) association with synsedimentary faults and e) regional trends in intensity of deformation in relation to these faults (Obermeier et al., 1995). A number of deformed beds in the Ordovician of the southern Cincinnati Arch area have been interpreted as seismites (Pope et al., 1997; Rast et al., 1999) and in some cases the deformation intensity has been shown to increase toward faults (Kulp, 1995; Jewell and Ettensohn, 2001; Jewell and Ettensohn, 2004). The earthquakes that produced deformation are thought to have been the result of far-field tectonic stresses that reactivated basement faults in the Kentucky River fault zone. McLaughlin and Brett (2004) argued that the seismites are nonrandomly distributed and that they required both deformation prone strata, typically interbedded siliciclastic or carbonate silts, sands, and thixotropic muds (generally expandable lattice clays). Clusters of deformed beds are associated with the appropriate sedimentary facies, but many instances of the nearly identical interbedded lithologies show no deformation. McLaughlin and Brett also note an association of seismites with K-bentonites and relate both to tectonic pulses (tectophases sensu Ettensohn, 1987).

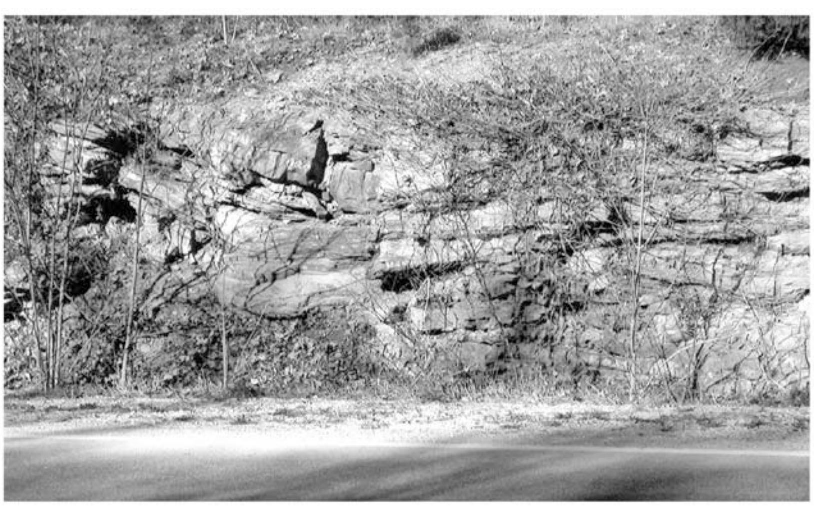


Figure 3.2.16: Strongly deformed beds of middle and lower Portwood divisions; probable seismites; Rte. 52 cut near Waco (loc. 3).

The lower to middle Portwood appears to be deformed at several localities in the Waco to Irvine area (Figs. 3.2.16, 3.2.19, 3.2.20). Deformed beds within the Portwood show several features suggestive of seismic deformation. First, they appear to represent “deformation-prone” lithologies: interbedded carbonate silts and siliciclastic clays. Second, they show severe deformation that in places involves more than one bed. The successions do not match the general features of soft-sediment deformation due to simple foundering of sediment masses because of rapid sediment loading (storm-rollers), or slumping as in rapidly prograded pro-deltaic sands. The deformed beds probably represent slowly accumulated carbonate sediment and/or early diagenetic concretionary cementation within carbonate-rich muds. These are not rapidly accumulated sands or silts, but they are interbedded with clays. In many cases, several beds rather than a single depositional unit are involved in the deformation. In places there is evidence for in situ foundering. Also, flame structures and other diapiric injections of mud into pillowed carbonates are common. In some cases, deformed masses show brittle breakage suggesting that the beds had already undergone a degree of cementation before deformation.

The Duffin breccia may represent another distinctive type of seismically related sediment. As noted above, it contains angular fragments of Boyle dolostones and cherts, plus some black shale floating in matrix. We suggest that this reflects a sharpstone breccia derived from karsting of the Boyle and collapse of overlying sediments during exposure in a semi-arid region. The unit is typically homogenous in appearance, but may show slight grading. Barnett and Ettensohn (1992, 1993) interpreted the Duffin as a tsunamite. The generally homogenized aspect and localized distribution of the Duffin lenses suggest that other processes may be at play. We suggest that the karstic breccias were buried by calcareous mud and that the two phases became homogenized when the mud became liquefied by seismic shaking. The local lenses could represent debris flows off local high areas, as suggested by Barnett and Ettensohn to explain the superposition of the Duffin over Carpenter Fork shale. Alternatively, the Duffin is a later unit that developed on the upper surface of the Boyle, after infilling of cavities with Carpenter Fork black shale.

We suggest that lithospheric flexure associated with the second tectophase of the Acadian Orogeny (Ettensohn, 1987, 1992b, 2004) produced reactivation of basement faults in the Kentucky River fault zone. The internal stratigraphy of the Tully Limestone in the Appalachian Basin provides abundant evidence for syntectonic deformation, including reactivation of basement faults (Heckel, 1973; Baird and Brett, 2003); heavily deformed sandstone beds, also interpretable as seismites, are present in the lower Tully clastic equivalents in eastern New York (see Baird et al., 2003). As in the Taconic Orogeny in the Ordovician, collisional docking of Avalonian terranes during the late Middle Devonian and associated flexure, could have reactivated Kentucky River fault zone fractures causing local seismicity near the southeastern end of the Cincinnati Arch. A precursor of the Cincinnati Arch also may have existed at this time. The Portwood, as well as underlying Boyle and Silurian formations down to the Estill Shale are removed by erosion beneath Fammenian black shales to the east of the study area. Hence, arching may have been developing during the late Middle Devonian. Moreover, Barnett and Ettensohn (1992) documented syntectonic faulting in the late Middle Devonian, including development of a local graben (Carpenter Fork graben) immediately prior to deposition of the Duffin Breccia in the vicinity of Junction City.

SEQUENCE STRATIGRAPHIC PATTERNS OF THE MIDDLE DEVONIAN IN KENTUCKY AND BROADER CORRELATIONS

Figure 3.2.17 shows the sequence stratigraphic interpretation of the Middle Devonian strata of the Irvine-Waco region. Without doubt, the base of the Devonian is the largest unconformity in the middle Paleozoic of central Kentucky. It represents a combination of at least three major unconformities seen in the Appalachian Basin, most notably, the second order Wallbridge unconformity that separates Sloss's (1963) Tippecanoe/Tutelo (Silurian) and Kaskaskia (Middle Devonian-Mississippian) supersequences. As noted, the erosion surface crosscuts a variety of Silurian units, such that the Boyle rests on a variety of different units. In addition, at least two third-order sequence boundaries are also stacked here. The late Emsian-middle Eifelian carbonates seen in many areas (Onondaga-Columbus-Jeffersonville Formations) are absent here or represented by a thin sandy bed. Either this region was locally uplifted during the Eifelian once existent sediments have been removed by early-Givetian erosion. It is not presently clear precisely what the basal succession represents. However, present evidence (conodont evidence cited above indicates assignment to the lower *Icriodus l. latericrescens* zone) suggests that the main Boyle grainstones belong to the lower *varcus* Zone (Pieracacos, 1983; Pieracacos and Helfrich, 1984; D. J. Over, pers. commun., 2004).

The black sandy shale that locally appears at the base of the Boyle near Irvine is of uncertain age, but it appears gradational with overlying dolostones carrying *Ambocoelia* and other Devonian fossils. This unit may represent highstand black shale facies of the lower Hamilton (Marcellus subgroup). Two overlying dolomitic units show firmground trace fossil assemblages, suggesting that these are minor (third-order?) sequence-bounding disconformities. We tentatively correlate these carbonates with the Speeds-Deputy members of the Sellersburg (North Vernon) formation in Indiana and the upper Delaware Limestone in Ohio.

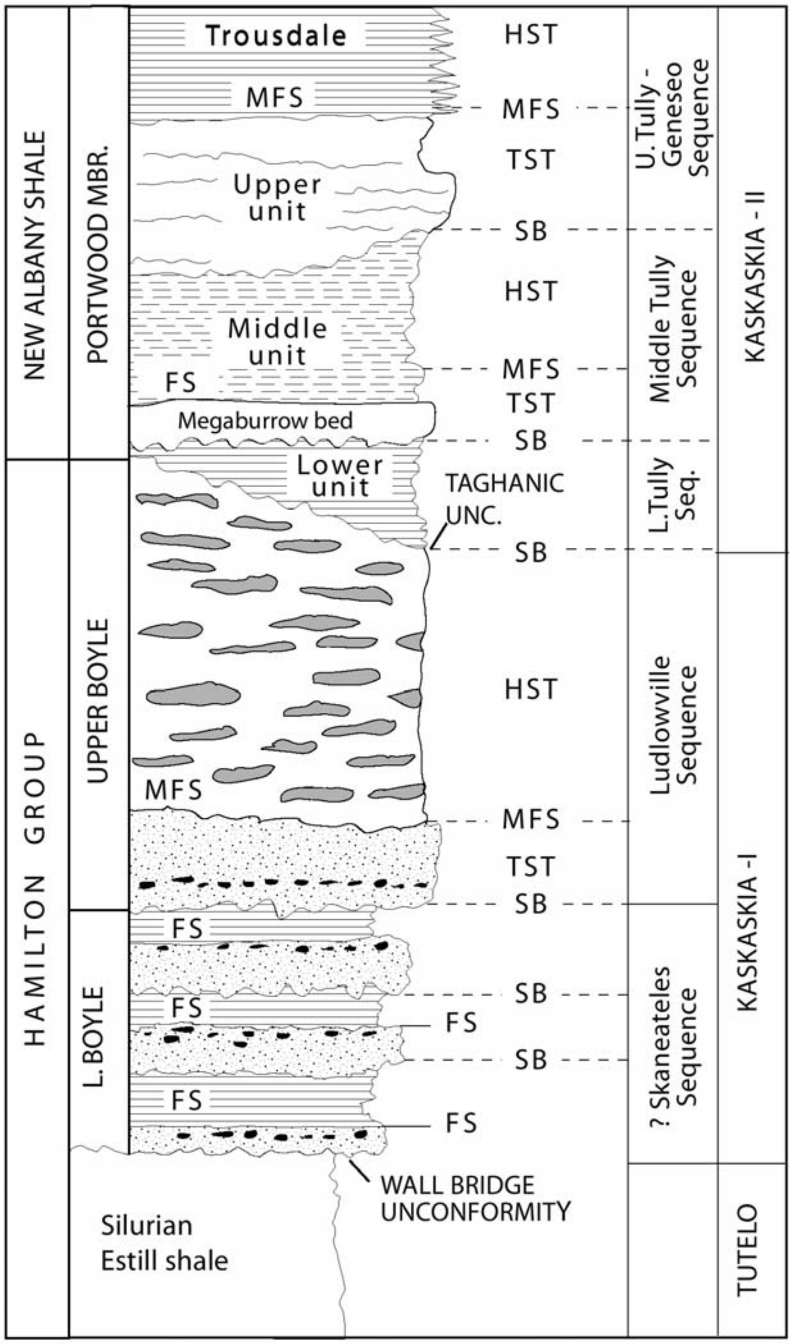


Figure 3.2.17: Sequence stratigraphic interpretation of the Boyle Formation and Portwood Member and tentative correlation with the sequences recognized in New York State; note Sloss (1963) megasequences listed on the right. Abbreviations: FS = flooding surface; HST = highstand systems tract; MFS = maximum flooding surface; SB = sequence boundary; SSB = minor (4th order) sequences; TST = transgressive systems tract.

The basal grainstones of the main Boyle and their lateral equivalents are thought to record a transgressive systems tract. Earlier workers tentatively correlate the grainstone unit with the Beechwood. The Beechwood Member, fossiliferous crinoidal grainstones of the lower *varcus* Zone age, expressed widely in southern Indiana and northern Kentucky west of the Cincinnati Arch. The basal conglomerate present east of Drowning Creek can be interpreted as a basal erosion lag deposit and provides evidence for substantial erosion at the contact. Similar erosion is seen at the base of the Beechwood Limestone in the Louisville area (Savage, 1930; McFarlan and White, 1952). The grainstones pass upward gradationally into sparsely fossiliferous laminated medium-gray cherty facies of the main Boyle Limestone. We consider this a highstand facies equivalent to Ludlowville Formation shales in the Appalachian Basin.

The Boyle is evidently bounded at its upper contact by a major unconformity. This erosion surface is responsible for removing much or all of the Boyle Limestone in certain outcrops within this area. We suspect that the top of the Boyle represents a karstified unconformity with a local relief of 5 to 10 m. In some areas of Kentucky breccias of dolomitic and chert clasts infill pockets in the upper Boyle. The Preston Iron Ore, an oolitic chamosite and hematite ironstone with Middle Devonian fossils, occurs in the position of the Boyle near Owingsville, Kentucky. Surprisingly, in most localities the Boyle is not mantled by a chert clast conglomerate, but seems to have at most a ferruginous to phosphatic stain and a thin-layer of phosphatic debris. This may imply that erosion of residual gravels also preceded deposition of the basal Portwood. Erosional debris may be concentrated in the lenses of Duffin breccia, although the rather low content of chert is enigmatic.

This sub-Portwood unconformity is thought to correspond to the second-order Taghanic Unconformity, which underlies the middle portion of the Tully Limestone in the Appalachian Basin (see Baird and Brett, 2003). The Portwood itself shows internal complexities. In particular, at least two sequence boundaries appear to be present. A thin dolomitic bed with large prods and megaburrows overlying the lower unit may represent a minor TST. The sharp erosion surface at the bed base is inferred to represent a sequence boundary, which locally removes much or all of the lower unit. In turn, the middle Portwood shales appear to be sharply and erosionally overlain by the upper "Harg" carbonates. As noted, the basal surface of the upper Portwood is sharp and appears to have substantial relief suggesting infilling of channels cut into the underlying unit. The deformed basal unit would presumably represent backfilling of channels during transgression. The upper portion of this unit is gradational but abrupt into the overlying Trousdale black shales, although near Rice Station, Foerste (1906) recognized several feet of interbedded gray and dark shale separating the upper Portwood beds from typical "Trousdale". This is considered to be a part of the upper Portwood TST and its abrupt upper contact with the overlying black shales is inferred to represent a maximum flooding surface (Fig. 3.2.18). Hence, the Portwood may itself be made up of as many as three third- or fourth-order sequences.

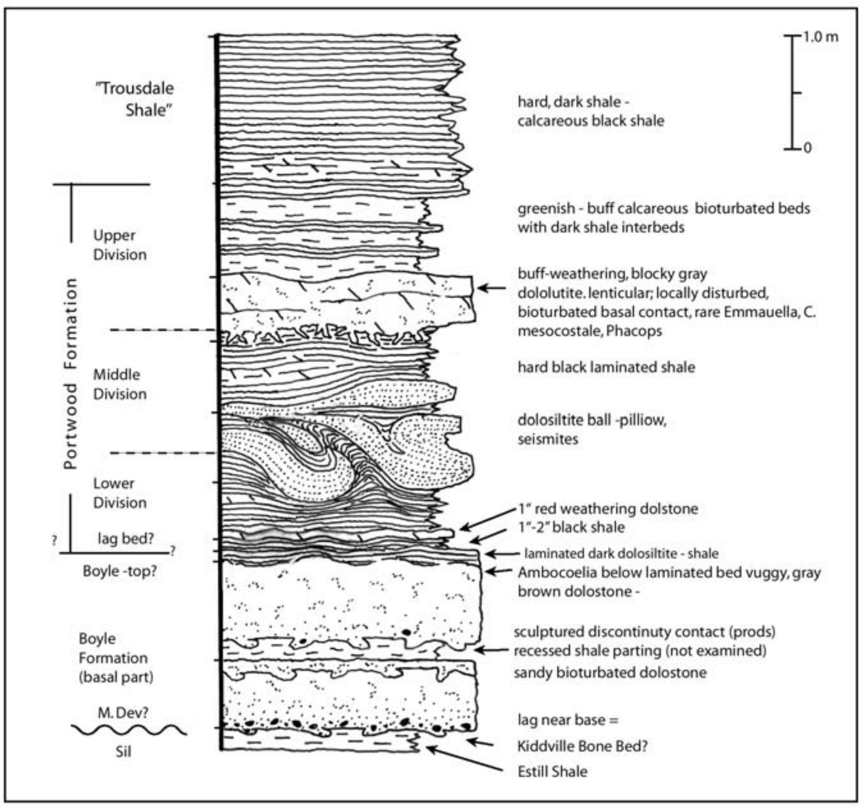


Figure 3.2.18: Diagrammatic section of Portwood Member showing strongly deformed beds along Rte. 52, 0.1mile east junction of KY Rte. 977 (BP convenient mart), Waco, Madison Co., Kentucky (loc. 3; Stop 1).

The biostratigraphic dating of the Portwood is poorly known at present, but it is constrained between the early Givetian date of the underlying Boyle and the late Givetian (*disparilis* zone) date of the Trousdale. Moreover, the distinctive *Tullypothyridina-Emanuella-Camarotoechia mesacostale* brachiopod assemblage of the middle Portwood has long allied it with the lower Tully Formation of late middle *varcus* Zone age in the foreland basin. In view of this we suggest, as did Campbell (1946), that the Portwood represents the interval of the Tully Limestone (Figs. 3.2.4, 3.2.17). If so, the Portwood is developed in quite dysoxic, basinal facies compared to most of the Tully. This is somewhat surprising in view of the seemingly rather shallow water facies of the Boyle as compared to coeval Hamilton beds in New York. This evidence suggests local tectonic effects, including possible migrating flexure through the central Kentucky area during the Middle Devonian.

It is noteworthy that our recent studies indicate that the Tully itself comprises at least three depositional sequences (Baird and Brett, 2003). The primary source of the *Tullypothyridina* fauna is in the lower and middle Tully, especially the Carpenter Falls Bed in New York. This basal transgressive succession is overlain by deep-water carbonate or dark shale facies of the Taughannock Falls Bed. These beds are sharply overlain by highly fossiliferous limestone and shale (Bellona, West Brook beds of the upper Tully). Throughout the Appalachian Basin these upper Tully strata show a totally different type of assemblage characterized by diverse recurrent Hamilton taxa. We suspect that the upper Portwood ("Harg" lenticular carbonates) represents this interval and it is noteworthy that a distinctive fauna, including corals and atrypids, has been collected from at least one locality in the upper Portwood.

By this interpretation the upper, thinly bedded carbonates and shales would record the transitional uppermost Tully units (Moravia-Filmore Glen) of the classic New York succession and the abrupt contact with Blocher ("Trousdale") black shales would correspond to the major flooding event (Taghanic onlap *sensu stricto* of Baird and Brett, 2003). "Trousdale" is thus a local manifestation of the maximum highstand and widespread dysoxia-anoxia recorded in the Geneseo black shales of equivalent late Givetian age in the Appalachian foreland (Fig. 3.2.4).

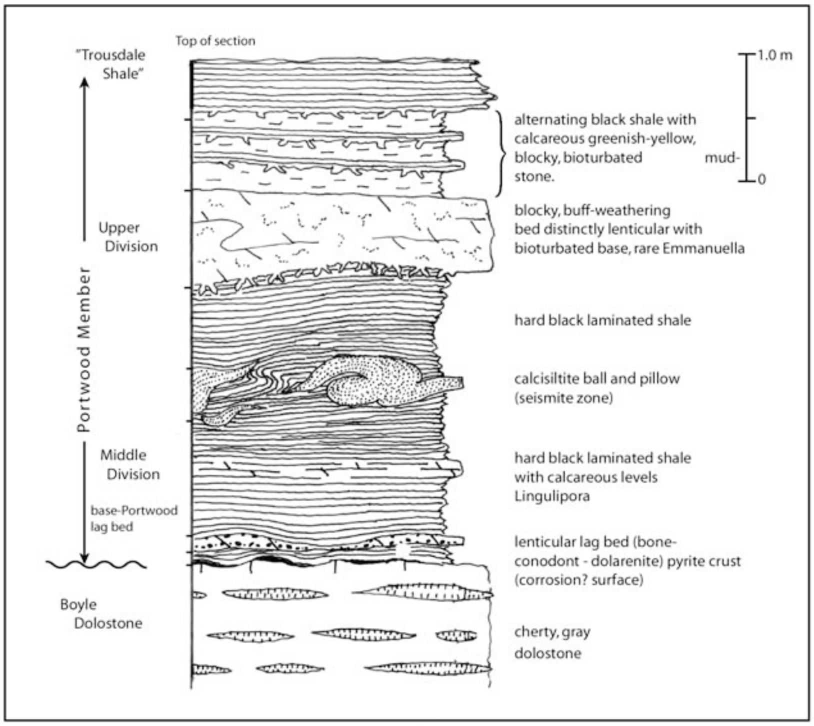


Figure 3.2.19: Diagrammatic section of upper Boyle and Portwood in newly expanded cut on north side of Kentucky Rte. 52, 1.0 mile west of Madison-Estill county line at Drowning Creek and 2.0 miles east of Waco, Madison Co., Kentucky (loc. 5; Stop 2).

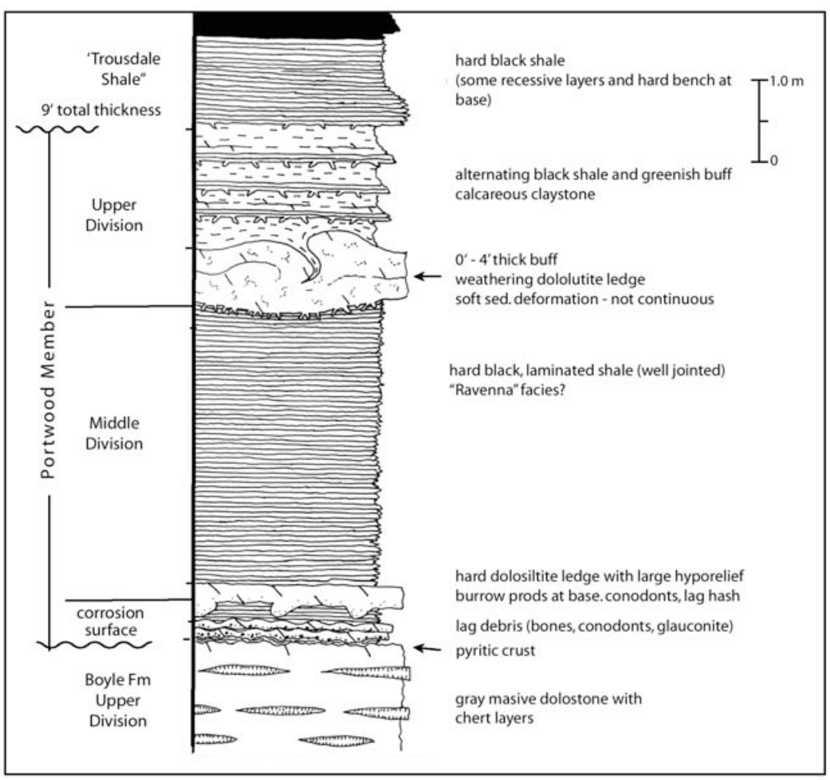


Figure 3.2.20: Diagrammatic section of Portwood Member in cut along Rte. 52 immediately opposite (north) of Emmanuel (Good Shepherd) Baptist Church; 3.5 miles west of Irvine, Estill Co., Kentucky (loc. 10; Stop 3).

DISCUSSION

To return to issues raised in the introduction, the Middle Devonian of Kentucky shows abrupt lateral changes in thickness and aspect. However, these changes do not represent a random facies mosaic. In fact, both the Boyle and Portwood units, comprising widespread depositional packages, show a traceable internal stratigraphy, despite the local change. This is epitomized by the occurrence of the distinctive suite of marker beds even where the Portwood Member is draped and contorted in pockets between pinnacles on the underlying karstified carbonates. Our tentative observation of a discrete lag concentration of fish bones and phosphatic debris at the base of medial Portwood black shale deposits within a meter-wide solution channel bounded by vertical walls of crinoidal carbonate (Fig. 3.2.6) may be an unprecedented discovery. The bone bed, floored by dark-gray dolomitic shale, and overlain by fissile, organic-rich, black, “Ravenna facies”, may be a correlate of the aforementioned base-middle Portwood ”megaburrow bed” observed in sections west of Irvine (Fig. 3.2.10). As such, a regional discontinuity is observed to retain its integrity within sediment-fills in a labyrinthine dissolutional setting showing extreme substrate irregularity.

To a degree, the local changes within the upper or main portion of the Boyle do record lateral facies changes between pelmatozoan grainstone and cherty calcisiltite facies. The grainstone is typical of the lower few centimeters of the unit but in some cases may extend upward for 2 m or more from the base. These changes can occur at the scale of a single outcrop in rare cases. It would appear that this unit, in part, records local shoals, possibly associated with bioherms and intershoal areas; the latter are typified by cherty calcisiltite to fine calcarenite (packstone) facies. In places a very high percentage of the rock is chert. The source of silica involved in formation of cherts within the Boyle is uncertain, but is likely to have been biogenic. The occurrence of well-preserved *Hindia* sponges within the chert nodules shows that sponges were present and locally common within the calcisiltite and fine calcarenite facies. Neither the number of chert beds per meter nor the relative percentage of chert is constant from outcrop to outcrop. Indeed, highly cherty and relatively chert-free facies may occur in adjacent outcrops along Rte. 52 and in a single exposure in the railroad cut at Irvine. Analogous rapid facies transitions between crinoidal pack and grainstones and cherty micritic facies occur in other carbonates, such as the Edgecliff Member of the Onondaga Formation.

However, despite these internal changes within the upper Boyle, the formation maintains a predictable stratigraphy in many outcrops. As shown in Figure 3.2.10, the units lying immediately below the main Boyle are quite similar throughout the study area. The primary change involves the thickening and thinning of the dark shale units and addition or deletion of units at the base of the formation. For example, a 40-cm-thick black shale found at the bottom of the Boyle at Emmanuel Baptist Church is apparently much thinner or absent at other locations and is underlain by additional carbonate units at five locations. These basal units are completely absent in western localities. We suggest that this change involves basal onlap and shingling out of units onto an irregular unconformable surface. This lateral change resulted from differences in sediment accommodation and an irregular topography.

A third major influence on lateral variation is the highly irregular erosion surface at the top of the Boyle or the underlying Silurian. Here, lateral variation is the result of truncation of preexisting beds. In most small outcrops the top of the Boyle appears as a relatively level, sharp contact. However, local topography is dramatically illustrated in at least two outcrops, wherein relief of the upper contact surface is greater than two meters between low areas and remnant pinnacles and rock fins of Boyle. Apparently, an interval of dissolution and physical erosion occurred during the late Middle Devonian, prior to deposition of the Portwood. In places the Boyle was removed altogether. The absence of thick chert pebble lags remains enigmatic.

The variations in the Portwood Member are similarly strong and result from several distinct sources. First, it is clear that local topography of the underlying contact provided important control. At the Irvine railroad cut near Rte. 89, the Portwood is draped, deformed, and locally thickened in pockets between pillars of crinoidal grainstone. Compactional deformation has rotated beds within the Portwood to steep angles at the margins of the pillars. The lower Portwood units are also somewhat differentially thickened in local lows on the contact, and successively higher beds butt against the upper portions of pinnacles. Here, evidently the high areas were too steep to allow sediment to accumulate until they were largely buried.

All evidence in concert suggest that the top-Boyle surface is the hybrid result of dynamic, sequential processes, commencing with localized phreatic, karstic modification, which produced networks of solution grikes, larger channels, and fracture-controlled features (small-scale columnar carbonate towers and rock fins). Subsequent, rapid landscape drowning because of a coincident combination of epeirogenic (flexural) effects and sea level-rise, brought this surface into a basinal marine setting of pervasive sediment-starvation and carbonate dissolution (for Ordovician analogs of uplift, karsting, and collapse, see Friedman and Lee, 1985; Mussman et al., 1988). Thus, black shale deposits at Irvine, and possibly elsewhere in central Kentucky, are presently observed to abut directly against vertical walls of crinoidal carbonate, a condition predicted by Baird and Brett (1991), but not actually seen by the present authors until discovery of the Irvine section.

A second control on Portwood thickness is the effect of internal truncation surfaces. At least two bed contacts, interpreted as sequence-bounding unconformities, apparently acted as erosion surfaces. The sharp and burrowed contact of the “prod bed” at the base of the middle Portwood apparently records an erosion surface that removed much or all of the lower Portwood shale in some localities. Similarly, there is evident channeling at the base of the upper Harg bed of the Portwood. This cuts as much as half a meter into the middle Portwood at some localities and may be responsible for thickness changes of up to 4 meters in the middle Portwood between localities. That said, the middle and upper Portwood units each also have a basically consistent stratigraphic motif that can be traced regionally.

Finally, some local variation especially in the middle Portwood is due to deformation of variable thicknesses of sediments. Deformed masses, attributable to seismites produce local variations in unit thickness of several decimeters.

Thus, in summary, the Middle Devonian Boyle and Portwood (Harg) units provide a fascinating case study in lateral variation. The extreme variability seen in these units is only attributable to facies change in small measure, and primarily only in the upper Boyle. Other changes resulted from multiple causes including, shingled onlap of irregular surfaces, and local channeling and truncation of older beds along at least three major erosional contacts. What is perhaps most intriguing is that despite local cut out and or pinch out, units still do retain an orderly internal stratigraphy and a number of markers can be traced at decimeter scale. Thus, in spite of local effects that may record minor local highs and lows controlled by basement faulting, a dominant control on internal stratigraphy is allocyclic and probably eustatic in nature.

ACKNOWLEDGEMENTS

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ROAD LOG FOR BOYLE-PORTWOOD FIELDTRIP

(Note: Log begins at Exit 187 off I-75 in the city of Richmond, Kentucky)

Mileage: Cumu-lative	Incre-mental	Description:
0	0	Exit 187 on I-75 onto Richmond Bypass; **turn left (northeast)**
0.5	0.5	shaly nodular carbonates of Upper Ordovician Richmond Group
1.3	0.8	Eastern Kentucky University entrance
1.95	0.65	Upper Ordovician carbonates
2.7	0.75	Upper Ordovician carbonates
3.0	0.3	Upper Ordovician carbonates
3.5	0.5	Upper Ordovician carbonates
3.6	0.1	junction KY Rte. 52; **turn right (east)**
3.9	0.3	intermittent Upper Ordovician carbonates
4.75	0.85	big new Richmond/Ashlock Upper Ordovician cuts
5.9	0.15	west edge of military base on south side of road
6.0-	0.1	noticeably flat stretch of road with no outcrops
7.7	1.7	
8.1	0.4	east edge of military base on south side of road
8.45	0.35	junction Rte. 374; stay on Rte. 52 East
9.0	0.45	lower Brassfield Formation (base Silurian); cut on north side of road
9.75	0.75	enter Waco
9.85	0.1	Muddy Creek crossing (Portwood outcrop to south in stream)
10.5	0.65	junction KY Rte. 977

OPTIONAL ROUTE TO PORTWOOD TYPE SECTION (reset mileage at junction)

0.0		turn left onto Rte. 977 (College Hill Road)
0.1	0.1	Waco; junction with Waco loop road (old Rte. 52); turn right
0.5	0.4	Waco high school
1.0	0.9	**OPTIONAL STOP A. Portwood type section**: Small outcrop in ditch along rural lane on south side of Waco Loop Road leading to home of G. Noblitt exposes most of Portwood Member; the Boyle is absent at this site (Fig. 3.2.11). This is the Andrew McLaughlin farm exposure referred to by Campbell (1946).
1.05	0.05	Stream cut just south of road shows contact of Portwood on Crab Orchard (Estill) Shale with hypichnial burrow casts on basal contact (see Fig. 3.2.5).
1.4	0.35	junction Drowning Creek Road on left, turn right (Bybee Pottery) out towards new Rt. 52
1.5	0.1	junction Rte. 52 (new) by Bybee pottery; turn left to return west on Rte. 52 to (Stop 1 is 1.1 miles to west, Stop 2 is 0.7 miles to the east)

Note: Mileage continues from before optional route returning to starting point at junction of Rtes. 52 and 977

		junction Rte. 52 and 977; continue on Rte. 52, note cut in fossiliferous Estill Shale behind BP convenient; Waco, Kentucky
10.55	0.05	begin cuts on both sides of Rte. 52l; pull off on shoulder to examine section

STOP 1. Waco Cut: Somewhat weathered cut on both sides of Rte. 52 (Fig. 3.2.18) shows a very thin succession of Boyle Formation with poorly exposed contact on Silurian Crab Orchard (Estill) Shale; overlain by Portwood Member showing three divisions; lowest is black to gray bioturbated mudstone; sharply overlain by an orange weathering dolostone bed with sharp hypichnial burrows on base, middle unit is mainly deformed dark-gray shale; upper unit is prominently channeled, pale-buff dolomicrite with sparse fossils; highest exposed unit is basal Trousdale black shale. Note very prominent deformation of multiple beds, here interpreted as seismites.

		continue east on Rte. 52
10.65	0.1	upper end of cut
11.75	1.1	junction Bybee Road; turnoff to left
12.25	0.5	roadcut in Trousdale Shale; Boyle Limestone in woods on north side of Rte. 52
12.35	0.1	pull off on shoulder opposite large new roadcut and cautiously cross Rte. 52 to examine cuts

STOP 2. Drowning Cut West: Newly expanded road cut on north side of Rte. 52 shows Silurian-Devonian systemic boundary (Wallbridge Unconformity) (Fig. 3.2.19). Excellent section of Silurian (Llandovery) Waco Limestone and Estill Shale (Crab Orchard Formation), overlain by about 8.5 m of Middle Devonian (Givetian) Boyle Formation, with a 0.6-m, greenish-gray, sandy glauconitic bed (Kiddville Bed?) at base resting unconformably on Crab Orchard (Estill) Shale; pelmatozoan grainstone facies overlain by laminated calcisiltite (dolomicrite) facies; about 3 m of Portwood Member on top of cut shows channeling of the upper dolostones into black shales; lower member present at Stop 1 is absent here.

		continue east on Rte. 52; Silurian cut continues on down the hill exposing (in descending order) the Waco Limestone, Lulbegrud Shale, Oldham Limestone, Plum Creek Shale, and Bassfield Formation with thin ironstones at top
12.65	0.3	top Brassfield Formation (basal Silurian unit); end of cut
12.75	0.1	roadcut on north side of Rte. 52; Brassfield Formation/Drakes Shale contact (Cherokee Unconformity; at Ordovician-Silurian systemic boundary)
12.95	0.2	beginning of fresh roadcut; shows long section of Upper Ordovician Drakes Formation greenish shales and dolostones; long downgrade into Drowning Creek Valley
13.4	0.45	lower end in Ordovician shales
13.75	0.35	cross Drowning Creek; Madison-Estill County line
13.85	0.1	junction. Rte. 1353, start long upgrade and outcrop in Upper Ordovician Drakes Formation east of Drowning Creek
14.15	0.2	upper end of outcrop
14.4	0.35	begin outcrop in Silurian Crab Orchard Shale
14.55	0.15	junction Winston Road on right; exposure of Boyle Formation on both sides shows facies similar to Drowning Creek west cut; thin basal grainstone, overlain by cherty Casey Member; a small mound of conglomerate is present in base of crinoidal grainstone unit.
14.85	0.3	end of outcrop
15.0	0.15	overgrown older cut in Boyle Formation on north side of road; note 1.5-m greenish-gray shale separating glauconitic dolostone from main upper Portwood; fossiliferous pelmatozoan grainstone-packstone facies well developed here and Boyle is thinner and

		less cherty than outcrop immediately to the west; base Portwood black shale on top
15.05	0.05	end of outcrop
15.2	0.15	outcrop of Boyle Formation on south side of Rte. 52 shows thin grainstone overlain by cherty Casey Member
15.25	0.05	end of outcrop
15.35	0.1	Picnic Rd. on left, Ohio/New Albany black shale outcrop
15.5	0.15	outcrop in Ohio/New Albany; note well-developed decimeter-scale cycles
15.75	0.25	outcrop of Ohio/New Albany Shale
15.95	0.2	outcrop Ohio/New Albany; well-developed decimeter-scale cycles
16.05	0.1	junction Winston Rd. on right
16.15	0.1	large Ohio/New Albany outcrop with decimeter-scale cycles
16.25	0.1	end outcrop
16.55	0.3	outcrop in Irvine Formation (Plio-Pleistocene) sands on north side
17.25	0. 7	outcrop of Ohio/New Albany Shale with decimeter-scale cycles
17.45	0.2	end of outcrop
17.65	0.2	beginning of long outcrop in Ohio/ New Albany downward to Boyle Formation
17.75	0.1	Emmanuel (Good Shepherd) Baptist Church on south side of road; **prepare to stop**
17.8	0.05	**pull off on shoulder past church; opposite east end of roadcut; proceed cautiously across road to roadcut**

STOP 3. Rte. 52; Emmanuel Baptist Church Cut: This is an excellent exposure of the Boyle and Ohio Shale/New Albany Formations (Fig. 3.2.20). Lowest exposures shows the Devonian-Silurian systemic boundary (Wallbridge Unconformity), unusual here in showing a basal black, sandy shale (of uncertain age) resting on weathered upper Estill (Crab Orchard) Shale; this shale is overlain sharply by sandy dolostone with excellent hypichnial burrows and pods of white certified *Ambocoelia* brachiopods; a second sandy, glauconitic dolostone with abundant phosphatic debris and scattered fossils (Kiddville Bed?) and upper, thin, brownish shale follows and is sharply overlain by pinkish-orange cherty dolostone of Casey Member of Boyle, much thinner than in sections near Drowning Creek and lacking pelmatozoan facies.

Basal middle Portwood shales are very thin and overlain a sandy dolostone with large hypichnial burrow casts ("megaburrow bed"); middle Portwood developed in "Ravenna facies" black shales with some soft-sediment deformation of a channel fill of silty dolostone; upper Portwood "Harg facies"dolomicrite bed occupies a broad channel and passes into heavily rust-stained argillaceous dolostones and shales; a thin bed of hard black shale separates this unit from strongly striped dolostone and shale at top of Portwood.

Portwood is overlain successively by overhanging Trousdale (= Blocher) black shale, greenish and black-striped facies of the Camp Run and rhythmically bedded Clegg Creek Member; Three Lick Bed and Cleveland Shale occur in the highest portions of the outcrop.

Optional route (if time permits) continue east on Rte. 52; alternatively reverse directions and return to I-75 in Richmond

18.6	0.8	Silurian Estill Shale
19.4	0.8	junction 1457 on north side
19.8	0.4	junction 499 on north side

19.95	0.15	Boyle Formation exposed at corner of Stacy Lane
20.3	0.35	Arby's/Long John Silver; possible rest stop on outskirts of Irvine
21.3	1.0	junction KY routes 89 and 52 continue on combined routes
21.4	0.1	start bridge over Kentucky River into Irvine, Kentucky
21.45	0.05	overpass over railroad cut along north bank of river and immediately west of Rte. 89 bridge (optional stop)
21.5	0.05	parking lot along Mack Street to left: for optional stop, pull into lot and park, then walk back south along road to overpass over railroad cut

OPTIONAL STOP B: Irvine Railroad Cut: Note highly disturbed appearance of Devonian Portwood Shales and chert Casey Member of Boyle which are draped over blocks and pillars of crinoidal grainstone assignable either to Silurian Bisher Formation or are pelmatozoan facies of the Boyle; in either case, outcrop shows extraordinary evidence of strong Devonian karstification and draping of Portwood Shale

21.55	0.05	junction Routes 52/89, in Irvine; Rte. 52 veers eastward; continue on Rte. 89
21.95	0.4	Carhart Street on left (access to Irvine railroad cut)
22.7-22.75	0.3	outcrops of Silurian shale on right
23.0	0.25	junction 499 on left; new Boyle/Estill cut on Rte. 499 just west of intersection
23.3	0.3	junction Rte. 1705 on right
24.5	1.2	Estill County Middle School; note large cut in Ohio-New Albany Shale behind school
24.7	0.2	outcrop of Portwood Member on left (west side of Rte. 89); note thick upper Harg facies dolostone bed
25.8	1.1	exposure of Boyle Dolostone and black shale ("Ravenna facies") of Portwood Member on left **(Optional Stop)**
26.6	1.2	junction 749
26.75	0.15	outcrop of Boyle Formation on left
27.1	0.35	outcrop of Ohio/New Albany Shale on right
27.6	0.5	outcrop of Ohio/New Albany Shale on left
27.65	0.05	outcrop of Ohio/New Albany Shale Bank on Right
28.0	0.35	junction Rte. 82, at Hargett, **Turn right onto 82**; old railroad grade on left into Hargett section
		(Type section of Harg facies, Portwood Member of Campbell (1946) extends 0.2 mi along the railroad cuts)
28.3	0.3	Ohio/New Albany Shale on right.
29.1	0.8	large outcrop on right exposes, Boyle, Portwood, Trousdale and bone bed 16 in upper New Albany Shale
29.2	0.1	upper end of outcrop
29.8	0.6	outcrop of Ohio/New Albany Shale on left
30.1	0.3	outcrop of Ohio/New Albany Shale on left
30.55	0.45	outcrop of Ohio/New Albany Shale on right

30.95	0.4	outcrop of Trousdale Shale
31.15-	0.2	outcrop of Trousdale Shale; Boyle carbonates (in field) on right
31.25	0.1	end outcrop
31.40	0.35	large outcrop of Boyle-Portwood on right
31.7	0.2	outcrop of Trousdale
31.8	0.1	junction 201
32.5-	0.7	outcrop of Portwood Member
32.6		
32.95	0.35	outcrop of Boyle on left
33.10	0.05	Powell County line
33.25	0.1	outcrop of Boyle Formation on right
33.3	0.05	outcrop of Portwood Member on right
33.8	0.5	outcrop of channeled upper Harg bed in upper Portwood
34.2	0.6	Red River crossing
34.3	0.1	outcrop of Boyle Formation
34.95	0.65	junction KY Rte. 1028
35.10	0.15	junction KY Rte. 15

(OPTIONAL ROUTE TO EXAMINE CUTS ON RTE. 15)

0.0	0.0	junction Rte. 82 and 15; turn left (west) on Rte. 15
0.4	0.4	quarry Boyle Formation to left exposing upper contact
0.75	0.35	(**Optional Stop; Rte. 15 Cut**) large outcrop of Boyle Formation showing base and top
1.70	0.85	outcrop of Portwood Member down to top Boyle in ditch at left
1.9	0.2	outcrop of Trousdale Shale on left
2.8	1.1	outcrop of Trousdale Shale on left
3.0	0.2	outcrop of Ohio/New Albany Shale
4.8	1.8	Clark/Powell County line at Lulbegrud Creek

End Alternate Route Log; reverse route and return to Rte. 82

35.15	0.05	entrance ramp to Mountain Parkway; "Bert Combs Parkway"
35.35-	0.2	**(Optional stop) Mountain Parkway northwest of Clay City**: Excellent outcrop of thin Boyle Formation and complete Portwood and Trousdale Members
35.45		
35.65	0.3	outcrop of Boyle Formation-Trousdale Shale
35.75	0.1	large outcrop of Ohio/New Albany Shale
35.25	0.5	outcrop of Portwood through Trousdale
35.5	0.3	outcrop of Trousdale Shale

34.55-	0.05	outcrop of Trousdale and upper New Albany Shale
36.15	1.6	outcrop of Ohio/New Albany Shale with decimeter-scale cycles
36.3		
36.55	0.4	**Optional Stop: Mountain Parkway south of Lulbegrud Creek** Outcrop of Duffin breccia bed resting on sharp upper unconfomity of Boyle Formation; upper beds of Portwood show extensive soft-sediment deformation, inferred to be seismites
36.7	0.05	cross Lulbegrud Creek; Powell-Clark County line
38.85	0.15	outcrop of Brassfield Formation on right
39.15	0.3	outcrop of Brassfield Formation on right
48.15	9.0	merge with I-64 westbound

END OF TRIP ROUTE

3.3. Origin and History of Bitumen in Geodes of the New Albany Shale

by
Mirela Dumitrescu, David B. Finkelstein, Remus O. Lazar, Juergen Schieber, and Simon C. Brassell
Department of Geological Sciences, Indiana University,
Bloomington, Indiana 47405

Introduction

The organic carbon richness of the Devonian New Albany Shale and its stratigraphic position relative to potential reservoirs are critical characteristics that establish its role as a major source rock for hydrocarbons in the Illinois Basin (Barrows and Cluff, 1984; Hatch et al., 1991; Lewan et al., 2002). Its importance as a petroleum source rock has prompted diverse studies of the New Albany Shale (see Lazar and Schieber, this guidebook). Geochemical studies, in particular, have primarily addressed questions regarding the type and abundance of the organic matter in the New Albany Shale (e.g., Frost, 1980; Barrows and Cluff, 1984; Cluff, 1993; Comer et al., 2000; Lazar and Schieber, 2003). Fewer studies have investigated the maturity of the organic matter or the biodegradation of its derived oils (e.g., Barrows and Cluff, 1984; Hatch et al., 1991; Lewan et al., 2002). The occurrence of bitumen in vertical, sub-vertical, or horizontal veins is considered strong evidence for hydrocarbon migration and has been the subject of studies in various basins of the world (e.g., Al-Aasm et al., 1992; Evans, 1995; Jochum et al., 1995; Parnell and Carey, 1995; Parnell et al., 2000; Haggan and Parnell, 2000). Bitumen-rich geodes associated with quartz-calcareous veins have been found in exposures of the New Albany Shale in various parts of Kentucky (see Road log and stop description, this guidebook). To our knowledge, there are no published studies of bitumen in geodes from the New Albany Shale. We have investigated the molecular organic geochemistry of such bitumens to determine their possible origin and formation history. We have also analyzed extracts of a shale sample and two basinal oils to assess the character of regional correlations of bitumen, oils, and organic matter in the New Albany Shale.

Sample Description

Bitumen-rich geodes associated with quartz-dolomite veins occur within the Trousdale/Blocher Member of the New Albany Shale exposed in a roadcut located south of Junction City in central Kentucky (Stop 3, Fig. 2.1, this guidebook). In this outcrop, the Trousdale/Blocher black shale is approximately 2 m thick. Seventeen vertical to sub-vertical veins, filled with quartz and dolomite occur in the Trousdale/Blocher Shale along the roadcut. The veins have been contorted and telescoped because of continued compaction of the surrounding shale after vein emplacement (Fig. 2.3.4., this guidebook). The veins are 0.18 to 1.47 m in decompressed length and are generally oriented in NW-SE direction. Centimeter-scale sub-spherical geodes, filled with calcite and quartz, and rich in bitumen, occur along or adjacent to these veins. We investigated the molecular organic geochemistry of the bitumen from four geodes, A through D. Geodes A, C, and D were open, whereas geode B appeared closed, without fissures or cracks. All the geodes contained black solid bitumen that can impart a brown tint to interior calcite crystals (Fig. 3.3.1). The bitumen had a petroliferous odor.

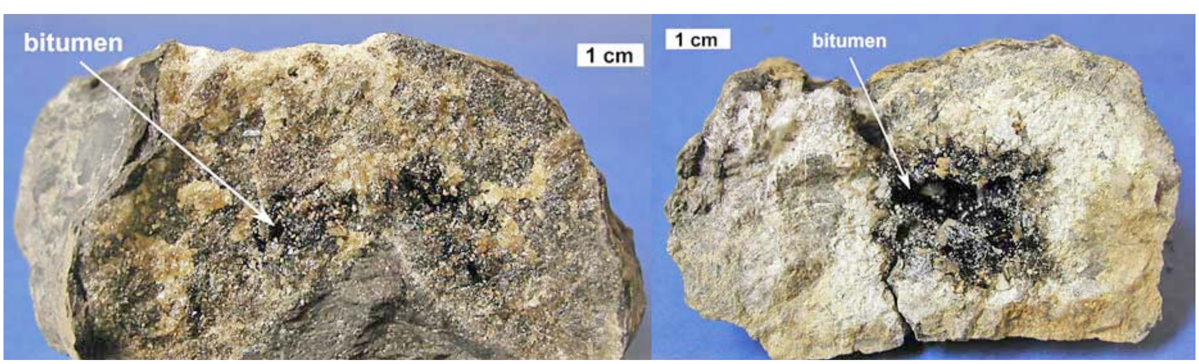


Figure 3.3.1: ***Left:*** Freshly broken bitumen-rich geode B. *Right:* Bitumen-rich geode A.

A shale sample (B shale) was collected adjacent to geode B after removing weathered surface material. Two oil samples were obtained from the Plummer Field, Greene County, Indiana (Plummer Field is located approximately 250 km northwest of the Junction City outcrop) and are named after their wells, namely, Page-Anderson #7 Oil and Plummer-E Oil. These oils are produced from the Salem Limestone at ~210 m depth, and the Middle Devonian Jeffersonville Limestone at ~514 m depth, respectively. The New Albany Shale is considered to be the source rock of both oils (Tom Partin and John Rupp, pers. commun., 2004).

Analytical Methods

The exterior surfaces of the geode and of the shale samples were cleaned with CH_2Cl_2. Geode samples were extracted ultrasonically (CH_3OH:CH_2Cl_2 1:2; 3x15min); the shale sample was extracted using an accelerated solvent extractor (Dionex ASE 200). Asphaltenes were removed from all extracts and oil samples. Deasphaltened extracts were separated by column chromatography (6-ml-volume columns) with 5 percent deactivated silica gel into saturated hydrocarbons, aromatic hydrocarbons, and nitrogen-sulfur-oxygen organic compounds (NSO) by successive elution (hexane, toluene, and methanol).

Gas chromatography of saturated and aromatic hydrocarbon fractions was performed using an Agilent Technologies 6890N gas chromatograph (GC) with a HP-5 capillary column (30m x 0.32mm). The GC oven was programmed from 60 to 320°C at 4°C/min and held isothermally for 50 minutes at 320ºC; helium was used as carrier gas.

Aromatic and saturated fractions were analyzed by gas chromatography-mass spectrometry (GC-MS) using a Finnigan TSQ700 coupled to a HP5890 GC. The GC was equipped with a Varian Factor Four (VF-1ms) capillary column (50 m x 0.32 mm) programmed from 60 to 320°C at 4°C/min, and held isothermally at 320ºC for 20 minutes. Helium was used as carrier gas. The transfer line was set at 320ºC and the mass spectrometer scanned from m/z 50-650 in 1.2s. Compounds were identified from mass chromatograms of diagnostic ions and their mass spectra by comparison with published literature (e.g., Peters and Moldowan, 1993; Killops and Killops, 1993). Biomarker ratios were calculated from GC-MS responses.

Results

Various geochemical ratios have been calculated to assess the origin and fate of the bitumen associated with geodes within the Trousdale/Blocher Member of the New Albany Shale in Kentucky. To explore the source of the bitumen and the nature of the correlation with the Trousdale/Blocher Shale and the oil samples, *n*-alkane distribution patterns, the pristane/phytane (Pr/Ph) ratio, and the $C_{27}/(C_{27}+C_{29})$ sterane ratio were compared (Fig. 3.3.2; Table 3.3.1). The carbon preference index (CPI), the C_{29} sterane ratios (20S/(20S+20R) and $\beta\beta/(\beta\beta+\alpha\alpha)$), the triaromatic steroid ratio (TAI/(TAI+TAII)), the methylphenanthrene index (MPI-1), and vitrinite reflectance (R_o) were computed to assess the maturity of the organic matter with respect to the oil generation window (Table 3.3.1). Vitrinite reflectance was measured on a whole-rock (B shale) polished pellet mount and an average R_o value of 0.53 percent was obtained from 24 measurements. The distribution pattern of *n*-alkanes and two isoprenoid/*n*-alkane ratios (Pr/*n*-C_{17} and Ph/*n*-C_{18}) were examined to evaluate the level of biodegradation (Fig. 3.3.2; Table 3.3.1).

Discussion

Source considerations

The source of organic matter is a major control on the compositions of source rocks and oils. *N*-alkane distribution patterns, values of computed Pr/Ph, $C_{27}/(C_{27}+C_{29})$ sterane, Pr/*n*-C_{17}, and Ph/*n*-C_{18} ratios, as well as polished pellets were examined to address the question of the origin and depositional history of the bitumen. Distinct distribution patterns of saturated hydrocarbons are presented in Figure 3.3.2. The *n*-alkane distributions of all bitumens are characterized by a high abundance of pristane and phytane and by a smooth distribution of *n*-alkanes with low odd-carbon predominance in mid-chain *n*-alkanes and a relatively small abundance of high-molecular-weight *n*-alkanes (Fig. 3.3.2; Table 3.3.1). The *n*-alkane distribution of the B shale extract is characterized by a high abundance of pristane and phytane. It also shows a smooth distribution of *n*-alkanes with low odd-carbon predominance in mid-chain *n*-alkanes and a relative increase in the abundance of high-molecular-weight *n*-alkanes (Fig. 3.3.2; Table 3.3.1).

In contrast to the bitumens, the two oils are characterized by a relatively lower abundance of pristane and phytane (Fig. 3.3.2). The oils are also characterized by *n*-alkanes with low odd-carbon predominance in mid-chain *n*-alkanes and the highest abundance of high-molecular-weight *n*-alkanes (Fig. 3.3.2; Table 3.3.1). In addition, the *n*-C_{12} to *n*-C_{14} *n*-alkanes of the Plumer-E Oil show a more pronounced decrease compared to the *n*-C_{12} to *n*-C_{14} *n*-alkanes in the Page-Anderson #7 Oil (Fig. 3.3.2). This decrease could be the result of the preparatory procedures used (rotary evaporation and/or nitrogen blowing; Ahmed and George, 2004) or of storage losses.

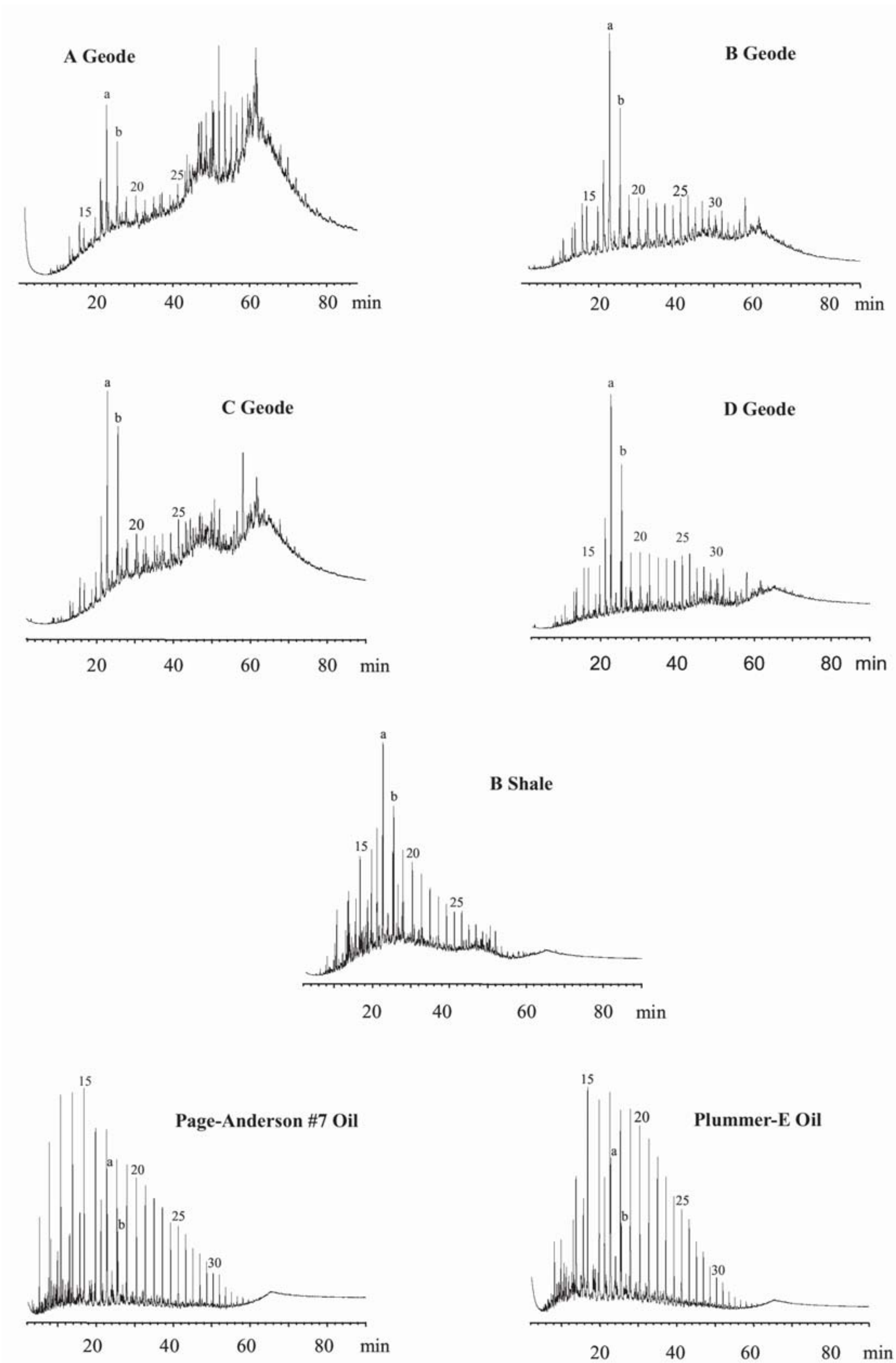


Figure 3.3.2: Gas-chromatrograph traces showing the saturated hydrocarbon distributions of bitumen present in the geodes, shale, and oils. *Numbers* represent *n*-alkanes, *a* represents pristane, and *b* represents phytane.

Table 3.3.1: Summary of calculated geochemical ratios.

Sample	Pr/Ph	C_{27}/ (C_{27}+C_{29})	MC-CPI	20S/ (20S+20R)	ββ/ (ββ+αα)	TAI/ (TAI+TAII)	MPI-1	R_o %	Pr/*n*-C_{17}	Ph/*n*-C_{18}
Geode										
A	1.49	0.32	1.28	0.43	0.39	0.05	0.66	0.8	8.20	4.83
B	1.38	0.34	0.92	0.42	0.38	0.05	0.75	0.85	11.89	5.70
C	1.27	0.37	1.00	0.33	0.36	0.12	1.2	1.12	9.15	7.06
D	1.38	0.28	1.06	0.35	0.31	0.11	0.91	0.95	4.98	3.71
Shale										
B	1.43	0.37	1.05	0.40	0.31	0.21	0.65	0.79	2.33	1.80
Oils										
Page-Anderson #7	1.74	n.d.	1.12	0.50	0.57	n.d.	n.d.	n.d.	0.76	0.50
Plummer-E	2.01	n.d.	1.06	0.42	0.65	n.d.	n.d.	n.d.	1.06	0.58

Notes:
$C_{27}/(C_{27}+C_{29}) = C_{27}/(C_{27}+C_{29})$ sterane.
MC-CPI = ½{[($C_{15}+C_{17}+C_{19}$)/($C_{14}+C_{16}+C_{18}$)]+[($C_{15}+C_{17}+C_{19}$)/($C_{16}+C_{18}+C_{20}$)]}; Guthrie and Pratt (1995).
20S/(20S+20R) = 5α(H),14α,17α 20S / [5α(H),14α,17α 20S + 5α(H),14α,17α 20R] sterane (C_{29}); Mackenzie et al. (1980).
ββ/(ββ+αα) = 14β(H),17β(H) sterane / [14β(H),17β(H) sterane + 14α(H),17α(H) sterane] (C_{29}); Mackenzie et al. (1980).
TAI/(TAI+TAII) = short chain triaromatic steroids / (short chain + long chain triaromatic steroids). TAI = C_{20} + C_{21}; TAII = C_{26} + C_{27} + C_{28} (S and R isomers); Mackenzie and McKenzie (1983).
MPI-1 = 1.5 x [(2-MP + 3-MP) / (P + 1-MP + 9-MP)]. MP = methylphenanthrene; P = phenanthrene; Radke et al. (1986).
R_o = (0.6 x MPI-1) + 0.4; Radke et al. (1986).
Pr/*n*-C_{17} = Pristane/*n*-heptadecane ratio; Shanmugam (1985).
Ph/*n*-C_{18} = Phytane/*n*-octadecane ratio; Shanmugam (1985).
n.d. = not determined

The distribution of *n*-alkanes in the Page-Anderson #7 and Plumer-E oils resembles the distribution of Sangamon County Oil from central Illinois, of New Albany Shale extract from Franklin Co., southern Illinois (Bethke et al., 1991, their Fig. 26-3), and of New Albany rock extract representative for 21 shale samples collected from cores in Indiana, Illinois, and Iowa (Hatch et al., 1991, their Fig. 24-8 H). The similarity between *n*-alkanes distributions of the two oil samples we examined and that of published oil and shale samples suggest that the New Albany Shale is the source rock of the Page-Anderson #7 and Plumer-E oils.

The values of the Pr/Ph ratio and of the $C_{27}/(C_{27}+C_{29})$ sterane ratio of the bitumen from the four geodes fall in a narrow range (Table 3.3.1) suggesting a common source for the bitumen. The B shale is characterized by ratios similar to those obtained for the bitumen samples. The similarity of the Pr/Ph ratio raises the possibility of a common source for the bitumens and the B shale. In contrast, the Pr/Ph ratio of the two oils is higher (Table 3.3.1). Although the Pr/Ph ratio reflects the nature of the contributing organic matter, this ratio should be used with caution (Peters and Moldowan, 1993) because some of the pristane and phytane might be derived from sources other than phytol during diagenesis (e.g., ten Haven et al, 1987).

The isoprenoid/*n*-alkane ratios (Pr/*n*-C_{17} and Ph/*n*-C_{18}) have also been used to indicate source of organic matter (e.g., Chou and Dickerson, 1985; Shanmugam, 1985). A plot of Pr/*n*-C_{17} versus Ph/*n*-C_{18} suggests different sources, more terrestrial and somewhat different for the four bitumens, and more mixed, marine and terrestrial, for the B shale organic matter and the oils (Fig. 3.3.3).

Maceral characterization revealed that amorphinite is the dominant organic component in the B shale, and that together with alginite represents more than 90% of the organic matter in the sample. The organic matter of the black Trousdale/Blocher Shale had a mixed source of both marine and terrestrial inputs (Mastalerz, pers. commun., 2004). The marine algae inputs have been expected because of the observation of abundant *Tasmanites* in thin sections (Fig. 2.3.5, this guidebook). Terrestrial input in the Trousdale/Blocher Shale, possibly derived from bacterial degradation of higher plant material, has been also expected taking into consideration the location of the outcrop on the Cincinnati Arch, presumably a shallower water or even exposed region during the Late Givetian to Early Frasnian. Our preliminary results suggest that the organic matter in the bitumen and the B shale came from different sources. Future investigations of polished pellets containing bitumen and analyses of specific biomarkers used as indicators of biological input (Peters and Moldowan, 1993, their Table 3.1.3 a and b) will assist in the clarification of the source of the bitumen and its relationship to the B shale.

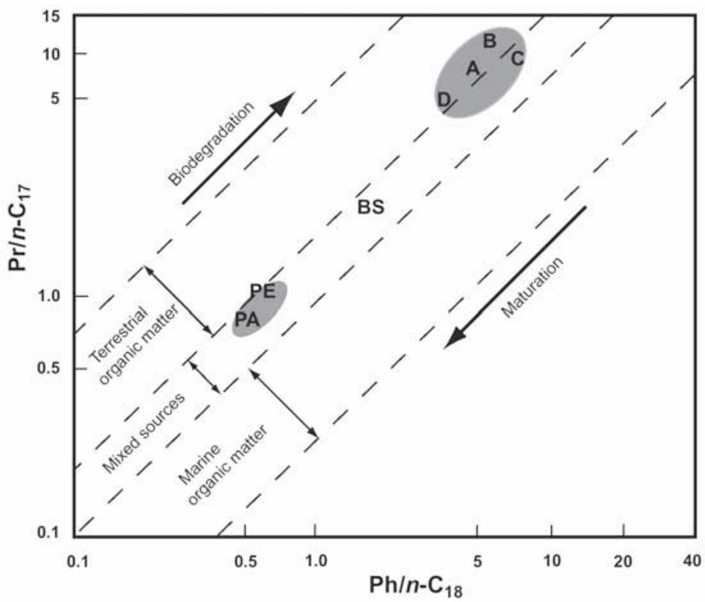


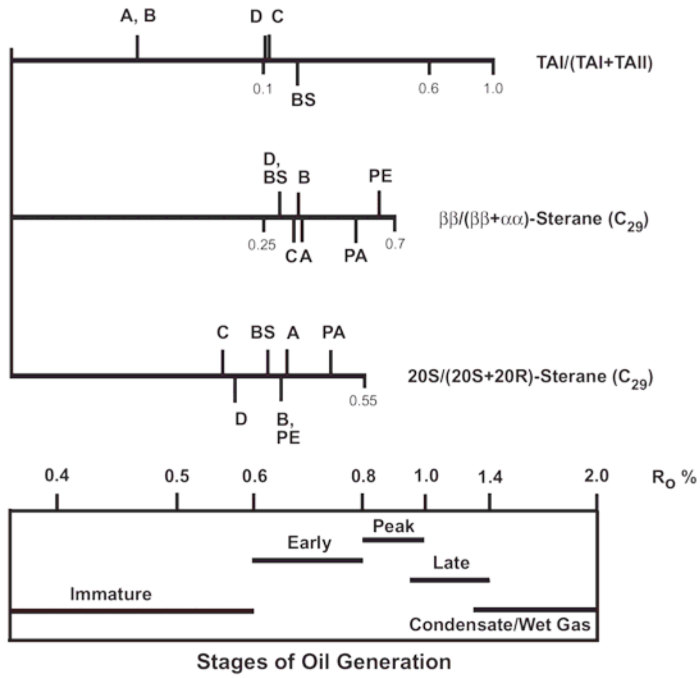
Figure 3.3.3: Plot of Pr/n-C_{17} versus Ph/n-C_{18} showing relative source, maturation, and biodegradation of the bitumen from geodes **A** to **D**, the B shale organic matter (**BS**), and Page-Anderson #7 (**PA**) and Plummer-E (**PE**) oils (modified after Shanmugam, 1985).

Maturity considerations

Maturation is the process of chemical change in sedimentary organic matter that is induced by burial (increasing temperature and pressure) over geologic time (Tissot and Welte, 1984). In general terms, organic matter can be described as immature, mature, or postmature depending on its relation to the oil generation window (Tissot and Welte, 1984). Assessment of the level of thermal maturity of bitumen and oils assists in oil-source correlation studies. Six maturity parameters, the MC-CPI, 20S/(20S+20R), ββ/(ββ+αα), TAI/(TAI+TAII), MPI-1, and R_o, have been calculated to assess organic matter maturity (Table 3.3.1). The carbon preference index (CPI), the ratio of the relative abundance of odd versus even carbon number n-alkanes, decreases with increasing maturity (Peters and Moldowan, 1993). CPI values significantly above (odd preference) or below (even preference) 1.0 indicate that an oil or extract is thermally immature, whereas values of 1.0 suggest but do not prove that an oil or extract is thermally mature (Peters and Moldowan, 1993). The 20S/(20S+20R) and ββ/(ββ+αα) C_{29} sterane ratios are thought to increase from 0 to approximately 0.55 (20S/(20S+20R)) and from 0 to about 0.70 (ββ/(ββ+αα)) during thermal maturation (Fig. 3.3.4) (Seifert and Moldowan, 1986). The triaromatic steroid ratio (TAI/(TAI+TAII)) increases up to 0.1 at the end of the immature stage and up to 1.0 at the end of the oil window (Fig. 3.3.4) (Peters and Moldowan, 1993). The methylphenanthrene index (MPI-1) values bracket the end of the immature stage (0.5) and the end of the oil window (1.6) (Killops and Killops, 1993). Vitrinite reflectance (R_o) is a commonly used maturation parameter which is based on the change in the reflectance of polished vitrinite particles with increasing time and temperature. R_o values range from 0 to 0.6 percent for the immature stage of oil generation, and from 0.6 to 1.4 percent for the mature stage of oil generation (Fig. 3.3.4) (Peters and Moldowan, 1993).

The values of the 20S/(20S+20R), ββ/(ββ+αα), and TAI/(TAI+TAII) ratios of the geode bitumens are broadly similar (Table 3.3.1) and indicate that the bitumens are immature-very early mature (Fig. 3.3.4). In contrast, the MPI-1 and R_o values suggest an early to peak mature stage (Fig. 3.3.4; Table 3.3.1). The C_{29} sterane and the triaromatic steroid ratios are considered to be independent of the source of organic matter input and, therefore, sensitive and effective for inferences of higher levels of maturity, whereas the MPI-1 and the calculated R_o can be adversely affected by the source of organic matter input (Peters and Moldowan, 1993). Assuming there are subtle differences in the source of organic matter input for the four bitumens, the 20S/(20S+20R), ββ/(ββ+αα), and TAI/(TAI+TAII) ratios are considered to be more accurate maturity indicators, implying that the geode bitumens reached an immature to very early mature stage.

Calculated maturity parameters from the B shale indicate that it reached an early mature stage (Fig. 3.3.4; Table 3.3.1). In contrast, the vitrinite reflectance measurements suggest an immature stage (R_o = 0.53 %; Mastalerz, pers. commun., 2004). Similarly, fully transparent to pale yellow conodonts and yellow *Tasmanites* indicate that both the conodont alteration index (CAI) and thermal alteration index (TAI) have a value of one, indicative of immature source rocks (Taylor et al., 1998). Although geochemical maturity indices such as those presented in Table 3.3.1 are considered to provide, for lower maturity rocks, a more accurate assessment of thermal maturity than vitrinite reflectance (Peters and Moldowan, 1993), the observations from three different petrography-based indices makes one wonder whether the organic matter of the B shale did in fact reach the early mature stage.



The values of the 20S/(20S+20R) and ββ/(ββ+αα) ratios obtained here indicate, as expected, the highest level of thermal maturity for the two oil samples (Fig. 3.3.4; Table 3.3.1).

Figure 3.3.4: Ranges of maturity of bitumen from geodes **A** to **D**, the B shale organic matter (**BS**), and Page-Anderson #7 (**PA**) and Plummer-E (**PE**) oils as indicated by vitrinite reflectance (R_0), and the 20S/(20S+20R), ββ/(ββ+αα), and TAI/(TAI+TAII) ratios (modified after Peters and Moldowan, 1993).

Biodegradation considerations

Degradation of petroleum by bacteria is commonly referred to as biodegradation. Peters and Moldowan (1993) proposed a scale, similar to that of Volkman et al. (1983a, b), for assessing the extent to which an oil has been biodegraded based on the relative abundances of various hydrocarbon classes. On the Peters and Moldowan (1993) biodegradation scale, *n*-alkanes are easiest to be biodegraded (light biodegradation, levels 1 to 3), followed by isoprenoids (moderate, levels 4 to 5), steranes (heavy, levels 6 to 7), hopanes (very heavy, levels 8 to 9), aromatic steroids, and porphyrins (severe, level 10). The isoprenoid/*n*-alkane ratios (Pr/n-C_{17} and Ph/n-C_{18}) have been used to indicate maturation and biodegradation (e.g., Chou and Dickerson, 1985; Shanmugam, 1985). Both ratios decrease with maturation because of the increasing prevalence of *n*-alkanes, and increase with biodegradation because of the loss of *n*-alkanes (Peters and Moldowan, 1993; Hunt, 1996).

Relative to the B shale the bitumens are biodegraded. The distribution patterns of *n*-alkanes indicate a sequence of decreasing biodegradation from bitumen A to C to B to D (levels 3 to 2 on the biodegradation scale of Peters and Moldowan, 1993) (Fig. 3.3.2; Table 3.3.1). The bitumen from the A and C geodes is characterized by a marked decrease in *n*-alkanes between n-C_{14} and n-C_{27}, and by the presence of an unresolved complex mixture that displays a "hump" that rises above the baseline of the GC trace that we interpret to be the result of biodegradation (Fig. 3.3.2; Table 3.3.1). The two oils show minimal biodegradation (the *n*-alkanes are more abundant than pristane and phytane) (Fig. 3.3.2; Table 3.3.1). A plot of Pr/n-C_{17} versus Ph/n-C_{18} illustrates also that, relative to the B shale organic matter, the bitumens have been biodegraded (Fig. 3.3.3). It is to be expected that bitumen present in open geodes will undergo biodegradation. The bitumen from the B geode, however, appears to have the highest level of biodegradation (Fig. 3.3.3). This is surprising since the B geode was found closed, with no visible fissures or cracks detected when it was collected. The fact that biodegradation also affected the bitumen from geode B suggests that this geode could have had micro-fissures that allowed microbes to enter the geode and attack the hydrocarbons. Alternatively, the bitumen might have been under microbial attack sometime before the geode closed.

Concluding remarks

To summarize, it appears that the bitumens might have had a different source of organic matter than the Trousdale/Blocher Shale. Also, the bitumens and the two oils experienced different levels of biodegradation. These bitumens have been collected from geodes associated with vertical to subvertical veins present in the shale. Several studies have attributed comparable vein development in other successions to fluid overpressuring (Marshall, 1982; Stoneley, 1983; Al-Aasm et al., 1993; Parnell et al., 1994; Parnell and Carey, 1995). Quartz-calcareous veins that occur in the Trousdale/Blocher Member of the New Albany Shale could possibly be related to the movement of overpressured fluids underneath the Devonian shale seal. Preliminary investigations allow the suggestion that the bitumen and the shale organic matter might not share the same origin. If this is correct, then the Trousdale/Blocher Shale could have been hydro-fractured during oil generation from older, Ordovician or Silurian strata, and Ordovician/Silurian bitumen could have migrated along open fractures and then trapped in hollow geodes. However, further sedimentologic and geochemical analyses are required to firmly establish the source of the bitumen, the timing of veins and geodes, and its relationship to the shale organic matter.

ACKNOWLEDGEMENTS
We would like to thank John Rupp and Tom Partin for their assistance in obtaining the oil samples. We thank Leigh Fall, Grzegorz Lis, and Stephanie Puchalski for their assistance in the field. We thank Maria Mastalerz and Grzegorz Lis for their assistance with measurement of the vitrinite reflectance of the B shale.

3.4. Demand and High Price Spurs a New Era of Drilling for New Albany Shale Gas Wells in Harrison County, Indiana

by

Thomas H. Partin
Department of Geological Sciences, Indiana University,
Bloomington, Indiana 47405

Abstract
From the late 1800s to the early 1900s, one hundred New Albany Shale wells were drilled in a gas play in Harrison County, Indiana, on the eastern flank of the Illinois Basin. The gas production was shut in the early 1930s because of economic constraints. In the mid-1990s the rising price of natural gas was the catalyst for a new period of more extensive drilling for shale gas in Harrison County. The Harrison County fields were the most gas-productive shale reservoirs in both time periods in Indiana. The relatively large geographic area, the long-lived wells, and the low finding costs make Harrison County an attractive area for exploration for the New Albany Shale. New methods for fracturing the shale and propping open natural fractures associated with structural anticlines, terraces, and closures have generated excitement for the current exploration and development play. The play in Harrison County is similar to other exploration and production programs in other U.S. fractured shale basins. The produced gas reserves from shale basins will help to meet the increasing demand for natural gas.

Introduction
Gas production from wells in fractured shales is not a new exploration and development concept in the continental U. S. hydrocarbon basins. The Appalachian was the first basin with Devonian-age organic-rich shale gas production in the state of New York State from wells drilled as early as the late 1820s (Shirley, 2001). Since those early days of the natural gas industry, companies have explored and discovered shale gas reservoirs in other basins such as the Illinois, Michigan, Williston, San Juan, Denver-Julesburg, and Fort Worth Basin.

The first New Albany Shale gas wells in the Indiana portion of the Illinois Basin were drilled approximately 120 years ago near Tobacco Landing close to the Ohio River in Harrison County (Sorgenfrei, 1952). These wells started an exploration play in Harrison County that lasted until 1931 when competition from more economic wells in eastern Kentucky and West Virginia forced an end to the flurry of drilling activity (Sorgenfrei, 1952). The history of shale gas production from Harrison County Fields can be found in Sorgenfrei (1952), Sullivan (1995), and Hamilton-Smith and others (2000).

The recent rising demand for natural gas and the corresponding high prices resulted in new and dynamic exploration and production plays in Harrison County. In this paper I will discuss the historical and recent New Albany Shale gas plays in Harrison County, Indiana, focusing on the New Albany gas fields/wells, reservoir zones, completion methods, economics, and structure/fracture relationships. In addition, I will explore the reasons for the rise of natural gas prices and the importance of the New Albany gas in Harrison County as a regional source for present and future natural gas reserves and briefly touch on the importance of other shale gas basins and their role in the U.S. gas markets.

New Albany Shale Gas Fields and Wells
Both fields and single gas wells producing from the New Albany Shale can be found in Harrison, Clay, Crawford, Daviess, Dubois, Floyd, Gibson, Greene, Jackson, Lawrence, Martin, Orange, Pike, Scott, Sullivan, Warrick and Washington Counties in Indiana (Fig. 3.4.1). The most productive gas fields are located in southeastern Harrison County (Fig. 3.4.2). From 1885 to 1991, over 150 shale gas wells were drilled in seven fields from central Harrison County near Corydon to the banks of the Ohio River (Indiana Geological Survey Map No. 30A). Sullivan (1995) reported that most of the gas production in this area came from the Laconia Field. Harris and Esarey (1940) pointed out that over 100 shale gas wells had been completed in the Laconia Field up to 1926. The Kentucky Heating Company, the parent company of the present-day Louisville Gas and Electric Company, was the most active operator until 1920 when the Railroaders' Gas Company was established. After Louisville Gas and Electric shut down their drilling program, the Railroaders' Gas Company continued to develop the Laconia Field. A total of 40 previously drilled gas wells produced 7,500 thousand cubic feet of gas per day (Mcfgpd; M is a Roman numeral and stands for 1000) by the end of 1928. A string of consecutive dry holes and high pipeline construction costs in 1929 pushed the Railroaders' Gas Company into bankruptcy and into the ownership of the Indiana Utility Company.

Competition from newly discovered gas fields in eastern Kentucky and West Virginia made the wells owned by Railroaders' Gas unprofitable and their shale gas operation was shut down in 1931. Indiana Utilities continued to drill five to six wells per year through 1935 (Sorgenfrei, 1952).

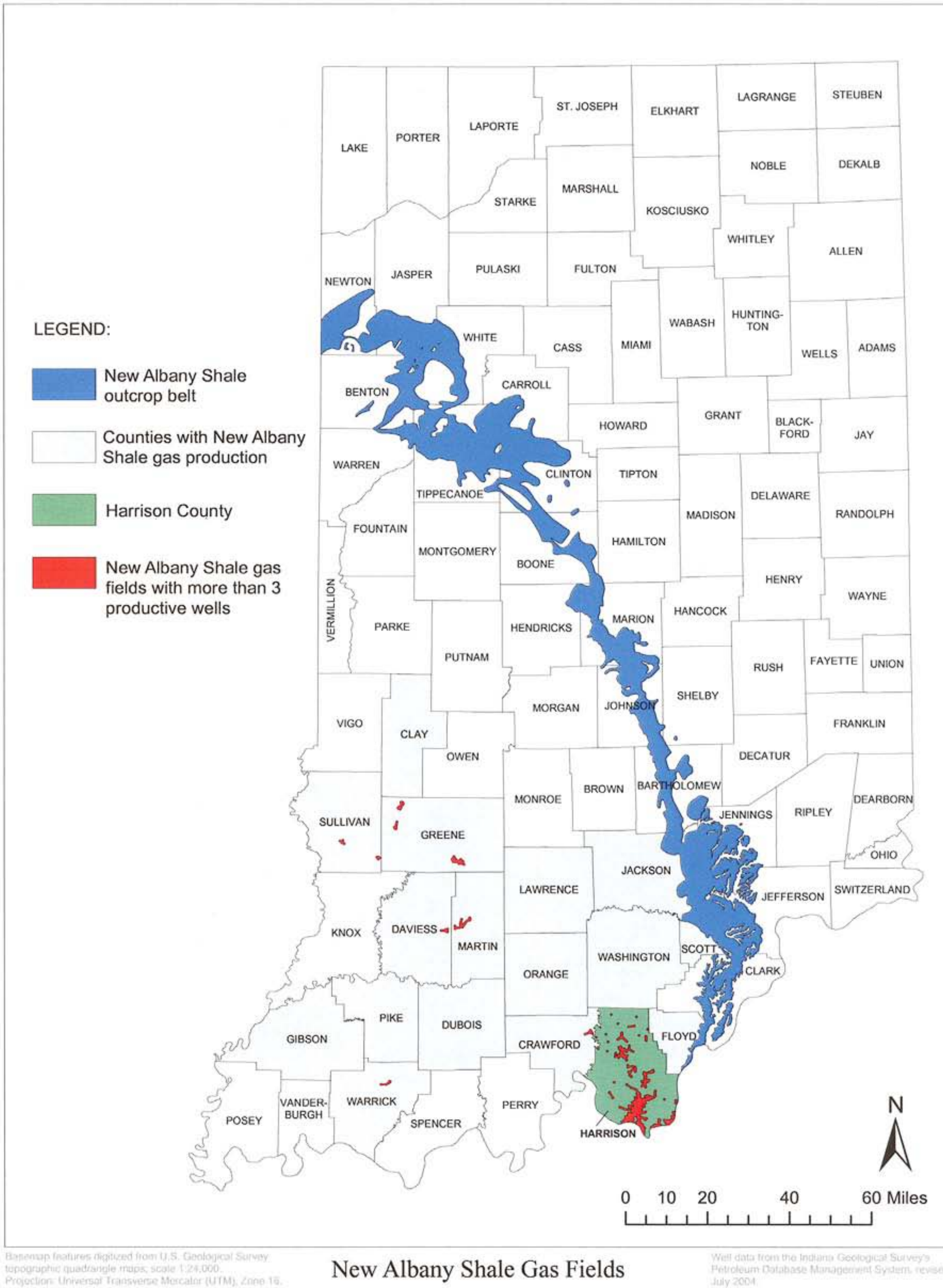


Figure 3.4.1: Map of Indiana showing counties with New Albany Shale gas fields (modified after Indiana Geological Survey Miscellaneous Map 48).

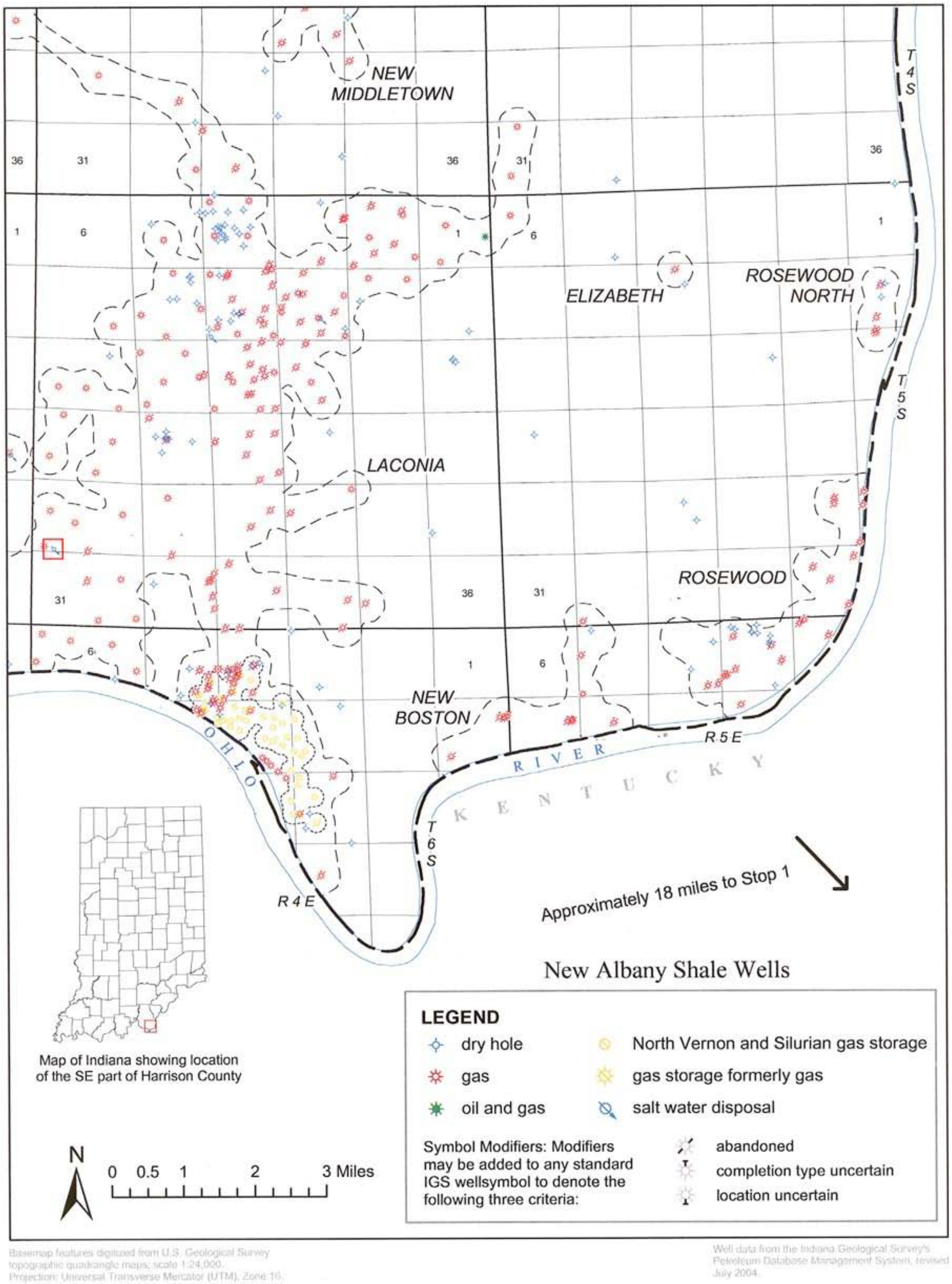


Figure 3.4.2: Map of New Albany gas fields in southeastern Harrison County, Indiana.

From 1935 to 1995, a limited number of wells were drilled for New Albany Shale gas in Harrison County. In 1995 the price of natural gas began to increase and the interest in the New Albany Shale was rekindled. As a consequence, one permit was issued by the Indiana Division of Oil and Gas to Mercury Exploration Company in 1995. From this one drilling permit in 1995, the number quickly escalated to 74 drilling permits by 2003; the natural gas prices followed a similar trend rising from an average wellhead of $1.73 per thousand cubic feet (Mcf) to $5.16 per Mcf (Fig. 3.4.3). The new era for drilling and production of New Albany Shale gas wells remains moderately strong in Harrison County with 26 new drilling permits issued to Quicksilver Resources (formerly Mercury Exploration) through June 30, 2004 (Scout Check Report).

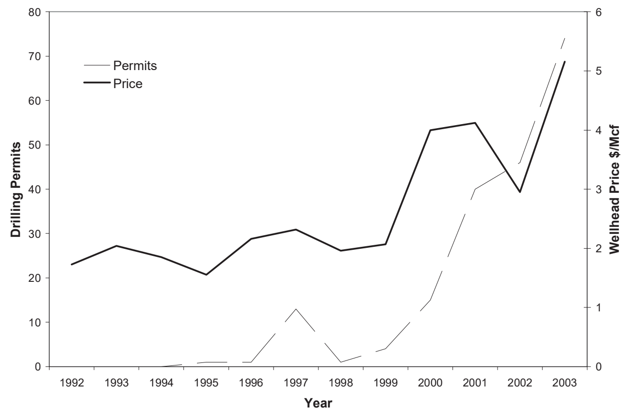


Figure 3.4.3: Comparison of the drilling permits and natural gas price increase from 1992 to 2003. Data from Indiana Geological Survey and Louisiana State University Center for Energy Studies.

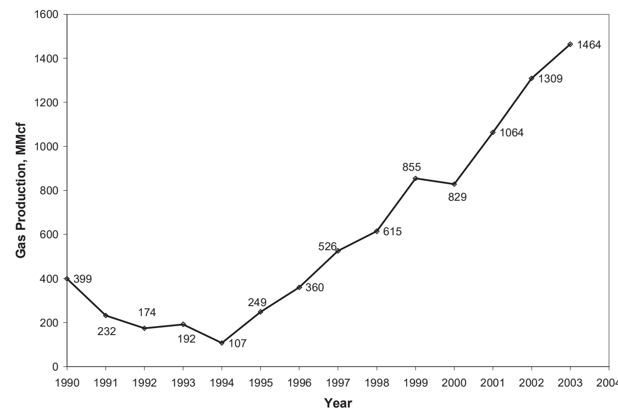


Figure 3.4.4: Annual gas production in Indiana from 1992 to 2002. Data from Indiana Geological Survey.

The increase in drilling has significantly improved the natural gas production in Indiana since 1995 (Fig. 3.4.4). Total gas production was 107,210 Mcfg for 1994 and 1,309,120 Mcfg for 2001 (Cazee, 2002). Much of the jump in natural gas production is attributed to the successful exploration and development of New Albany gas fields in Harrison County as well as in Pennsylvanian coalbed methane wells from Gibson, Knox, Sullivan, and Vigo Counties. The quantity of increased gas production is anecdotally reported to be two-thirds from Devonian shale gas and one-third from Pennsylvanian coalbed methane gas (Charles Zuppann, pers. commun., 2004).

An estimated 5 billion cubic feet of gas was produced from 1885 to 1935 in Harrison County, with 4 Bcf produced by Louisville Gas and Electric (Railroaders' Gas Company) and 1 Bcf by the Indiana Utility Company (Sorgenfrei, 1952). Natural gas production rates recorded for the early wells in the Laconia Field vary with different sources. For example, according to Harris and Esarey (1940), the early wells in the Laconia Field had an average initial production rate of approximately 200 Mcfgpd. Sorgenfrei (1952) listed 17 shale gas wells in the Laconia Field belonging to the Railroaders Gas Company showing a lower average rate of 149 Mcfgpd from a report dated September, 1926. Hasenmueller (1989) reported that initial production rates for all wells in Harrison County on file at the Indiana Geological Survey ranged from a minimum of 24 Mcfgpd to a maximum of 1,100 Mcfgpd. Well completion records from Scout Check Incorporated showed that thirty-one gas wells completed from 1995 to 2002 averaged only 56 Mcfgpd in the Laconia Field. The smallest initial production amount of the 31 wells was 15 Mcfgpd and the largest was 111 Mcfgpd. Newer wells, particularly horizontal ones drilled in 2004, are producing gas at higher rates. It has been rumored among operators that one of the recent 2004 horizontal wells is flowing at a rate of 550 Mcfgpd whereas other vertical wells average about 100 Mcfgpd.

Specific production data for the New Albany is not commonly available because operators often do not report the initial flow rates to the Indiana Oil and Gas Division or to scouting services. Many times, state completion reports filed by operators list the well only as a completed New Albany Shale gas well. The only way to find out the accurate initial production or current producing rate for a gas well is to contact the operator directly. The operator may also request the Division of Oil and Gas to hold production information confidential for two years before information is released to other energy companies.

New Albany Shale Gas Zones

The New Albany Shale is present throughout the southwestern part of Indiana (see Lazar and Schieber, this guidebook). The New Albany Shale overlies Middle Devonian carbonates and generally underlies the Rockford Limestone except in areas where the Rockford is missing, namely, in an area near the Illinois-Indiana state line, in portions of Harrison, Floyd, and Clark Counties, and in other confined localities (Hasenmueller and Leininger, 1987; Hassenmueller, 1989). Throughout Indiana, the New Providence Shale rests directly on the New Albany Shale where the Rockford is missing (Lineback, 1966).

The New Albany Shale is 90 to 100 ft thick in Harrison County (Hasenmueller and Leininger, 1987). The greatest gas-producing zone in Harrison County is found in the upper 15 to 30 feet of the New Albany Shale (Sorgenfrei, 1952). Illinois Basin operators consider this zone, the Clegg Creek Member, to be the primary target for Devonian shale gas production in the Illinois basin (Fig. 3.4.5). Sorgenfrei (1952) also reported a lower zone 6 m to 9 m (20 to 30 ft) above the base of the New Albany that also gave up gas in some wells. Hamilton-Smith and others (2000) interpreted this lower zone to correspond with the Morgan Trail Member. However, it is possible that this lower zone may actually be the Selmier Member. Without a core or sample cuttings, the correlation is strictly based on the log character and an assumed thickness of the New Albany Shale member for the correlation area. I am not aware of any gas production from the middle section of the New Albany.

There is a concern that the gas in the lower part of the New Albany may not be sourced from the shale. Sorgenfrei (1952) indicated that R. E. Henshaw of Louisville Gas and Electric believed that some of the gas in the area was not shale gas but was produced through natural fractures from the underlying Devonian Limestone (North Vernon). There is nothing wrong with producing Devonian carbonate gas with shale gas but problems can occur if (1) the operator does not have a drilling permit to the depth of the North Vernon, (2) the North Vernon produces an excessive amount of saltwater, or (3) drilling takes place above a storage field. In Harrison as well as other counties such as Greene, Daviess, and Pike, local gas storage operators have indicated that the New Albany is considered to be part of the cap rock for the underlying Devonian carbonate storage field. Therefore, Henshaw was probably correct in stating that some gas considered to be New Albany Shale was coming from the deeper North Vernon Limestone (Sorgenfrei, 1952). During an unpublished study of the Greene County storage fields, I witnessed on numerous occasions where later gamma-ray-neutron logs clearly illustrated that storage gas had migrated upward into the overlying New Albany Shale from the

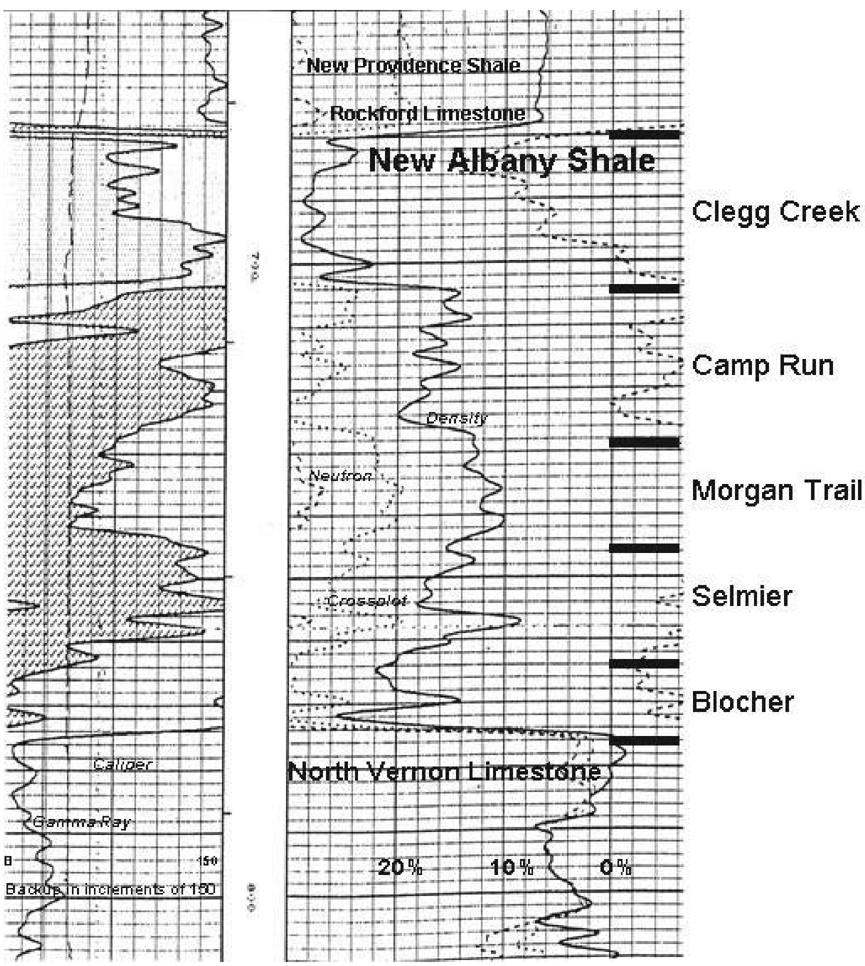


Figure 3.4.5: New Albany Shale members on the Gamma Ray/Density-Neutron log of Quicksilver D1-30 SWD well, located at 220 ft x 550 ft SW-SW-SW of 30-T5S-R4E, Harrison County, Indiana.

Devonian carbonate rocks. The gas kick seen on the gamma-ray-neutron logs is strong evidence for natural fracture communication between the New Albany and the underlying Middle Devonian.

Completion Methods

Based on my own experience, there is a high percentage of completion failures when fractures are not present in the New Albany Shale wells. Fractures must intersect or be near the wellbore for a successful gas well completion. Since the fractures serve as a conduit for the gas in the shale, knowing the trend and intersection of fractures is an important exploration and development tool when searching for the most productive gas wells and fields. Published core data on natural fractures in the New Albany are available for the Anschutz-No. 16-19 Voelkel well in Dubois County, Indiana, the Energy Resources of Indiana-No. 1 Phegley Farms well in Sullivan County, Indiana, and the Orbit No. 1 Clark well in Christian County, Kentucky. Fractures in these cores were near vertical features striking northwest-southeast; a secondary set strike was slightly north of east-west (Hamilton-Smith and others, 2000).

Several types of well completion methods have been used to enhance natural fractures in an attempt to increase the flow of natural gas trapped in the New Albany Shale to the bore hole. In the early years until the mid-1950s, a gelatinated nitroglycerine charge was exploded in an open hole or across from a perforated interval in the production pipe. In the 1980s and 1990s, most Indiana operators switched to a nitrogen-foam fracture to stimulate the New Albany Shale. The nitrogen-foam method usually included 500 gallons of 15 percent hydrochloric acid and a mixture of 250 barrels potassium chloride nitrogen-foamed water with 60,000 pounds of sand used as a proppant (to keep newly created fractures open). This completion procedure used pressure to hydraulically fracture the zone of interest. In Harrison County, some wells using the nitrogen-foam frac method communicated with other wells decreasing the flow of natural gas and increasing the flow of saltwater (Mark Jones pers. commun., 2004). The two most recent forms of stimulation used for vertical shale gas wells are (1) the foam fracs which consist of 12,000 to 15,000 gallons of foam and nearly 100,000 pounds of sand and (2) the cross-link fracs which encompass 300 to 500 barrels of cross-linked fluid and about 100,000 pounds of sand. The larger amounts of sand proppant are creating better drainage avenues and thus better gas wells (Jerry Robinson, pers. commun., 2004).

Structure and Gas Production

The New Albany Shale gas production in Harrison County is associated with structural terraces, anticlines, and closures (personal studies; Sorgenfrei, 1952; Bassett and Hasenmueller, 1981; Hamilton-Smith and others, 2000). Significant positive structural anomalies are present near the cities of Corydon, New Middletown, Laconia, and an area approximately seven miles east of Laconia. The regional dip in Harrison County is about 30 ft per mile. Relative to sea level, the top of the New Albany Shale dips from +262 ft along the eastern edge of the county to –339 ft on the western border of the county. The structural closure on the Laconia Field, for example, is 30 ft and there appears to be a fault along the eastern side of the field (personal study in progress). The Laconia structural anomaly is not associated with any thickness anomalies, suggesting postdepositional deformation as the cause. Based on initial production rates on Scout Check completion cards, the majority of the most productive New Albany gas wells in the Laconia Field are associated with the positive structural anomaly. Concentrations of natural fractures are probably closely coupled with the Laconia structure.

Economics of a New Albany Shale Gas Well

The costs that are necessary to consider when drilling, completing, and equipping a New Albany Shale gas well for production are numerous, expensive, and variable depending upon the operator. An estimated expenditure for drilling and completing a well in Harrison County may be as high as $175,000 plus $1,500 per month per well for operating and production costs. Simple economic calculations can be used to determine the value of such a well. Consider, for example, the case of a conservative well that produces an average 50 Mcfgpd for 20 years; consider further a 0.875 net working interest, and a wellhead price of $5/Mcf. The return on investment is calculated as follows:

Total Production: 50Mcfgpd x 365 days x 20 years……………………………….365,000 Mcf
365,000 Mcf x $5/Mcf…………………………………………………….....$1,825,000
Less royalty interest of 0.125……………………………………………........$ 228,000
Less drilling and completion costs………………………………………………$175,000
Less operating and production costs of $1500/month x 12mo. x 20 yrs……………$360,000
Net working interest income…………………………………………………....$1,061,875
R.O.I.: $1,061,875 ÷ $175,000 = 6.1 to 1

The above scenario can change abruptly because of the numerous variables and assumptions applied to the above calculations. For example, the total depth of a New Albany gas well may range from approximately 300 ft to 1,000 ft. The total depth of the well will change significantly the costs of drilling and completion. Other cost factors to consider when establishing the prospect economics are:

- Geology, seismic, and well design
- Lease acquisition, surveying location, state permit, depth, and drilling/completion
- Well head equipment, gas production facilities, water disposal system, and gas compression
- Production maintenance, gas transportation, and labor
- Price of natural gas at the wellhead, royalties / over-rides, and production / severance taxes
- Completion method, gas production rate, the number of produced barrels of salt water to be lifted and deposed, and the time to de-water the well

The economics for drilling New Albany Shale gas wells in Harrison County is attractive to operators at the present time. Reasons driving the favorable economics include a high success rate, the long life of the well, slow production decline rates, inexpensive exploration costs, moderate drilling and operational expenses, the high price of natural gas, and the soaring demand for an environmentally cleaner-burning fuel source. As with any exploration play, the supply and demand for the use of hydrocarbons is critical to the economics.

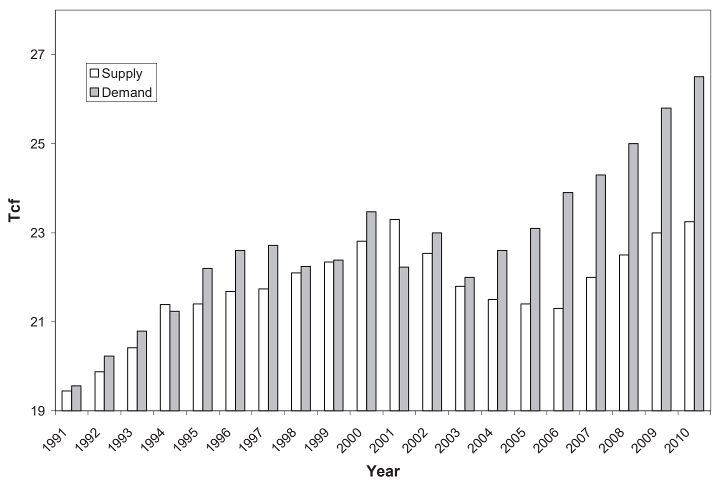


Figure 3.4.6: Supply and demand for natural gas in the U. S. Data from the Energy Information Administration, April 2004.

Demand for Natural Gas and High Prices

If not for the rise in natural gas prices (Fig.3.4.6), it is doubtful that the current exploration play in Harrison County would have ever become a reality. A good working knowledge of the background reasons for the increased price of natural gas from $2 to $6 per Mcf is necessary before a large outlay of capital is expedited. The companies involved presumably did their research and anticipated higher gas prices before spending significant amounts of money pursuing large leaseholds in Harrison County. There are at least five causes that pushed the price of natural gas in an upward direction:

1. The increased use of natural gas to generate electricity. The national trend is to build gas-fired peaking plants to meet the incremental electricity requirements. The U.S. uses more electricity than any other country in the world and gas-fired units are expected to exceed a demand of 3.35 trillion cubic feet (Tcf) by 2010 and 5.7 Tcf by 2015 (Weissman, 2003).
2. Production output is lagging behind the demand for natural gas due to the maturity of the U. S. gas fields and the rapid aging of the large Canadian fields. No longer can the number of drilling rigs outpace depletion and production declines. A record 6,300 gas wells is required each year to maintain demand in Western Canada; more than 7,500 completions would be required to outpace demand (Beims, 2000).
3. Natural gas production has plateaued even with the deep-water exploration and despite the huge potential of the Gulf of Mexico (Shirley, 2004). Problems with the deep shelf gas play at a depth of 15,000 feet are numerous. They include the need for perfecting seismic interpretation, improving inadequate drilling fluids, and maintaining safety during drilling-completion procedures due to high pressures and temperatures. In addition, the drilling of a well in a high-risk environment where the potential exists to lose a $10 million investment is not acceptable for many exploration companies. The U.S. Minerals Management Service estimates that the area may hold 55 Tcf (Shirley, 2004).
4. The Rocky Mountain area produces about 15 percent of the North American gas supply (Beims, 2001); however, the anticipated gas production has not met industry expectations. Proven gas reserves are 36 Tcf and additional

estimated resources are 346 Tcf (Beims, 2001). The exploration effort for this area requires a significant cash outlay, an improved drilling technology, and a great deal of regulatory patience (Beims, 2001). Until these roadblocks are overcome, drilling will be slow going in the Rockies.

5. Natural gas from the North Slope in Alaska is stranded until a North Slope pipeline is constructed. It is estimated that 35 Tcf has been discovered. Alaska is the third largest gas-producing state with 9.6 billion cubic feet per day. Natural gas reserves are projected to be nearly 200 Tcf in the Alaskan North Slope, Mackenzie Delta area, and the Arctic Islands (Woods, 2001).

Supply of Natural Gas in U.S. Shale Basins

The Harrison County gas wells are a large part of Indiana's current New Albany Shale production. Harrison County and the other counties (Clay, Crawford, Daviess, Dubois, Floyd, Gibson, Greene, Jackson, Lawrence, Martin, Orange, Pike, Scott, Sullivan, Warrick, and Washington) having shale gas production in the Indiana portion of the Illinois Basin are part of a larger group of fractured shale basins. These shale gas basins, namely, the Appalachian, Michigan, Fort Worth, San Juan Williston, Denver-Julesburg and Illinois all contain significant shale gas reserves (Hill and Nelson, 2000). The New Albany in Harrison County and other shale gas Indiana counties are similar to the Antrim Shale in the Michigan Basin (Table 3.4.1); the reservoir characteristics of the New Albany in western Kentucky is more like that of the Ohio Shale in the Appalachian Basin (Hill and Nelson, 2000). According to the Gas Research Institute there are trillions of cubic feet of gas to be recovered from the continental shale gas basins (Table 3.4.2).

Property	Barnett	Ohio	Antrim	New Albany	Lewis
Depth, ft	6,500-8,500	2,000-5,000	600-2,200	500-2,000	3,000-6,000
Gross Thickness, ft	200-300	300-1,000	160	180	500-1,900
Net Thickness, ft	50-100	30-100	70-120	50-100	200-300
Bottomhole Temp.,^{0}F	200	100	75	80-105	130-170
TOC%	4.5	0-4.7	1-20	1-25	0.45-2.5
% R_0	1.0	0.4-1.3	0.4-0.6	0.4-1.0	1.6-1.88
Total Porosity, %	4-5	4.7	9	10-14	3-5.5
Gass Filled Porosity, %	2.5	2.0	4	5	1-3.5
Water Filled Porosity, %	1.9	2.5-3.0	4	4-8	1-2
Kh, md-ft	0.01-2	0.15-50	1-5,000	NA	6-400
Gas Content, scf/ton	300-500	60-100	40-100	40-80	1-45
Adsorbed Gas, %	20	50	70	40-60	60-85
Reservoir Pressure, psi	3,000-4,000	500-2,000	400	300-600	1,000-1,500
Pressure Gradient, psi/ft	0.43-0.44	0.15-0.4	0.35	0.43	0.2-0.25
Well Costs, $1000	450-600	200-300	180-250	125-150	250-300
Cpm[letion costs, $1000	100-150	25-50	25-50	25	100-300
Water Production, Bwpd	0	0	5-500	5-500	0
Gas Production, Mcf/d	100-1,1000	30-500	40-500	10-50	100-200
Well Spacing, Acres	80-160	40-160	40-160	80	80-320
Recovery Factors, %	8-15	10-20	20-60	10-20	5-15
Gas-In-Place Bcf/Sec.	30-40	5-10	6-15	7-10	8-50
Reserves, MMcf	500-1,500	150-600	200-1,200	150-600	600-2,000

Table 3.4.1: Key properties for five productive gas shales in the U. S. (modified after Hill and Nelson, 2000).

Table 3.4.2: U.S. gas-bearing shale resources in historically productive plays (modified after Hill and Nelson, 2000).

Basin	States	Major Shale-Bearing Formation or Group	Basin Area (mi2)	Total Organic Carbon (TOC)%	Thermal Maturity (%R0)	Shale Gas-in-Place Resource (Tcf)		Estimated Recoverable Shale Gas Resource (Tcf)		Estimated Total Undiscovered Shale Gas Resource (Tcf)
Appalachian	OH, KY, NY, PA, WV, VA	Ohio Shale	160,000	0.4-4.5	0.4-1.3	225-248	1980 & 1992 NPC Estimates	14.5-27.5	1980 & 1992 NPC Estimates	90.7
Michigan	MI, IN, OH	Antrim Shale	122,000	1-20	0.4-0.6	35-76	1980 & 1992 NPC Estimates	11-18.9	1992 NPC & 1995 USGS Estimates	40.6
Illinois	IL, IN, KY	New Albany Shale	53,000	1-25	0.4-10	86-160	1980 & 1992 NPC Estimates	1.9-19.2	1992 NPC & 1995 USGS Estimates	NA
Fort Worth	TX	Barnett Shale	4,200	4.5	1.0-1.3	NA		3.4-10.0	Schmoker, 1996 Kuuskraa, 1998	NA
San Juan	CO, NM	Lewis Shale	1,000	0.45-2.5	1.6-1.88	96.8	1997 Burlington Resource Estimate	NA		NA

The U.S. is entering a new phase for natural gas consumption and demand. The current gas price of \$5 to \$6/Mcf makes what was not such an economically attractive shale gas play 10 years ago a good investment today. The New Albany gas wells in Harrison County and shale gas wells in other basins will add to the needed supply of natural gas for the U.S. markets.

Concluding Remarks

Gas production from the New Albany Shale in Harrison County has had a long history. The drilling and development of the New Albany in Harrison County was abundant and profitable in the late 1800s and early 1900s and a similar scenario is present today. The big difference is the ominous near-future shortage of natural gas in the United States. There is a lot of undrilled acreage in Harrison County and plenty of room to expand existing fields and discover new ones. In addition to the relatively large geographic areas the New Albany Shale covers, the long-lived reservoirs and attractive finding costs will keep the exploration play strong as long as the gas prices will support the financial investment. The Clegg Creek Member is the most productive gas zone within the New Albany section. Approximately 100 wells were drilled during the historical era of Harrison County; it is apparent that this new flurry of drilling activity will surpass that number. Key exploration parameters are the positive structures and associated natural fractures. The larger frac methods used to prop open existing fractures are the most efficient completion techniques so far. Although operators in other counties have not attained the success reached in Harrison County, it may be just a matter of more exploratory wells before more economical fields are discovered.

Acknowledgements

Conversations concerning the New Albany Shale with D. Busch, J. Schieber, N. Hasenmueller, J. Robinson, M. Jones, C. Zuppann, D. Jones, and J. Rupp have been very informative during the past years. I would like to thank J. Schieber, R Lazar and B. Keith for their excellent suggestions that led to a more organized paper and G. Partin for preparing figures and proofreading. I am grateful to Renee Stubenrauch for the maps prepared and the use of records on file at the Indiana Geological Survey.

4. Presentation Abstracts

4.1. Unlocking Geological History: The Key Roles of Mudstones and Sequence Stratigraphy

by

Kevin M. Bohacs, George J. Grabowski, Jr,, Jack E. Neal,
ExxonMobil Upstream Research Company
3120 Buffalo Speedway
Houston, Texas 77098
email: Kevin.M.Bohacs@exxonmobil.com

Mudstones contain the bulk of the sedimentary record and are vitally important to reconstructions of paleoclimate and paleoenvironments, as well as containing signficant economic resources. They provide the source and seal of hydrocarbons, host mineral ores, and are key elements in ground-water and reservoir models as baffles and barriers. Sequence stratigraphy provides a robust and helpful framework within which to integrate the many scales of physical, chemical, and biological observations necessary to understand these rocks across the spectrum of depositional settings. Flooding surfaces and depositional-sequence boundaries, although subtly expressed in mudstones, can, however, be recognized through distinct changes observed in core, outcrop, well-logs, and on seismic data. Beyond the chronostratigraphic utility of the correlative conformity, abundant paleoenvironmental information is recorded in fine-grained strata; depositional sequences do not just fade away into obscurity in distal reaches, but have objective attributes that allow extension of stratigraphic frameworks and rock-property predictions over very large areas.

Depositional-sequence boundaries record a critical decrease in accommodation relative to sediment supply, commonly accompanied by an increase in depositional energy or a significant change in sediment supply, or both, over hundreds to thousands of square kilometers in both fine- and coarse-grained lithologies. This is recorded even in fine-grained lithofacies by regional erosional truncation with subsequent onlap, exposure, reworked fossils, decreased continuity at lamina to bedset scale, along with increased accumulations of advected clastics and fossils or secular changes in biogenic lithology. All these attributes (except subaerial exposure) are observed in physically correlative distal reaches of unconformities across their correlative conformities.

Flooding surfaces fundamentally record a critical increase in accommodation relative to sediment supply, commonly recorded in mudstones by laterally extensive accumulations of authigenic and pelagic components, along with evidence of sediment starvation and low bottom-energy levels. Some may record minor erosion, reworking, and lag formation due to low sediment supply, but all are marked by a significant decrease in advected clastic input, in distinct contrast with sequence boundaries.

Interactions of sediment supply and accommodation with preexisting topography control the expression of depositional sequences. Marine environments tend to have the most widespread, gradually varying facies tracts, whereas paralic facies tracts tend to be most localized and abruptly changing. Lacustrine sequences vary according to lake-basin type, and range from very similar to shallow-marine siliciclastic sequences to very dissimilar.

4.2. Geochemical Paleoredox Indicators: What Can They Tell Us about Devonian-Mississippian Black Shales?

by
Susan M. Rimmer
216 Slone Building
Department of Geological Sciences
University of Kentucky
Lexington, KY 40506-0053
Phone: 859-257-4607
e-mail: srimmer@uky.edu

The degree of anoxia that existed during accumulation of Devonian-Mississippian black shales in central Kentucky has been debated. Various geochemical paleoredox indicators can be used to decipher paleodepositional environments for these units, such as C-S-Fe relationships, degree-of-pyritization (DOP), redox-sensitive trace-element enrichments (e.g., Mo), geochemical ratios including Ni/Co, V/Cr, and V/(V+Ni), and framboid-size analysis, among others. Several of these have been applied to a series of cores from the outcrop belt in central Kentucky to evaluate redox conditions during accumulation of the Sunbury Shale (Tournasian, Lower Mississippian) and the Cleveland and Huron Members of the New Albany Shale (Famennian, Upper Devonian).

C-S-Fe relationships and DOP values suggest variable redox conditions for these units, with anoxic, possibly even euxinic, conditions during accumulation of the Sunbury Shale; anoxia with intermittent dysoxia is implied for the Cleveland Member; and a relatively wide range of conditions, from anoxic, to dysoxic, to possibly oxic may have existed during Huron accumulation. In addition, these units exhibit different degrees of trace-element enrichment, with the approximate order of enrichment relative to an average shale being Mo > Pb > Zn > V > Ni > Cu > Cr > Co. The Sunbury shows the highest levels of enrichment, followed by the Cleveland, with the Huron showing only slight enrichment for most of these trace elements. Geochemical ratios, including Ni/Co, V/Cr, and V/(V+Ni), also indicate variable paleoredox conditions for these shales. Interestingly, V/(V+Ni) ratios tend to indicate consistently lower oxygen regimes than do other paleoredox indicators, and this discrepancy is greatest for the Huron Member.

It is suggested that thresholds established for paleoredox indicators in previous studies should not be applied strictly, but that *relative* differences in these indicators *collectively* can infer variations in the degree of anoxia. It is likely that the Devonian-Mississippian black shales of central Kentucky accumulated under variable bottom-water conditions. At least anoxic conditions prevailed during accumulation of much of the Sunbury Shale and the upper part of the Cleveland Member, and possibly euxinic conditions for the Sunbury. Bottom-water conditions may have been intermittently anoxic and dysoxic during deposition of the lower Cleveland. During accumulation of the Huron Member, it is likely that conditions ranged from anoxic to dysoxic, and possibly to marginally oxic during accumulation of the lowermost part of the Huron.

4.3. Connecting the Dots: Sequence Stratigraphic Correlations in Devonian Black Shales of the Eastern U.S. and Relationship to Global Sealevel Variations

by
Juergen Schieber
Department of Geological Sciences
Indiana University
Phone: 812-855-5322
e-mail: jschiebe@indiana.edu

Although the Late Devonian black shales of Tennessee, Kentucky, Indiana, and Ohio are known under various names depending on location, most subunits are contiguous over large areas. In Tennessee, initial sequence stratigraphic studies have shown that the Chattanooga Shale can be subdivided into as many as 14 erosion-bounded shale packages (Fig. 4.3.1).

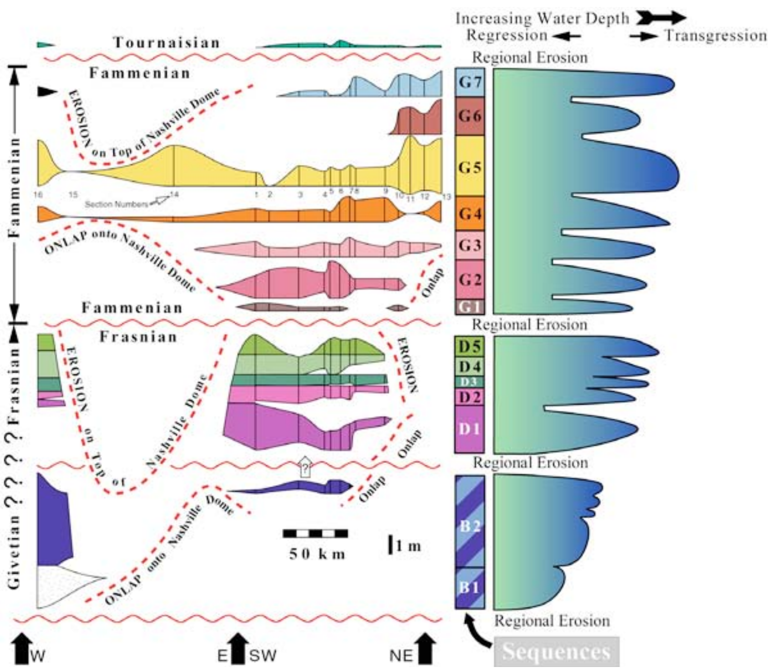


Figure 4.3.1: Sequence stratigraphic subdivision of the Chattanooga Shale (Schieber, 1998b). The succession forms three packages that are separated by regional erosion surfaces. Geometric presentation of "slices" takes into account observed amounts of erosion on top, and perceived onlap on the Cincinnati Arch/Nashville Dome. Geometry may need to be modified as more conodont data become available. The vertical dimension of "slices" is the actual thickness, and the sequences thin due to smaller rates of net deposition closer to the arch. Evaluation of currently available data led to synthetic sea-level curve at right. The question marks between the Givetian and the Frasnian indicate the current uncertainty about the age of the lowermost package. Preliminary conodont data (courtesy Dr. J. Over, SUNY Geneseo) suggest that sequence B1 may be latest Givetian, and that sequence B2 may be lower Frasnian in age. This suggests that the B1-B2 interval falls into the same age bracket as the Blocher/Trousdale interval in Kentucky and Indiana. The color coding for the sequences in this and successive figures is intended to highlight intervals that are likely correlatives across the study area.

The subdivisions in Figure 4.3.1 are based on outcrop studies in central Tennessee and south-central Kentucky that revealed extensive erosion surfaces (Schieber, 1994, 1998a, 1998b) that formed in response to sea level drop (Schieber and Riciputi, 2004) and are the basis of a sequence stratigraphic approach. In the subsurface of Indiana, sequence boundaries are identified by a combination of core studies and tracing of gamma-ray signatures from the outcrop belt (Schieber, 2000). In addition, truncation of gamma-ray motifs provides independent confirmation of sequence boundaries in the subsurface (Johri and Schieber, 2000).

How the scheme in Figure 4.3.1 carries over into areas further to the north is shown in Figure 4.3.2. What the figure also shows very clearly is the significant thickness changes of the Devonian black shale succession across the area. From less than 10 meters at locality 6 (Tennessee) it swells to more than 500 meters in northeastern Ohio (loc. 4). What also becomes apparent is that there are considerable differences in the time interval that the sections represent in different areas. For example, the Chattanooga Shale interval in Tennessee covers approximately the same time interval as the New Albany Shale in Indiana (see paper by Lazar and Schieber, this guidebook, Fig. 1.1), but the Chattanooga Shale in south-central Kentucky (loc. 5, Fig. 4.3.2) has little stratigraphic overlap with the type Chattanooga Shale in central Tennessee. All of the Dowelltown Member (Frasnian) and the lower half of the Gassaway Member are missing, and we pick up new units (*Foerstia* through Cleveland Shale interval) that are not common (though preserved locally) further south. Such disparities in the stratigraphic succession between outcrop areas have caused considerable confusion in earlier attempts at detailed correlations in the past. As long as one adhered to the (now defunct) dogma that these black shales represented condensed but by and large continuous successions, "successful" correlation was only possible through postulation of (however improbable) lateral facies changes.

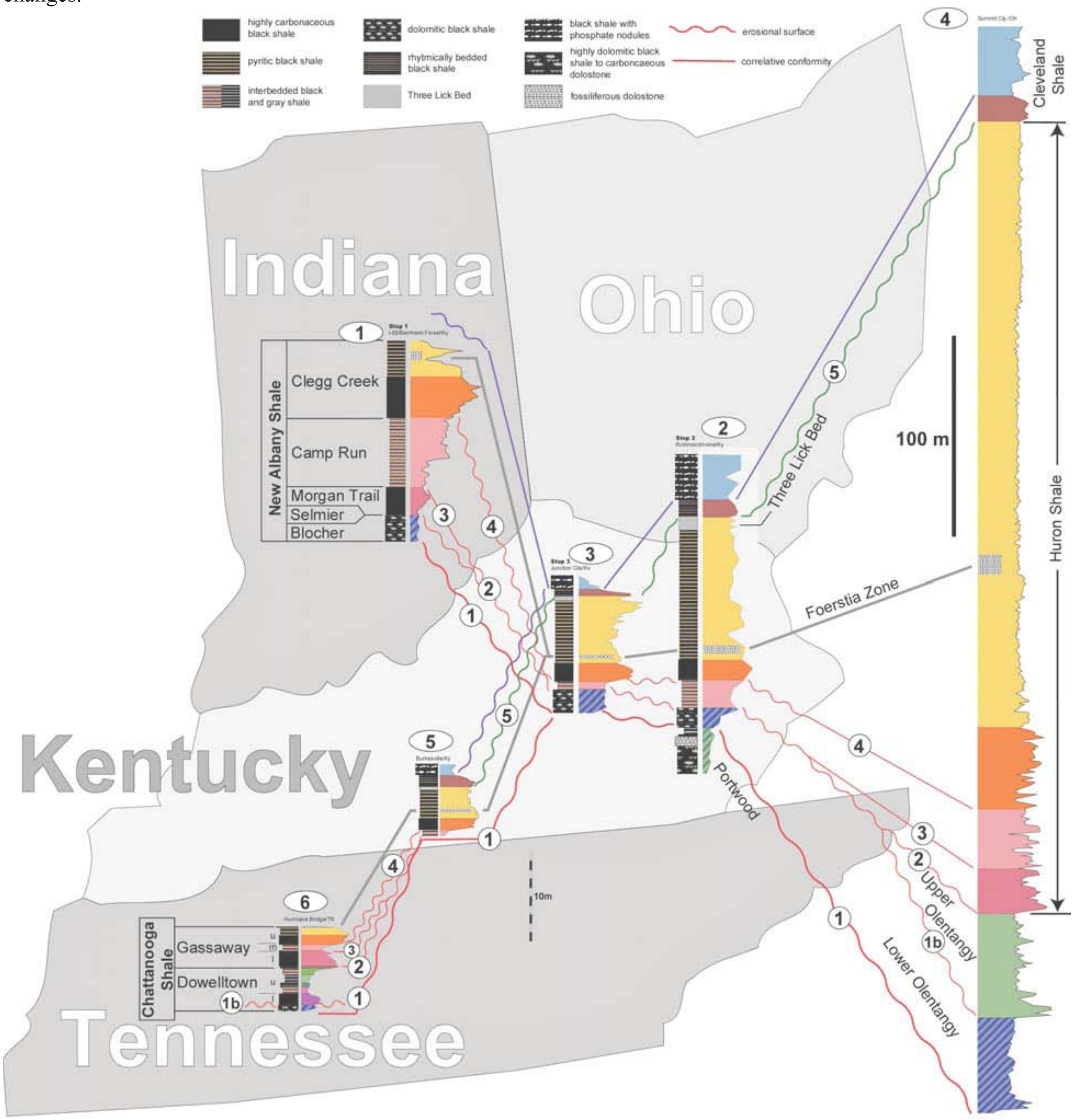


Figure 4.3.2: Stratigraphic overview for Tennessee, Kentucky, Indiana, and Ohio. Numbers in white ovals are localities of sections, placed in their approximate geographic position on the underlying map. Localities 1 through 3 are the stops discussed in the road log (Section 2, this guidebook). Locality 4 is an interpreted gamma-ray log from a well in northeastern Ohio, and is not at the same scale as the other sections (it would need to be expanded by a factor of 4.5 to be the same scale). The section for locality 1 has been moved NW (into Indiana) in order to allow space for

correlation lines. The displacement is permissible because this section (with the Selmier Member missing) is also representative of New Albany sections one might encounter along the outcrop belt in SE Indiana. Numbers in circles correspond to erosion surfaces examined in the road log stops. The Dowelltown Member of Tennessee (Frasnian), the temporal equivalent of the Selmier Member of Indiana, can be subdivided into several subunits (see also Fig. 4.3.1), that have yet to be recognized in other Frasnian intervals of the study area. In Ohio, the Frasnian equivalent of Selmier and Dowelltown is known as the Upper Olentangy Shale, and the Trousdale/Blocher equivalent is known as the Lower Olentangy Shale. In Tennessee, strata that are age-equivalent to the Blocher/Trousdale interval occur only locally as erosional remnants (below surface 1b). The thickest-developed Blocher equivalent sections outcrop near Olive Hill/Tennessee (east of Savannah/TN), in the western vicinity of Nashville/TN, and in the Flynn Creek impact crater (south of Gainesboro/TN). In many other areas no Blocher age strata are preserved. Color coding matches Figure 4.3.1. The base of the Cleveland Shale (erosion surface 5) is clearly an erosion surface in NE Ohio (locality 4), yet how much erosion occurred elsewhere in the basin and what its relationship is with regard to the Three Lick Bed is not as clear-cut. This still requires a careful determination of the origin of the Three Lick Bed (as indicated in the description of Stop 2, this guidebook). There is also an upper portion of the Cleveland Shale that contains phosphate nodules in black shale matrix, and in places in Tennessee and Kentucky this portion is in erosional contact with underlying shales. How consistent this erosional contact is still must be determined. Reworking of these phosphate nodule-bearing shales during the terminal Devonian to Kinderhookian regression probably provided the raw material for the Falling Run Bed, the erosional lag that separates Devonian from Mississippian strata in many areas.

Black shales may have been deposited in comparatively shallow water, within wave base of strong storms (Schieber, 1994, 1998a) in the vicinity of the Cincinnati Arch, as well as in the deeper water of basins adjacent to the Cincinnati Arch (Illinois and Appalachian Basins). Sequences may diminish in thickness or disappear completely as we approach the Cincinnati Arch, reflecting onlap as well as erosion during emergence of the arch (Fig. 4.3.1). Using available biostratigraphic data, detailed lithostratigraphic correlations, and matching of transgressive-regressive cycles, it is possible to link the sequences in the study area to equivalent Devonian strata in Iowa, New York, and to the global Devonian sea-level curve. Figure 4.3.3 shows the global TR cycles proposed by Johnson et al. (1985), starting with the Taghanic onlap, the base of TR cyle IIb and also the base of the Portwood interval (see contribution by Brett et al., this guidebook).

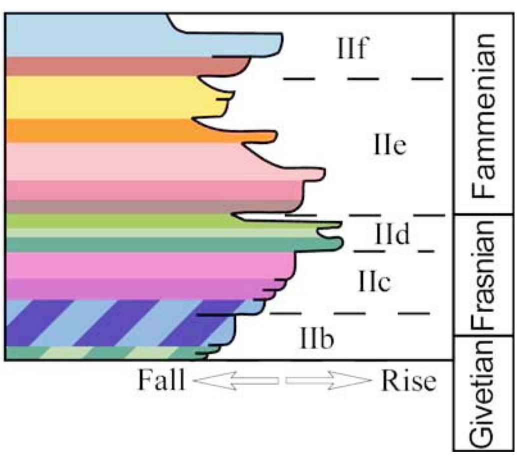


Figure 4.3.3: Tentative correlation of the global TR cycles of Johnson et al. (1985) with the sequences (color stripes) recognized in the Late Devonian black shales of the eastern U.S. Color coding matches Figures 4.3.1 and 4.3.2. Note that the Blocher/Trousdale interval straddles TR cycles IIb and IIc. Improved conodont data and tracing of lags/erosion surfaces should allow reproducible subdivision of this interval in the future, permitting the placement of the TR IIb/IIc boundary. Correlation of sequences to the bases of TR cycles agrees with available conodont data (Sandberg et al., 1994; Over, 2002). Matching of sequences to subsidiary transgressions within TR cycles is consistent with available conodont data, but additional confirmation is highly desirable. Overall, the match-up suggests that currently recognized sequences largely reflect eustasy.

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Roadmap to Field Trip Locations from New Albany, Indiana