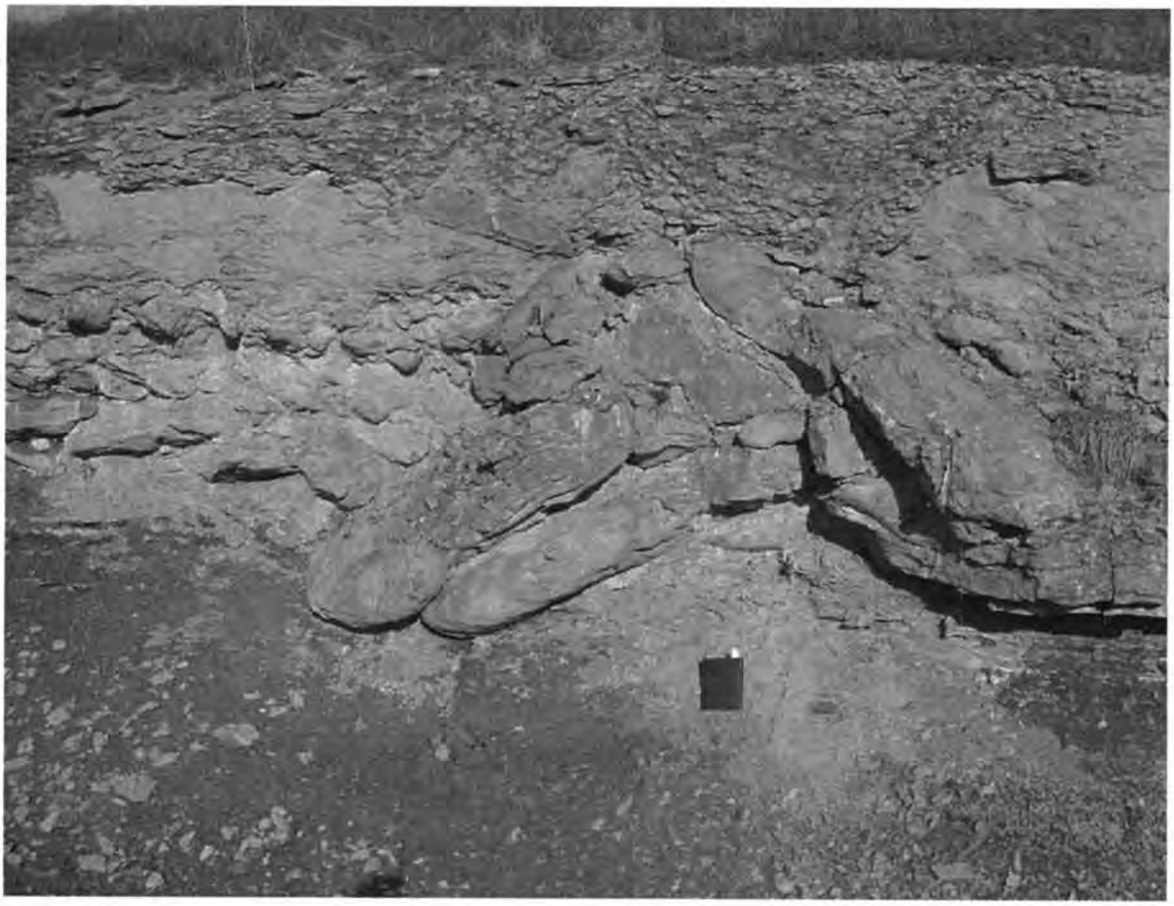
Guidebook for Geology Field Trips in Kentucky and Adjacent Areas

Edited by
Frank R. Ettensohn
and
Margaret Luther Smath



2002 Joint Meeting of the North-Central Section and Southeastern Section of the Geological Society of America, Lexington, Kentucky

Kentucky Geological Survey
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Field Trip Guidebook
in conjunction with the
2002 Joint Meeting of the North-Central Section and
Southeastern Section of the Geological Society of America
Lexington, Kentucky

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Our mission is to increase knowledge and understanding of the mineral, energy, and water resources, geologic hazards, and geology of Kentucky for the benefit of the Commonwealth and Nation.

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Editors' Introduction

The study of Kentucky's geology has been an ongoing pursuit since the first formal geologic studies in the state in the 1740's, and the state provides an interesting array of rocks and sediments from the Precambrian basement to Pleistocene drift. Although many view the state as an area of simple, layer-cake sedimentary units that have been uplifted and truncated along the Cincinnati Arch, the geology has proven to be much more complex, because the state is underlain by two basement rift systems that have been periodically reactivated. As a result, our layer-cake units are not so uniform and contain many unexpected and complex variations that result from the interaction of reactivated structures with eustatic sea-level changes. These rocks also have many environmental, cultural, and economic implications for the state, and we will be examining many of these aspects on our trips. Hence, we welcome you to Kentucky, and are pleased to show you some of the continuing work of geologists from the Kentucky Geological Survey, as well as that of students and faculty from several universities in the state and just beyond the state. We also eagerly welcome your comments and questions; in fact, it is our hope that you may even help us to see things a little differently than we now do.

Our role as editors of this guidebook was to establish guidelines and collect manuscripts in a timely fashion. We assembled the guides and made minor changes in format and grammar for consistency, but otherwise the guides have not been reviewed or altered from the manuscripts delivered to us by trip leaders. We are very grateful to all our field trip leaders and our participants for making this guide possible.

Frank R. Ettensohn
Margaret Luther Smath

March 2002

Cover Photo: Two horizons of possible seismites from the upper tongue of the Tanglewood Member, Lexington Limestone, which foundered into an underlying tongue of the Clays Ferry Formation, on U.S. 127 near Lawenceburg, Ky. Stop 5 on field trip 9. Photo by F. Ettensohn.

Contents

Carbonate Buildups in the Fort Payne Formation (Lower Mississippian), Cumberland County, Kentucky

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Introduction

This field trip, focusing on the carbonate buildup facies of the Fort Payne Formation of southern Kentucky, was organized to showcase a series of spectacular new roadcuts that have been developed in the past few years just north of Burkesville. Previous studies of the Fort Payne buildups, conducted mostly on the shores of Lake Cumberland (Fig. 1), have at times been hindered by excessively weathered, and incompletely exposed outcrops. However, the new outcrops offer a unique perspective in that they show fresh exposure of key contacts, and contain, in one very localized area, the complete lower Fort Payne Formation. To offer a complete view of the variability of the buildup interval, several older, well-studied lower Fort Payne cuts south of Burkesville will be examined as well. By the end of the day, we hope to have provided an in-depth look at both the enigmatic buildups and their surrounding facies. Above all, we wish to generate discussion of our ideas (and yours) about the genesis of carbonate buildups and the implications it had for the paleoenvironment of the Fort Payne Formation in this region.

The study area offers plenty of exciting questions for sedimentologists, stratigraphers, and paleontologists alike, only some of which can be answered at present. The exposures we will study offer an unprecedented look at a unique phenomenon: the nucleation, growth, and termination of a series of carbonate buildups. Some of the questions to be addressed are as follows: What factors (physical or biological) were important for the inception of mound growth? Why did they grow where they did? Where did the carbonate sediment come from in this dominantly siliciclastic setting? What is the community structure of the buildups, and how does it differ from the level-bottom community? How do the buildups of the lower Fort Payne Formation fit into a sequence stratigraphic framework? This is just a sample of the questions that will be discussed throughout the day.

Geologic Setting

The Lower Mississippian (Osagean) Fort Payne Formation of southern Kentucky has long interested sedimentologists and paleontologists alike because of the enigmatic carbonate buildups contained therein. Although these buildups have received considerable attention during the past century (Thaden and others, 1961; Marcher, 1962; Chowns and Elkins, 1974; Lewis and Potter, 1978; MacQuown and Perkins, 1982;

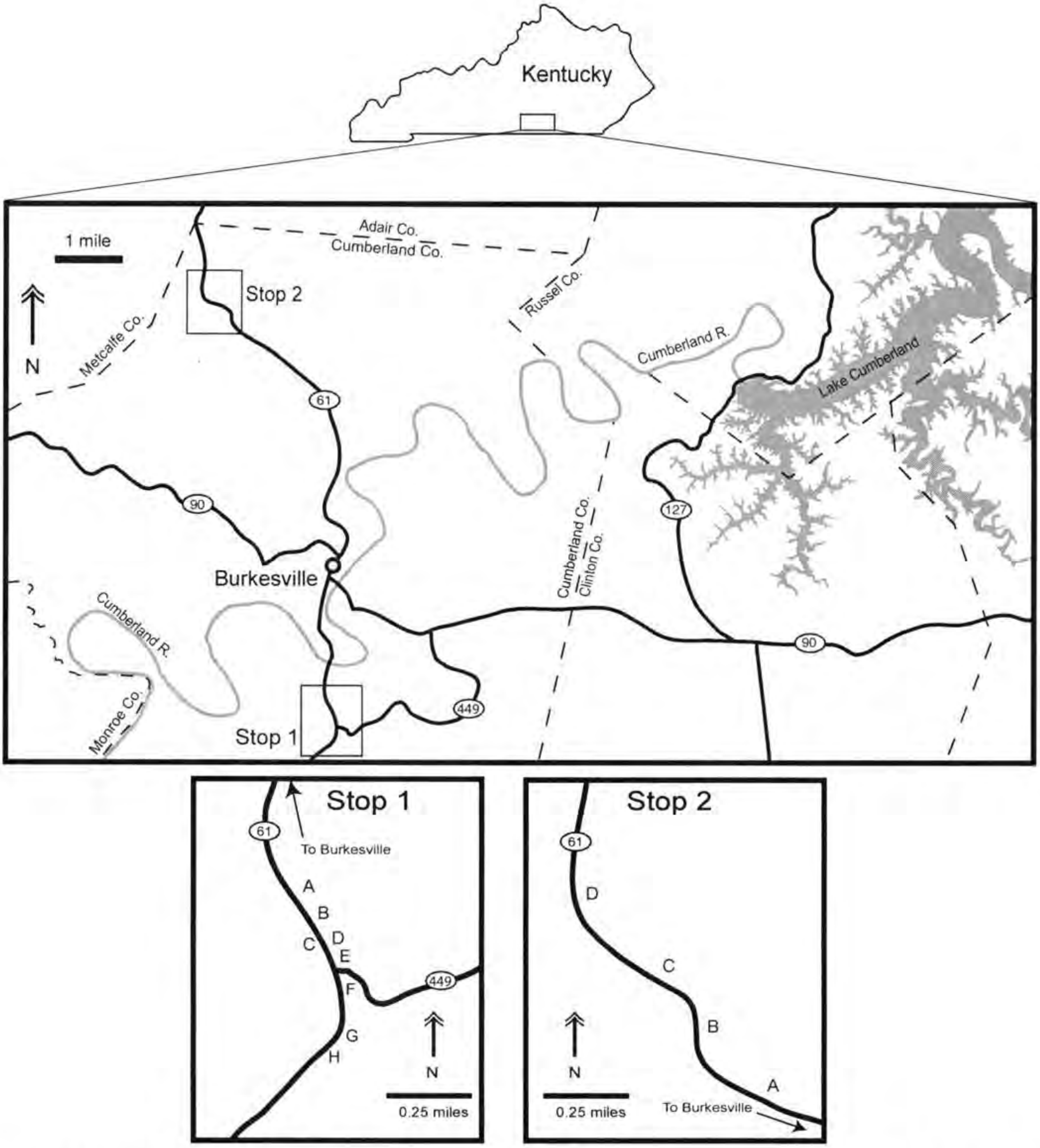

Figure 1. Location of the field trip area in south-central Kentucky, west of Lake Cumberland. Enlargements of stops 1 and 2 are shown below the regional map.

Lumsden, 1988; Ausich and Meyer, 1990; Norris, 1991; Meyer and Ausich, 1992; Meyer and others, 1995; Khetani, 1997), especially the classic exposures on the shores of Lake Cumberland, there are many unanswered questions regarding both the mechanisms of deposition of these enigmatic structures, and their possible affinities with other Lower Mississippian carbonate buildups (e.g., Waulsortian mounds).

The area on which we will focus during this field trip is located immediately southwest of the outcrop area of the Lower Mississippian (Kinderhookian-Osagean) Borden Group, a former delta lobe (Fig. 2). This delta lobe exerted major control on sedimentation in the region even after it was abandoned during early Osagean time and the main pulse of siliciclastics shifted northward to the Illinois Basin (Lasemi and others, 1994, 1998). The abandoned delta lobe produced a shelflike geometry in the local area, and it was in this sedimentation regime that the carbonate buildups nucleated and grew on mid- to lower-slope environments. The remainder of Mississippian (post-Osagean) time in the area is characterized by basin-filling and establishment of a carbonate ramp (Lewis and Potter, 1978; Khetani, 1997).

Previous Work

Two hypotheses have been proposed regarding the nature and origin of carbonate bodies in the Fort Payne Formation. Some workers have focused on the effects of progradation of a carbonate platform into this slope environment. It has been proposed that the carbonate bodies of the lower Fort Payne Formation were deposited by infrequent sedimentation episodes in the form of large debris flows sourced by prograding carbonates farther upslope (Klein, 1974). According to this model, debris flows were responsible for the deposition of the wackestones and packstones, which were interpreted to be biohermal deposits by earlier workers (Thaden and others, 1961; Marcher, 1962).

One possible problem with this hypothesis is that during Fort Payne deposition there was an insufficient volume of up-ramp, carbonate equivalents to account for the large amount of sediment in the buildups (Meyer and others, 1995; Khetani, 1997). While localized resedimentation of some thin carbonate deposits likely occurred, larger-scale carbonate deposition sourced from the delta top did not play a major role in this lower-slope environment until middle Mississippian time. The delta top during Early Mississippian time was composed mostly of thick sequences of silt and fine sand, which could not have served as a source area for the buildup-

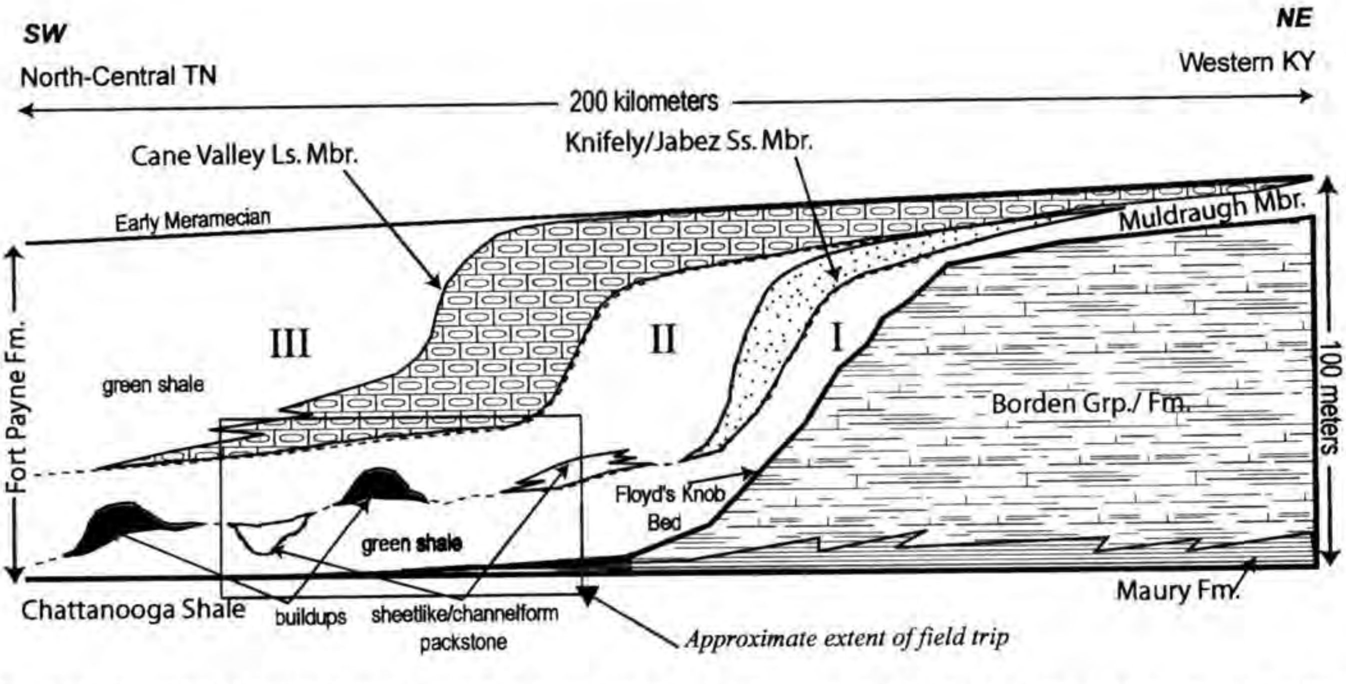

Figure 2. Simplified lithostratigraphic relationships between the Borden siliciclastics and the Fort Payne Formation (Kinderhookian-Osagean). The basal datum is the top of the Chattanooga Shale. Sequences discussed in text are indicated by roman numerals, and their boundaries are indicated by dashed lines. Modified from Lewis and Potter (1978); Khetani (1997); Khetani and Read (in press).

core wackestones and packstones of the Fort Payne Formation.

A second, alternative hypothesis, supported by several workers (Thaden and others, 1961; Marcher, 1962; Lewis and Potter, 1978; Ausich and Meyer, 1990; Meyer and Ausich, 1992; Meyer and others, 1995; Khetani, 1997), recognizes the importance of localized slope reorganization resulting in channel-form and sheet-like packstones of allocthonous origin, but distinguishes several carbonate facies that have distinctly different origins. These studies proposed an autochthonous origin for distinct fenestrate bryozoan-crinoidal wackestones and closely associated facies, with the implication that the structures formed by these facies are, indeed, bioherms. However, this hypothesis lacks definitive evidence in several key respects, including a limited understanding of the source for, or mechanism to stabilize, the large amounts of carbonate sediment of the lower Fort Payne Formation.

Facies of the Study Interval

The Fort Payne Formation is an extraordinarily heterogeneous unit, and it would be very difficult for a 1-day field trip to cover all of its component facies. Thus, this trip and this field guide are intended to provide a survey of the facies that are closely associated with the buildup interval, which makes up most of the lower Fort Payne in south-central Kentucky. The outcrops that we will visit are dominated by seven distinctive facies spanning two formations, although only the five within the buildup interval of the Fort Payne Formation will be emphasized. These facies will hereafter be referred to as (a) laminated black shale, (b) nonfossiliferous, glauconitic shale, (c) fossiliferous green shale, (d) crinoidal packstone/grainstone (two distinct types), (e) shaly packstone, and (f) massive wackestone/packstone. The first two of these lithologies (a, b) are exposed only below the buildup interval. The remaining five facies (c-f), all part of the Fort Payne Formation, are intimately related to each other and together make up the buildup interval, which spans third-, fourth-, or fifth-order sedimentary sequences (Fig. 3). These strata exhibit an overall shallowing-upward trend related to the establishment of a carbonate ramp by late Osagean time (Khetani, 1997; Khetani and Read, in press). Understanding their respective compositions, modes of deposition, and relationship to each other is the key to developing a genetic history for the buildups of the Fort Payne.

Laminated, Black Shale

The Late Devonian (Famennian) Chattanooga Formation is a relatively thin black-shale deposit (< 10 m in north-central Tennessee) but is related to an extensive Late Devonian black-shale complex that accumulated as the distal portion of the Acadian clastic wedge. This highly condensed deposit spans as many as 18 conodont zones in just over 9 m and represents the western extent of sedimentation in the Appalachian Basin during Late Devonian time (Ettensohn, 1998; Schieber, 1994, 1998; Lobza and Schieber, 1999). The depositional environment (especially the depth and availability of oxygen) of this condensed shale has been debated in recent years, with estimates ranging from deep, anoxic basin to relatively shallow with an occasionally aerated water column (Schieber, 1998). In the study area, it consists of finely laminated, highly carbonaceous shales with several pyritic concretionary horizons and a phosphatic conodont lag bed at the top, which is the Devonian-Mississippian boundary.

Unfossiliferous, Glauconitic Shale

Directly overlying the Chattanooga is a thin (> 2 m), glauconitic shale (Figs. 2-3), which is equivalent to the Maury Formation of Tennessee. This bed is considered to be the base of the Fort Payne Formation in the area (Lewis and Potter, 1978; Ausich and Meyer, 1990; Leslie and others, 1996). Recent biostratigraphic studies by Leslie and others (1996) have shown that the basal Fort Payne shales record more or less continuous, yet very sparse, sedimentation for the entire Kinderhookian Stage, a period of roughly 17 million years. This deep-water, basinal shale contains abundant small calcareous concretions and a depauperate macrofauna. This interval is directly overlain by a thin (2-3 cm), glauconitic, shale horizon, which may or may not be correlative to the informally designated Floyds Knob Bed. In any case, this glauconitic shale represents a flooding surface that is considered to be the basal sequence boundary for sequence I of the study interval (Krause, in preparation), and this shale reflects the beginning of the buildup interval in the lower Fort Payne Formation.

Fossiliferous Green Shale

This gray to green, organic-rich, fossiliferous clay shale occurs throughout the lower Fort Payne Formation, but is most commonly found in close association with the carbonate buildups. The facies can be divided into two distinct zones, one below and one above the buildup interval. The basal contact of the lower green shale can be difficult to locate because of its similarity to the underlying condensed intervals discussed above. However, the fossiliferous green shales are less condensed than the underlying sediments, as evidenced by the lack of extensive glauconite and calcareous concretions, and were deposited in a fully oxygenated water column, judging from the more extensive bioturbation

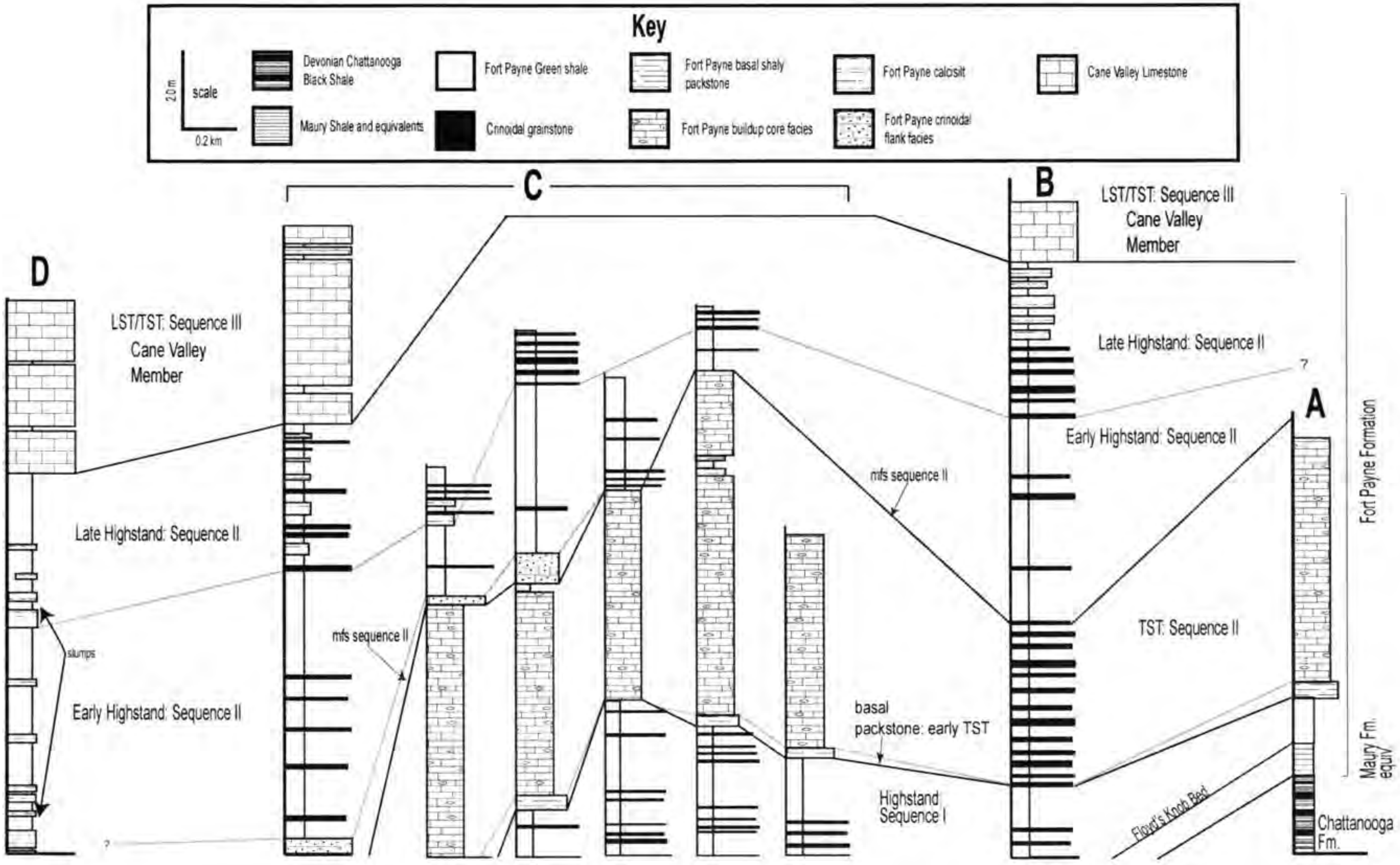

Figure 3. Correlated stratigraphic sections measured for the outcrops of stop 2. Basal datum is road level of Ky. 61. Letters above each section correspond to the outcrop at which it was measured (see Fig. 1 for locations). Correlations seen here used prominent stratigraphic horizons present throughout the study area; often these horizons correspond to important sequence stratigraphic horizons. Sequence boundaries are represented by black lines, while other sequence stratigraphic surfaces are represented by gray lines. These interpretations have been included on the diagram, and are discussed in the text. Note the stacking of highstand systems tracts throughout the lower study interval.

and diverse macrofauna (Ausich and Meyer, 1990; Norris, 1991; Meyer and others, 1995; Krause, in preparation).

Preservation of skeletal elements in the green-shale facies (lower and upper zones) encompasses a large range. Echinoderms, which are the most abundant taxa, are common as completely disarticulated plates, yet pluricolumnals and aggregations of radials and other cup plates (likely from single individuals) are common on some bedding planes. Complete crinoid calyces are not common but do occur (Ausich and Meyer, 1988, 1990, 1992; Norris, 1991; Meyer and Ausich, 1992, 1997; Meyer and others, 1989, 1995; Krause, in preparation). The most common complete calyces belong to the genera *Gaulocrinus* and *Agaricocrinus*. When present, they tend to occur with other examples of exceptional preservation (e.g., aggregations of sponge-spicule impressions, and nearly complete fenestrate bryozoan fronds), probably due to a sudden burial event. Additionally, in situ crinoid holdfasts have been identified with cirri penetrating the enclosing sediment (Ausich and Meyer, 1990; Meyer and others, 1995). Even the most delicate skeletal elements, such as large, unbroken fronds (5–7 cm long) of delicate bilaminate and fenestrate bryozoans, are typically nearly unbroken on bedding planes. Preservation of delicate macrofauna and intact portions of multi-element skeletons precludes high-energy deposition and transport for this facies (Norris, 1991). Rather, this evidence implies that sedimentation rates were low enough that complete disarticulation of skeletal elements was common. Currents were not strong enough to transport these elements, and they were not exposed long enough to be heavily encrusted or biogeochemically corroded. This suggests a moderate sedimentation rate punctuated by rare burial events (Meyer and others, 1989, 1995).

The sediment source for the green-shale facies is most likely the upper slope and shelf of the Borden Delta, and may represent reworking of the delta sediments after its abandonment during early Osagean time (Lewis and Potter, 1978; Lasemi and others, 1994, 1998). The lower occurrence of the green-shale facies (below the buildup interval) is interpreted to have been deposited during the late highstand of sequence I, and the upper green shales (above the buildup interval) represent the late highstand of sequence II (Krause, in preparation).

Bedding in the green shale is generally even and parallel, with few obvious discontinuities. Nonetheless, it should be noted that there are instances of localized faulting in the lower green shale, especially in close proximity to the carbonate buildups. Most faults encountered are minor, with offsets of several centimeters. However, other faults have offset of as much as 1 m in some cases. In some cases it is difficult to determine the exact direction of movement along these faults; thus, their significance for the lower Fort Payne Formation is debated.

Thin, Tabular Crinoidal Packstones and Grainstones

Interbedded with the green shale in several locations are thin, tabular, crinoidal packstone-grainstone beds, interpreted to be storm deposits because of the abundance of mud rip-up clasts. Because these deposits occur only with the fossiliferous green shale, they are considered to be part of the HST for sequence I.

The faunal makeup of these beds is almost exclusively coarse crinoidal debris, and disarticulation and some breakage is common. There is a small degree of scour associated with the base of most of these beds, but it is difficult to estimate the amount of the sedimentary record that has been lost because of storm events. Additionally, these storm beds, with their abundance of disarticulated echinoderm material, offered a temporary hard substratum suitable for colonization by pedunculate brachiopods, such as the orthid *Rhipidomella*. In some cases, the upper surfaces of these grainstone beds appear to have supported a substantial low-diversity community of brachiopods for a brief period. This phenomenon is well illustrated at stop 2B.

Shaly Packstone

A coarse, crinoidal, shaly packstone is present, with a variable thickness, at the base of all buildups in the study area, and has been recorded in nearly all known occurrences of the Fort Payne buildups (Ausich and Meyer, 1990; Meyer and others, 1995). This facies is often closely associated with the buildups, and is equivalent to thin sheetlike and channel-form packstone bodies also present in the lower Fort Payne Formation. The shaly packstones forming the base of buildups of the Fort Payne are always deposited on top of the aforementioned topographic highs on the sequence boundary in the underlying shales. The geometry of these deposits is such that they attain their greatest thickness near the sides of, and pinch out onto the apex of the underlying green-shale "mounds."

The basal, shaly packstones contain coarse and commonly articulated echinoderm debris. Echinoderms are, by far, the dominant faunal component in terms of abundance and diversity, and it is not uncommon to encounter whole calyces, as well as partially articulated arms and stalks. Fenestrate bryozoans are moderately abundant in this facies and always exhibit intense breakage. Other elements of the fauna include strophomenid and rhynchonellid brachiopods and proetid trilobites, but these commonly occur in rather low abundance. Taphonomy of echinoderms in this facies suggests rapid burial as the dominant depositional process, but some transport likely occurred, yielding the aforementioned complete breakage of fragile skeletal elements such as fenestrate fronds.

These deposits are not uniformly distributed throughout the region but occur as channels and discontinuous sheets, some of which drape over preexisting highs in the underlying shale. Brett (1995, 1998) recognized that thin, reworked lag deposits such as the shaly packstone are commonly deposited during the initial stages of a transgression. This facies, along with the closely related (and roughly time-equivalent) channel-form and sheetlike packstones of the Fort Payne, represents a series of small-scale debris flows, which occurred during the latest lowstand and early transgressive systems tract of sequence II in the study area (Krause, in preparation).

Massive Crinoidal-Fenestrate Bryozoan Wackestone/Packstone (Buildup Core)

The dominant lithology making up the core of the Fort Payne buildups is a poorly sorted crinoid-fenestrate bryozoan wackestone. Carbonate buildups constitute only a small portion of all facies in the lower Fort Payne Formation, but, where present, they may be the dominant exposed features in an area because of their relative resistance to weathering in comparison to the background shales. These features have a convex upper surface and an undulose base, which conforms to the topography of the underlying basal packstone and shale. In some cases, bedding in the underlying shale is truncated below the buildup.

The buildups examined on this field trip range from 15 to 20 m in height and 150 to 200 m in width. Research on other Fort Payne buildups has demonstrated that these features are roughly circular in plan view and sometimes coalesce to form mound complexes (Ausich and Meyer, 1990; Meyer and others, 1995). The buildups are further characterized by the presence of coarse crinoidal packstones and grainstones that were deposited in a flanking position around each buildup, with depositional slopes reaching as much as 20° in some cases. That these carbonate buildups were topographic highs on the Mississippian seafloor can be demonstrated by the onlapping relationship of the overlying shale beds, as can be seen at stop 2C. Buildups in the Fort Payne Formation are limited to the basal 30 m of the formation, but have a wide geographic distribution. For example, buildups on Lake Cumberland Reservoir, in southern Kentucky, occur locally along the entire shoreline and are everywhere found within the range of normal lake level (3–5 m).

The buildup core is characterized by a drop in faunal density as compared to the underlying green shales and packstones and the overlying shales and crinoidal grainstones (Krause, in preparation). It is likely that algal or microbial mats were common in the buildup core. Evidence for such a mat comes partially from outcrop observations, but mostly from observations of thin sections. Outcrop evidence for mats includes the steep (~20°) depositional slopes of the buildups. Maintenance of such a slope might not be possible without some sort of binding agent, as studies have shown that the angle of repose for fine-grained sediments is approximately 6° (Schlager and Camber, 1986). However, examples to the contrary do exist, such as the shallow-water mud mounds of Florida Bay, which have depositional slopes of 15 to 20° without the influence of a surficial algal or microbial mat. Further evidence for a mat comes from the abundance of cavity structures in the buildups (discussed below). In unbound sediment of normal consistency, such cavities would probably not form because of the soupy consistency of carbonate mud.

Preservation of skeletal elements in the buildup core is highly variable. Much like the fossiliferous green shale, instances of exceptional preservation tend to be clustered together in the buildup core. Examples of such preservation include large fenestrate bryozoan fronds, reaching ~10 cm in length, and very long (up to 20 cm), thin, rugose coral specimens. Also rather common in some horizons of the buildups, especially near the bottom, are partially to fully articulated crinoid and blastoid individuals. Rootlike holdfasts of echinoderms, which penetrate the sediment, have also been encountered.

The buildup core is further characterized by abundant cavity formation. Two types of synsedimentary cavities have been recognized in the buildups of the Fort Payne Formation: skeletal shelter cavities and stromatactis cavities (Krause, in preparation). The abundance of shelter cavities is related directly to the abundance of whole fenestrate bryozoan fronds and extensive auloporid coral colonies. Such cavities likely formed when large intact fenestrate fronds or abundances of auloporid debris draped over other skeletal debris, precluding complete filling of the space beneath. Thus, these cavities indicate in situ accumulation of skeletal debris and argue for a relatively quiet-water environment for their formation. Shelter cavities are most common in the core of the buildups of the Fort Payne and are very abundant and easily seen in the buildups at stop 2C. A second type of cavity, one lacking obvious skeletal support and characterized by several generations of early marine cementation, is most abundant in the upper portions of buildups. These cavities are similar to the so-called stromatactis cavities that have been recognized in other buildups of early Carboniferous age (Bathurst, 1982; Lees and Miller, 1995; Pickard, 1996). For a thorough explanation of the origin and implications of such cavities, please consult those papers. The stromatactis cavities of the Fort Payne buildups are most easily seen at stop 2A and will be discussed there.

The main phase of buildup deposition occurred during the late TST and early HST of sequence II (Krause, in preparation). This portion of the sequence was especially conducive to bioherm or reef development, which was often initiated on firm substrates associated with older skeletal deposits (in this case the highstand deposits of sequence I) and was coincident with surfaces of extreme sediment starvation (Walker and Alberstadt, 1975; Sarg, 1988; Buchbinder, 1993; Brett, 1995). Sediment sequestration on the delta top during this stage would have been especially conducive to reef or bioherm development because of a clearing of the water column. The greatly decreased turbidity of the water column at this time would have benefited suspension-feeding organisms (Brett, 1995, 1998; Khetani, 1997), which are the main components of the macrofauna of the buildups. The algal/microbial components of the buildup fauna would have also undergone their maximum growth during this stage as they benefited from the extension of the photic zone (owing to decreased turbidity), and were forced to "keep up" with the rising sea level. Buildup growth was likely terminated at the mfs for sequence II.

Coarse Crinoidal Grainstones (Buildup Flank)

The buildup flank beds represent the fifth distinctive lithology associated with the buildup interval. These skeletal packstones and grainstones are dominated by coarse crinoidal debris, and contain little other fauna, and very little mud in many cases. Taphonomic aspects of this lithology, such as complete disarticulation and moderate breakage of crinoidal debris, indicate winnowing and long exposure times on the seafloor for most of the skeletal material in this facies. Some transport is inferred for this facies because of the geometry of the deposits. The buildup flanks always have a rather sharp basal contact with the underlying buildup core, and exhibit a draping morphology (thickest above the edge of the buildup core, and thinning both distally and onto the buildup apex), with depositional slopes exceeding 15° in some cases.

This facies is considered the cap of the buildup interval and represents the maximum flooding surface for sequence II. The flank facies is always associated with the buildups, and lowstand sedimentation is not present elsewhere in the study area. The flank deposits resulted from storms and winnowing currents that produced localized reorganization of the sediments of the inactive buildups. Without the benefit of a microbial mat to bind the as yet uncemented fine carbonate mud at the top of the buildup, it was winnowed away, leaving behind the characteristic coarse crinoidal debris, which in some cases slumped down, forming an apron around the margins of the buildups.

Cane Valley Limestone Member

As stated earlier, the upper portion of the fossiliferous green-shale facies represents the highstand portion of sequence II, and thus directly overlies (and onlaps) buildup flank deposits. Above this upper green shale is the lower portion of a third depositional sequence in the study area, which falls outside of the buildup interval, and is represented by the lower Cane Valley Limestone member of the Fort Payne Formation. The Cane Valley Limestone is a very coarse, homogenous, crinoidal grainstone, deposited as a crinoidal shoal in relatively shallow water as sea level rose (Sedimentation Seminar, 1972). As such, it may be the LST or early TST of sequence III. This member of the Fort Payne Formation is present in the upper reaches of several of the outcrops that will be visited in the afternoon. This lithology indicates much shallower environments of deposition than those of the previous three sequences. Thus, an overall shallowing trend of the early to middle Mississippian in the area, representing basin filling, is confirmed (see Khetani, 1997; Khetani and Read, in press, for a review).

Stop Descriptions

The field trip will examine two distinct groups of outcrops, collectively labeled stops 1 and 2. Of course, each "stop" will have multiple outcrops associated with it, each chosen to illustrate a special property of the lower Fort Payne Formation. Stop 1 will consist of a group of roadcuts exposed on Ky. 61, south of Burkesville and the Cumberland River. Our entire morning will be spent examining these cuts. In the afternoon we will move on to stop 2, which consists of five relatively new roadcuts exposed north of Burkesville on Ky. 61.

Stop 1

The 1997 publication, "A Deep-to-Shallow Transition in the Fort Payne Formation (Lower Mississippian), Kentucky Highway 61, Cumberland County, Kentucky," by Meyer and others, provides a map and stratigraphic sections for this series of exposures. Refer to this map and chart for location, description, and stratigraphy of the roadcuts. We will examine the following roadcuts as marked on that map.

Stop 1A

Basal Fort Payne Formation. A glauconitic shale interval about 30 cm thick containing phosphatic nodules occurs below Fort Payne carbonates and above the black Chattanooga Shale. This shale is considered to be equivalent to the Maury Shale of Tennessee and contains conodonts indicative of a condensed interval ranging from Kinderhookian through middle Osagean age (Leslie and others, 1996).

Stop 1B

This roadcut exposes the undulatory top of a wackestone mound in the Fort Payne, overlain by interbedded crinoidal packstones and green shale.

Stop 1C

Wackestones about 5 m thick, thought to be continuous with the mound facies of outcrop B, are exposed below road level to the west.

Stops 1D, E, F, G

Crinoidal packstones and fossiliferous green shales overlie the wackestone mound.

Stop 1H

Crinoidal packstones and fossiliferous green shales dip to the south. Below road level to the west it is possible to examine a poorly exposed wackestone mound, as well as a good exposure of green shale in the ravine.

Stop 2A

This outcrop is the southernmost and stratigraphically lowest of the new cuts, and exposes a similar section as that of stop 1A. The Devonian-Mississippian boundary, exposed in this roadcut, is characterized by a phosphatized conodont lag bed with abundant pyritic concretions. Directly above this contact is the unfossiliferous, glauconitic-shale facies.

The southern end of the outcrop is dominated by a slightly overgrown exposure of the fossiliferous green-shale facies, and we will see better examples of this facies at the later stops. This cut also exposes a partial buildup (northern half erosionally truncated) that starts at about 3 m above the base of the Fort Payne, and dominates the northern third of the outcrop. Although this is only a partial buildup, it offers a good view of several key features.

First, there are at least two synsedimentary faults developed in the green shale directly beneath the buildup. The exposure of these faults is such that they can be traced up into the buildup for a short distance. This indicates that the faults developed as a result of overburden pressure on the underlying shale at some point during the early stages of buildup growth. In one case, the amount of offset associated with one of these faults may be as much as 1 m, demonstrating a significant amount of reorganization during the growth history of this particular buildup.

The second feature of interest in the buildup is an excellent exposure of a skeletal, shelter-cavity-rich interval. It occurs about 1 m above the base of the buildup and offers probably the best chance we have to examine these structures.

Finally, the upper portion of this buildup (southern side) contains the best exposure that we will see of the stromatactis cavities that are common in many Fort Payne buildups.

Stop 2B

This is the next cut to the north of stop 2A. Here we will see an excellent exposure of the fossiliferous green-shale facies with abundant interbedded crinoidal grainstone beds. This is an opportunity to examine strata that are laterally equivalent to the buildup interval (there is a buildup in close proximity to this outcrop, which will be examined at stop 2C). There are cuts on both sides of the road here. The cut on the western side of the road is only about 4 m high, but offers an excellent vantage point to view the much larger cut on the other side of the road. The large planed surface of this cut also offers a great place for fossil collecting. Crinoids are the most abundant fossils and are commonly preserved as whole cups, especially the flexible *Gaulocrinus*.

Another striking feature of this cut is the abundance of small-scale faults, which can be seen on the eastern side of the road. These faults cannot be explained by the same mechanisms used for those at the previous stop, as there is no buildup in this outcrop. Some of the faults are clearly a result of much later (post-Osagean) deformation, but others seem to be growth faults. These growth faults may result from some underlying structure, perhaps along the Devonian-Mississippian boundary, but this cannot be proven at present.

Stop 2C

This roadcut will be the focus for most of the afternoon. It offers an excellent exposure of two carbonate buildups that coalesced on top of a local topographic high in the underlying fossiliferous green shale (Fig. 4). There are several interesting features to note here.

We will first investigate the bedding and overall geometry of the lower green shale. The topographic high formed by the lower green shale just below the buildups is similar to what has been referred to as "green shale mounds" (Ausich and Meyer, 1990; Meyer and others, 1995). It was originally thought that such mounds were biogenically produced buildups of siliciclastic sediment, resulting from baffling by elevated suspension feeders. However, this exposure has several features that seem to support a different hypothesis (Fig. 4). First, there is no significant increase in suspension feeding fauna in the shale mound, and what fauna are present do not seem sufficient to baffle large amounts of sediment (Krause, in preparation). Furthermore, the shale-mound hypothesis necessitates roughly mounded bedding due to mode of accumulation. In fact, just the opposite is true, for the green shale just below the buildup in this outcrop seems to occur in a "synform" configuration, with upturned beds on both northern and southern ends. This bedding configuration is difficult to interpret, but could have formed in one or both of the following ways.

First, this portion of the outcrop may represent the remnant of a semicoherent slump block of green shale, which was inclined to the north (in the upslope direction), during the lowstand of sequence II (Krause, in preparation). Sequence lowstands are commonly represented by erosional unconformities and slumping in shelf and upper-slope settings because of sediment bypass to the lower slope (Baum and Vail, 1988; Posamentier and Vail, 1988; Brett, 1995, 1998). The synform bedding could also have been caused by slump-block rotation, with beds on the northern end accommodating the rotation while beds on the southern end remained coherent. Second, this bedding configuration may have been caused by the loading of large amounts of carbonate mud during buildup growth.

Additionally, shearing events may have taken place as the carbonate buildups accumulated on top of the shale and began to settle and creep downslope slightly (both to the north and to the south). It is difficult to quantify the amount of shearing that took place during these events, as the buildup strata were not coherent enough to record them, and the shale bedding is warped downward only slightly on either side. However, the shearing events were probably minor because large amounts of creep downslope would have easily separated the two buildups in this cut.

It is likely that both green-shale slumping during sea-level lowstand (sequence II) and compressional loading and shear during later stages of buildup growth contributed to the configuration of green-shale bedding seen in this outcrop. However, it is difficult to determine which mechanism was more important.

This cut also offers very good exposures of all of the facies of the buildup interval, including the basal shaly packstone, and the flanking crinoidal grainstone beds. Note the geometry and overall composition of each (see above).

Another interesting aspect of this buildup is that the porosity is not completely occluded. Similar to most

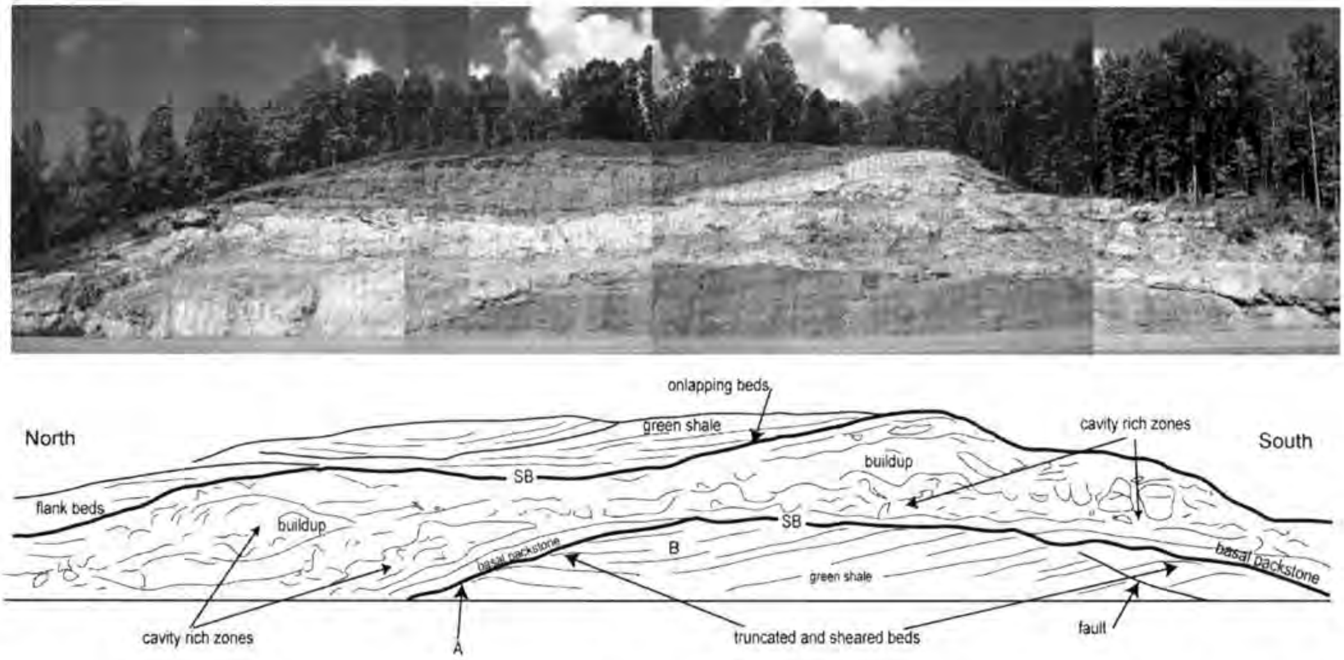

Figure 4. Line drawing of outcrop at stop 2C showing bedding relationships. Note the truncation and shearing of shale bedding beneath the buildup, and shale onlapping above the buildup. Bold lines indicate sequence boundaries (SB) between sequences I and II and II and III. (A) Surface that underwent modification during lowstand of sequence II (see text). (B) Shale bedding organized into a synform configuration (see text).

examples of this facies studied previously, much of the core is a massive wackestone. However, there are rubbly zones that have a higher porosity. These uncemented zones contain hydrocarbons and may be a model for oil-producing buildups in this facies in the subsurface of Tennessee and elsewhere.

Finally, since this cut exposes the only complete buildup that we will see on this trip, this stop will be a chance to review some of the buildup features that we saw at other outcrops. For example, both types of cavities mentioned earlier are quite abundant in this cut. After examining this cut you should start to develop a picture of what the average Fort Payne buildup looks like. This is, of course, invaluable for attempting to decipher the growth history of these buildups.

Stop 2D

This will be our final stop. This is the northernmost of the outcrops we have studied, and it exposes in calcisiltites a complex series of slump structures that occurred mostly during the post-buildup phase of Fort Payne deposition in the area. The slump structures resulted from early stages of progradation of a carbonate shelf from the north into this area during latest Osagean and early Meramecian time (Sedimentation Seminar, 1972).

This outcrop also exposes the Cane Valley member of the Fort Payne Formation, which we have seen at other outcrops. This deposit represents the TST of a third depositional sequence in the Fort Payne of the study area (Krause, in preparation).

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Middle and Upper Mississippian Stratigraphy and Depositional Environments in East-Central Kentucky: The New Bighill Exposure

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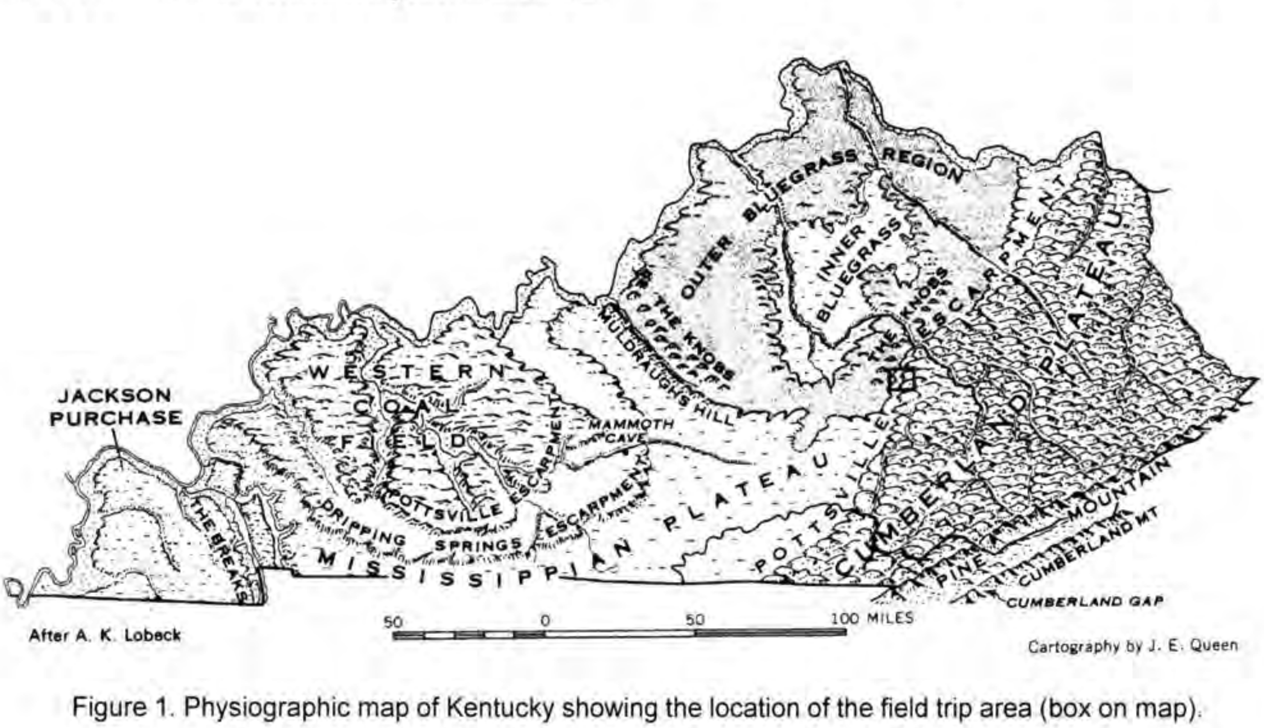
Introduction

Approximately 30 percent of Kentucky is underlain at the surface by Mississippian rocks, especially carbonates, and these rocks are responsible for much of Kentucky's physiography and karst landforms. These rocks are also economically important as sources of crushed stone, groundwater transit routes, and hydrocarbon reservoirs. On this trip to Bighill, Ky., we will examine a representative exposure of these rocks, which contains clastic and carbonate components and illustrates both physiographic and economic aspects of the section. Although the section is about 4 years old, its presence on a part of the Pottsville Escarpment that is narrow (Fig. 1) provides a fresh, nearly continuous, and easily accessible exposure of Middle and Upper Mississippian rocks from the upper Borden, Slade, and lower Paragon Formations over a short distance along a new stretch of highway with broad shoulders. Not only is the section easily accessible for study, but also its location allows for ready explanation of relationships be-



After A. K. Lobeck

Cartography by J. E. Queen

Figure 1. Physiographic map of Kentucky showing the location of the field trip area (box on map).

tween lithology and physiography, and many features are available for interpreting depositional environments, paleoecology, possible hydrocarbon reservoirs, and karst hydrology. These features will be briefly described for each unit below.

Physiography and the Field Trip Route

The field trip route follows U.S. 25/421 (Richmond Road) southwest out of Lexington, Ky., to exit 104 (Athens-Boonesboro) onto southbound Interstate 75. We enter onto I-75 and proceed south to exit 76 at Berea, Ky. At exit 76 we leave the Interstate and proceed east through Berea on Ky. 21. We remain on Ky. 21 until it intersects U.S. 421 in Bighill, Ky. At Bighill, we proceed south for 2 miles to the beginning of the exposure.

The route to Berea is present wholly in the Lexington Plain or Bluegrass section of the Interior Low Plateaus physiographic province (Fenneman, 1938) (Fig. 1). The Lexington Plain largely coincides with apical parts of the Jessamine Dome, a structural culmination on the Cincinnati Arch. Because the dome is nearly symmetrical and truncated, lithologic units and resulting landforms form roughly concentric belts around the Lexington area, which is located near the center of the dome. Consequently, the Lexington Plain is divided into approximately concentric Inner and Outer Bluegrass belts. The Inner Bluegrass is relatively flat-lying to gently rolling and is the agriculturally richest part of the Lexington Plain. The area is underlain by soluble, phosphatic, Middle Ordovician limestones of the Lexington Limestone (Fig. 2), which produce very fertile soils. The flat terrain and fertile soils make this an agriculturally prosperous region with large-scale tobacco farming, grazing, as well as the breeding and raising of horses. Karstic features are locally common, and the entire area may be a karstic solution plain. Some surface streams, such as the Kentucky River, which we will cross on I-75 just south of exit 99, are entrenched in steep-walled valleys.

The Inner Bluegrass typically gives way subtly to the Outer Bluegrass, an area of hummocky, irregularly rolling hills and low ridges underlain by Upper Ordovician shales and shaley limestones. Some workers divide the Outer Bluegrass into the Eden Belt and Outer Bluegrass proper. The Eden Belt is typically a highly dissected area with sharp, narrow ridgetops and steep-sided valleys developed on the nonresistant shales and interbedded limestones of the Clays Ferry Formation. On the field trip route, however, this belt is absent, because the Clays Ferry Formation is largely faulted out on the southern, downthrown side of the Kentucky River

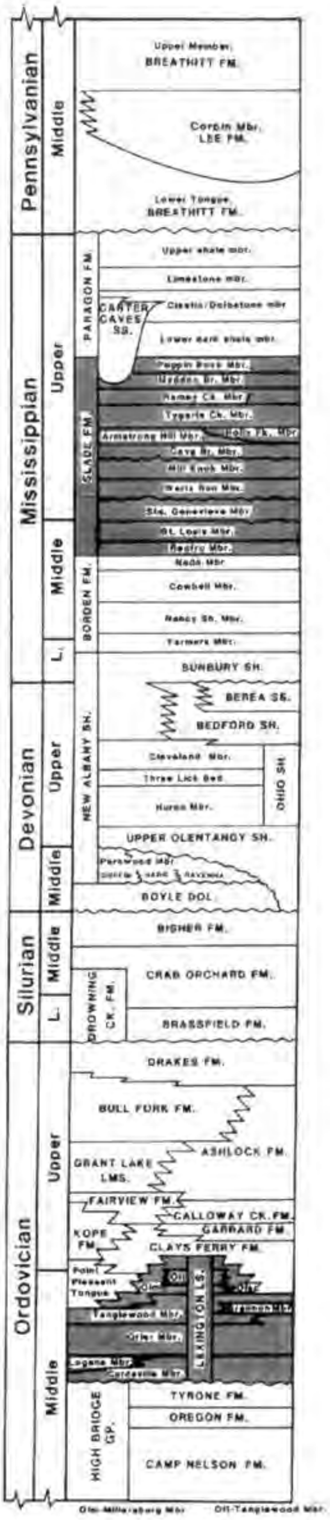


Figure 2. Generalized stratigraphic column for central and east-central Kentucky showing units traversed during course of the trip. The lower darkened section is the Lexington Limestone, in which the trip will begin, and the upper darkened section is the Slade Formation, which comprises most of the section at Bighill.

Fault Zone (Black, 1968). We cross the fault zone on the southern side of the Clays Ferry Bridge, just south of exit 99, and move from the Inner Bluegrass directly into the Outer Bluegrass proper. The Kentucky River in this area is part of a 20-mi segment that roughly follows the Kentucky River Fault Zone.

The Outer Bluegrass proper is developed on Upper Ordovician limestones, siltstones, and interbedded shales of the Garrard Siltstone, Calloway Creek, Ashlock, and Drakes formations, and on its extreme western margins may include Lower and Middle Silurian carbonates and shales, as well as Middle Devonian carbonates (Fig. 2). Because carbonates are more abundant in this part of the section, the topography is not as steep as in the Eden Belt, and the soils are more fertile. Hence, farms are larger, and both cattle grazing and burley tobacco are major sources of income.

The gently rolling hills and low ridges of the Outer Bluegrass proper continue up to the city of Berea, where the low-lying topography in and near the city abruptly gives way to a hilly and "mountainous" topography of conical hills and detached ridges known as the Knobs region of the Outer Bluegrass (Fig. 1). The Knobs form a horseshoe-shaped belt that surrounds the Bluegrass (Fig. 1). Near Berea, the Knobs are generally 300 to 600 ft (91 to 183 m) high and are erosional remnants formed as streams cut into the Highland Rim, which defines the outer margin of the Bluegrass in east-central Kentucky (Fig. 1). South and east of Berea, the broad bases of the knobs are generally developed in nonresistant shales of the Upper Devonian/Lower Mississippian New Albany Shale or the Lower and Middle Mississippian Nancy Shale Member of the Borden Formation, whereas the flat, resistant caps are in upper Borden siltstones (Cowbell Member), or more commonly, in the Middle and Upper Mississippian Slade Limestone or Lower Pennsylvanian Lee Sandstone (Weir, 1967; Weir and others, 1971) (Fig. 2). In fact, Indian Fort Mountain, a detached ridge north of Ky. 21 on the way to Bighill, is capped with Slade carbonates and Lee sandstones (Weir and others, 1971). Some of the intervening valley bottoms and glades are floored with Silurian or Devonian shales with veneers of Pleistocene or Holocene alluvial deposits and are broad and flat enough to support farming.

About a mile south of Bighill, Ky., on U.S. 421, we begin to ascend the Highland Rim. Because the Mississippian outcrop belt is relatively narrow in this area and does not exhibit topography greatly different than that of Pennsylvanian rocks to the east, the Highland Rim here is effectively merged with the Pottsville Escarpment (Fig. 2). The cuts themselves are on the escarpment, and climbing to the top of the cuts and looking to the north provides an excellent view of the Bluegrass, Knobs, and the escarpment.

Procedures

The Bighill section was measured and described using standard U.S. Geological Survey procedures by the 2001 Advanced Stratigraphy class at the University of Kentucky. Representative samples were collected for thin sections, and the entire exposure was scintillated with a hand-held scintillometer according to procedures outlined in Ettensohn and others (1979) to generate the artificial gamma-ray log in Figure 3.

Borden Formation

Nancy and Cowbell Members

About a mile south of Bighill, as we begin to ascend the escarpment, exposures of the Nancy Shale Member and repaired slumps in the member appear on the right-hand or western side of the highway. The Nancy Member is composed of dark greenish-gray to olive-gray, noncalcareous, silty mudstones and crudely laminated shales with sparse siltstone lenses; it varies from 100 to 260 ft (30 to 79 m) in thickness (Weir and others, 1971). Septarian, siderite concretions up to a few feet in diameter and small pyrite nodules are locally common. Fossils are uncommon, but some siltstone lenses may contain the trace fossil *Zoophycus,* and some siderite nodules may contain nautiloids and ammonites.

The upper third of the cut is composed of the Cowbell Siltstone Member of the Borden Formation, which is inaccessible. The Cowbell is composed of greenish-gray, argillaceous siltstones and interbedded silty shales. Trace fossils, including *Zoophycus*, are more common, and calcareous bands and lentils of silty limestone containing brachiopod, crinoid, and bryozoan debris are present locally; the unit varies in thickness from 70 to 200 ft (21 to 61 m) (Weir and others, 1971).

Lower parts of the Borden Formation, discussed above, comprise parts of a coarsening-upward, clastic sequence typical of a prograding delta (Ettensohn, 1979a) (Fig. 2). The Nancy Shale is interpreted to represent prodelta muds in distal foreset and bottomset environments, whereas Cowbell siltstones are interpreted to represent delta-front deposition in more proximal, foreset environments on the westward-prograding, subaqueous, Borden Delta complex (Kearby, 1971; Mason and Chaplin, 1979; Chaplin, 1980; Sable and Dever, 1990; Lierman and others, 1992). Additional information on Borden stratigraphy can be found in Weir and others (1966) and Sable and Dever (1990).

The Borden Delta complex reflects the flooding of the Appalachian Basin with relaxational clastic deposits following the final Early Mississippian tectophase of

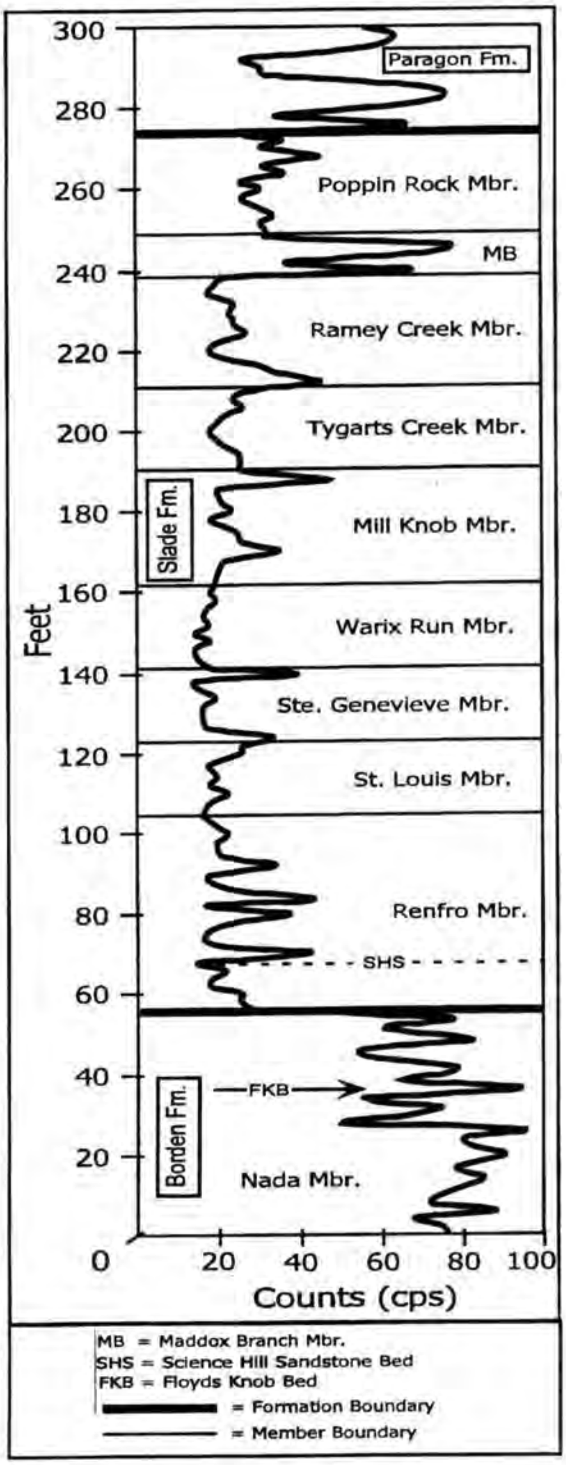


Figure 3. Artificial gamma-ray log of the Mississippian section at Bighill, showing the gamma-ray signature of each unit.

the Acadian Orogeny (Ettensohn, 1994, 2001). This deltaic wedge, known as the Price-Pocono, Grainger, or Borden Delta, immediately succeeded basinal, black-shale deposition in south-central parts of the basin. Price-Pocono clastics generally reflect subaerial parts of the delta complex, whereas the Grainger and Borden represent more distal, subaqueous parts of the complex.

Nada Member

The Nada is the upper member of the Borden Formation, and at least 37 ft (11.3 m) are present at the base of the exposure where the field trip begins (Fig. 4). This part of the Nada is divisible into three parts.

Lower Part. The lowermost part is composed of greenish-gray, dark gray, or grayish-red, noncalcareous, silty mudstone to poorly fissile shale. Six to 10 ft (1.8 to 3.0 m) above the base of the exposure is a thin horizon of rusty-brown siltstone lenses that probably represent starved current megaripples. Locally, broad to small, shallow scours in the mudstones are filled with lenses of silty calcarenite, composed mainly of fragmented bryozoan, brachiopod, crinoid, and phosphatized fossil debris. Local, calcareous, fauna-rich layers in the mudstones represent former in-place communities composed of fenestrate and rhomboporid bryozoans, spiriferid brachiopods, and crinoids; some layers also contain phosphorite nodules and phosphatized fossil debris. The late Osagean brachiopod *Syringothyris texta* (e.g., Butts, 1922) was found in one of these layers.

Middle Part. The middle part of the member is about 8 ft (2.4 m) thick and includes two rusty-brown beds of argillaceous, silty, glauconitic dolostone, separated by greenish-gray shale. The base of each dolostone is a glauconite- and phosphorite-rich pause or lag horizon, containing reworked fish bones and teeth, invertebrate fossil debris, and phosphorite nodules. Each bed is amalgamated and was probably composed of calcareous and glauconite pellets. Sedimentary structures are subtle, but hummocky crossbeds, scours, bioturbation, and rip-up clasts are present; the top of the lower dolostone may exhibit megaripples. The upper bed contains bands of silica nodules, which were formed early because overlying parts of the bed contain gutter casts and small scours that are filled with brecciated silica clasts, reworked from below.

Upper Part. The upper part of the Nada consists of about 15 ft (4.6 m) of thin-, even-bedded, greenish-gray siltstones interbedded with silty mudstones or shales of similar color. In the first of the shales, which separates underlying dolostones from the siltstones above, is an intensely glauconitic horizon that forms a prominent reentrant below the first siltstone; this is the widespread Floyds Knob Bed (Stockdale, 1939; Kepferle, 1971). This glauconitic horizon, 0.3 ft (0.1 m) thick, has

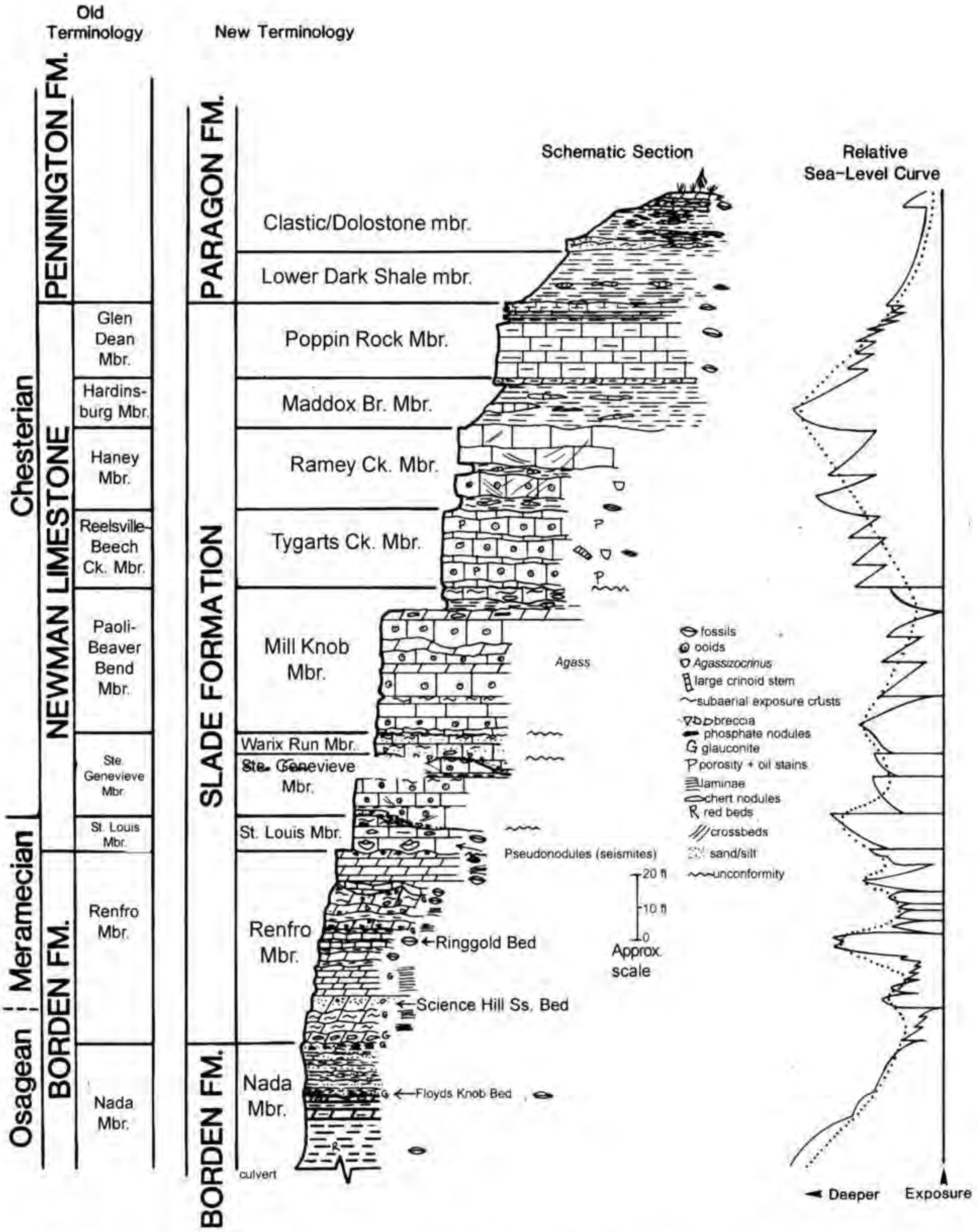


Figure 4. Schematic drawing of the section at Bighill, showing both old (McFarlan and Walker, 1956) and new (Ettensohn and others, 1984) stratigraphic terminologies and a generalized relative sea-level curve for the section.

a sharp base and is gradational upward; it contains phosphorite nodules, burrows, and phosphatized burrow fills.

At present, the siltstones are not weathered enough for sedimentary structures to stand out prominently; however, close examination reveals the presence of amalgamated beds, crude grading succeeded by micro cross-laminae, swaley crossbeds, scours, rip-up clasts, and bioturbation at or near the tops of each siltstone. The second siltstone bed has a horizon of phosphorite nodules at its top.

The top of the Nada is represented by another pause or lag horizon, up to 0.7 ft (0.2 m) thick, composed of glauconitic siltstone with phosphorite nodules that have been bored. Phosphatized gastropods, brachiopods, and fish bones, as well as bioturbation, are present.

Interpretation. The Nada Member has been interpreted to represent delta destruction after abandonment or diversion of Borden deltas in eastern Kentucky (Ettensohn, 1979a, 1980, 1981) (Fig. 5). In northeastern Kentucky, where much detailed work on the Borden Delta has been done (e.g., Chaplin and Mason, 1979; Chaplin, 1980), the Nada is characterized by abundant limestones and diverse faunas interpreted to represent shallow-subtidal, open-marine environments. This contrasts with the Nada in this exposure, 70 mi (117 km) to the south, in which limestones and fauna are rare. The differences are probably best explained by position relative to the Kentucky River Fault Zone, which was periodically reactivated during Mississippian time (Dever and others, 1977; Ettensohn, 1979a, 1980, 1992). Northeastern Kentucky occupied the upthrown side of the fault near the Waverly Arch, a situation that generated a very shallow, platform setting conducive to carbonate deposition and diverse faunas. The Bighill locality, however, is located about 50 mi (83 km) south of the fault zone on the downthrown side in conditions that were probably much deeper. South of the fault, the Nada is composed of mostly mudstones and shales and appears to represent an area of deep-ramp, shelf muds. The ramp, however, was not below storm wave base, because the presence of debris-filled scours, starved ripples, and laminae of fossil debris probably represents distal tempestites emplaced by storm backflow (e.g., Aigner, 1985). At times, moreover, sedimentation must have been slow enough to allow quiet-bottom communities of delicate bryozoans, brachiopods, and crinoids to develop on the soft bottoms.

The upward change into thicker, coarser dolostones and siltstones marks a transition into more proximal, mid-ramp, storm-shelf conditions with banks formed first of lime and glauconite pellets and then silt. The presence of thicker bedding, bed amalgamation, and swaley crossbeds points to more proximal, mid-ramp conditions (Aigner, 1985; Pashin and Ettensohn, 1987).

Overall, the Nada muds are glauconitic with major concentrations of both glauconite and phosphorite, most notably in the Floyds Knob Bed. Glauconite and phosphorite commonly occur together in areas transitional between deep and shallow waters, slightly deficient in oxygen, with slightly lower than normal pH, and where clastic sedimentation is very slow to nonexistent (Carozzi, 1960; Hatch and Rastall, 1965). Initial precipitation of phosphorite may have been related to episodic upwelling into the area (e.g., Carozzi, 1960; Prévôt and Lucas, 1990), but the fragmentation and boring of many of the nodules suggests repeated reworking and concentration, perhaps by storm currents, during times of sediment starvation. Although clay muds predominate in this area of Nada distribution, the glauconitic and phosphoritic nature of the muds strongly supports the idea of sharply reduced sedimentation on subaqueous parts of an abandoned delta and subsequent reworking by storms on a resulting deeper-water shelf or ramp.

Slade Formation

The Slade Formation consists largely of shallow-water, Middle (Meramecian) and Upper (Chesterian) Mississippian carbonates, formerly known as the Newman Limestone in east-central and northeastern Kentucky (e.g., Weir and others, 1971). In 1984, the name "Newman" was restricted to the type outcrop belts on Pine and Cumberland Mountains in southeasternmost Kentucky and adjacent states, and the name "Slade Formation" was instated throughout east-central Kentucky (Ettensohn and others, 1984). The concept of the unit was enlarged, new units were designated, and others were renamed. A comparison of old and new unit nomenclature is provided in Figure 4.

Renfro Member

The Renfro Member is unusually thick and well exposed in this cut, consisting of 56 ft (17 m) of grayish-orange to pale orange dolostone with a few thin interbedded limestones and shales (Fig. 4). The contact with the underlying Nada is sharp and represents another pause or lag horizon, but elsewhere in east-central Kentucky the contact may be gradational with intertonguing between the two members. The Renfro in this exposure exhibits many complexities, and for ease of description is subdivided into three parts by the two prominent limestone intervals.

Lower Part. The lower part, about 33 ft (10 m) thick, begins with glauconitic, hummocky-crossbedded

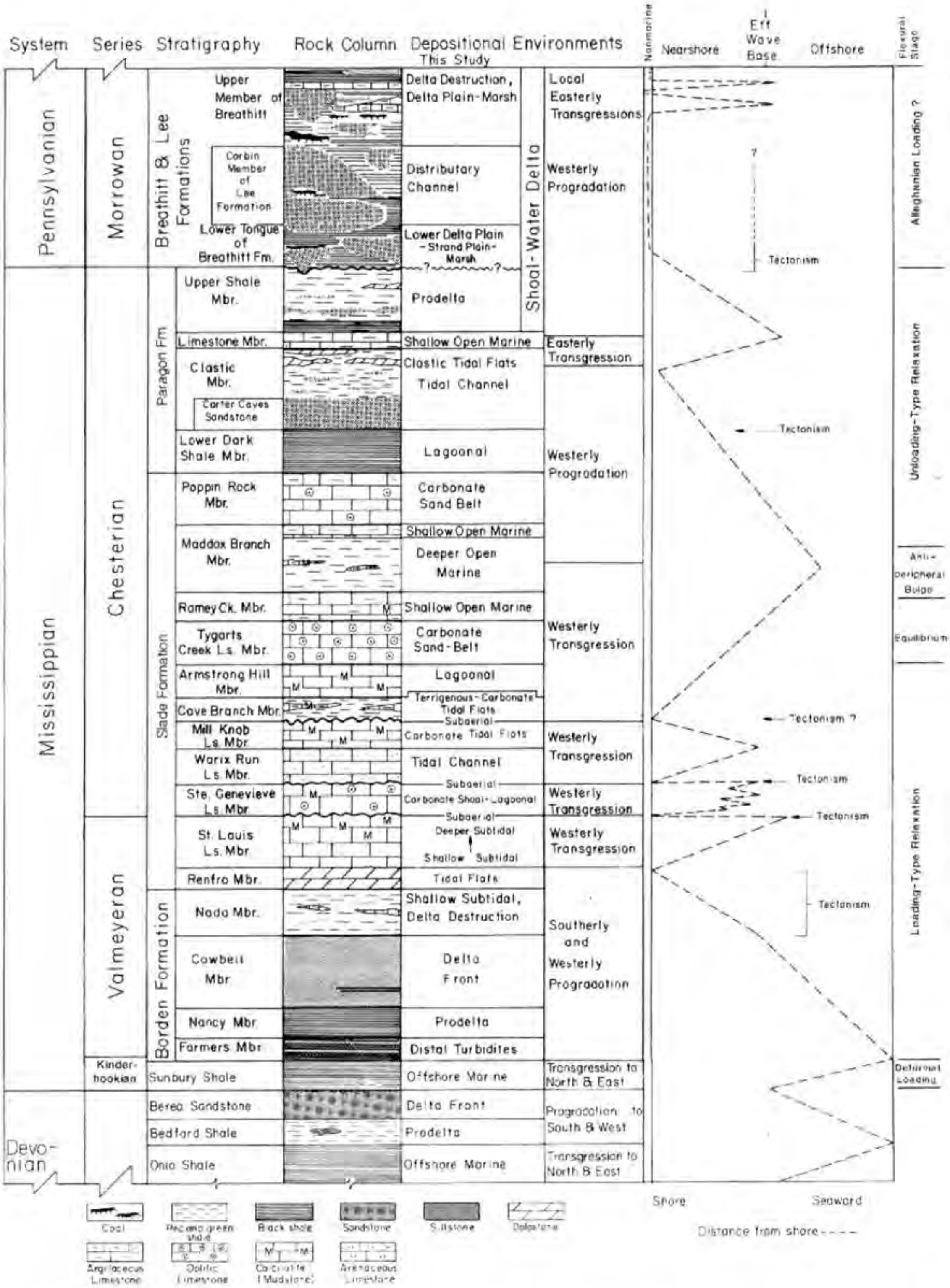


Figure 5. Generalized sequence of Upper Devonian and Carboniferous units in east-central Kentucky, showing inferred succession of environments, larger environmental continua, local tectonic events, and probable flexural stages (see Fig. 8) (from Ettensohn, 1992).

dolarenites that pass upward into ribbon-bedded dolosiltites, which contain breccias, reworked glauconite, and possible subaerial exposure crusts. This interval is interrupted by a 4-ft-thick (1.2-m-thick) bed of sandy dolostone, which is equivalent to the Science Hill Sandstone of Lewis and Taylor (1979). Overlying the Science Hill equivalent is about 9 ft (2.7 m) of massive dolosiltite with four shoaling-upward cycles of glauconitic, bioturbated, ribbon-bedded dolostone passing upward into laminated dolostones. This interval is capped by about 5 ft (1.5 m) of massive dolosiltite to skeletal dolarenite with rare fossils and subtle hummocky crossbedding, which underlie the first limestone.

The lower part of the Renfro represents a continuation of the regressive, shallowing-upward regime begun in the underlying Nada. The lowermost dolarenites with hummocky crossbeds seem to represent continuation of storm-shelf conditions, only in an upper-ramp setting. The regression and shallowing upward continue with several thin, cyclic sequences, composed of ribbon bedding, undulating laminae, and possible exposure crusts, and probably culminates with exposure just below the Science Hill equivalent. The Science Hill equivalent has been interpreted to represent distal parts of a highly constructive, shoal-water delta (Lewis and Taylor, 1979), but it may also be a lowstand fan on the underlying surface of exposure. The overlying interval of cyclic ribbon beds and laminites represents a return to alternating shelf-lagoon/intertidal-supratidal conditions, whereas the overlying crossbedded dolarenites represent inception of transgression and return to slightly deeper, storm-shelf conditions.

Middle Part. The middle part of the Renfro begins with about 5 ft (1.5 m) of greenish-gray to bluish-gray, argillaceous limestone and interbedded shale with bioturbation and locally abundant corals and brachiopods. The top of the limestone is erosionally truncated and slightly melanized, suggesting ephemeral exposure. This limestone is probably equivalent to the widespread Ringgold bed of Dever (1990) in equivalents to the south (Fig. 4). The overlying 12 to 15 ft (3.7 to 4.6 m) include massive ribbon-bedded to laminated dolostones like those below, but they have been subsequently altered by exposure, solution, and pedogenic processes. Up to six paleosols, indicated by brecciation, microkarst, soil teepees, subtle exposure crusts, and truncation, are present, and each caps a major dolostone unit. The last dolostone unit exhibits a prominent erosional knoll with relief up to 3.5 ft (1.1 m), around which the overlying limestone onlaps.

The Ringgold limestone equivalent that begins this part of the Renfro represents regional transgression and a return to shallow, open-marine, mid-ramp conditions; the muddy limestones and fossils suggest that the environment was situated below normal wave base. The paleosols capping each unit, however, indicate rapid sea-level lowering and exposure. Overlying dolostones and shales represent a return to cyclic shelf-lagoon/intertidal-supratidal environments with a few brief incursions of deeper-water or storm-shelf conditions. Each environmental interval, however, was abruptly ended by sea-level drop, exposure, and the development of a paleosol. The three massive dolostone units in the interval contain pockets of breccia, which are probably solution breccias, reflecting either karstic solution or dissolution of evaporites, both of which have been noted in equivalent rocks to the south (Dever and others, 1979; Dever and Moody, 1979; Dever, 1990).

Upper Part. The upper part of the Renfro begins with 1 to 3 ft (0.3 to 0.9 m) of a second limestone, which laps onto erosional highs in the underlying dolostone. The limestone is an argillaceous, fine-grained calcarenite with subtle cross-laminae and fossil corals, bryozoans, brachiopods, and crinoid debris; individual parts of the unit seem to form sand waves. Two feet (0.6 m) of dolarenite with colonial rugose and tabulate corals and crinoid debris sharply overlie the limestone and pass upward into 5.5 ft (1.7 m) of ribbon-bedded to laminated dolosiltites with possible exposure crusts at the top. The overlying 8.5 ft (2.6 m) of dolostone consists of thin-bedded dolarenites to dolosiltites with bands of fenestrate bryozoan, brachiopod, and crinoid fossils. This part of the Renfro appears to have been altered throughout by subaerial exposure crusts, and the upper 2 feet exhibits breccias, erosional relief, and cavities filled with shale from the overlying St. Louis.

The upper 12 to 19 ft (3.7 to 5.8 m) of the Renfro represents two smaller transgressions (Fig. 4). The lower one begins with a shallow, open-marine, mid-ramp limestone succeeded by shelf-lagoonal and intertidal-supratidal dolostones, capped with a probable paleosol. The overlying sequence, however, reflects rapid transgression and establishment of shallow, open-marine, muddy-shelf environments, which at the top of the Renfro appear to have been abruptly exposed, for there is no intervening shoaling-upward component. The top of the Renfro has been interpreted to represent a regional, mid-Valmeyeran unconformity (Ettensohn, 1994).

Interpretation. The Renfro overall reflects the final part of a major regional regression that ends Middle Mississippian deltaic deposition throughout most of the Appalachian Basin and adjacent areas (Fig. 5), although its middle and upper parts also indicate the inception of renewed transgression (Fig. 4). The resulting delta destruction, which is first apparent in the Nada at this exposure, transforms deeper-water, Borden Delta front slopes into a shallow-water, carbonate-ramp setting, on which overlying Middle and Upper Mississippian, Slade carbonates were deposited. The transition from clastics to carbonates and from deeper water to very shallow water is clearly seen in the Nada-Renfro succession. On a regional scale, however, these changes necessitate the complete shut-off or diversion of clastic influx and an episode of eustatic lowering and/or regional uplift. The likely tectonic and eustatic causes are discussed in a later section.

St. Louis Member

The St. Louis Member sits unconformably on top of the Renfro at the first major bench in the exposure (Fig. 4). The member is up to 12 ft (3.7 m) thick and consists of three widespread subunits A, B, and C (Philley, 1971; Dever, 1980). The lowermost unit A is composed of thin- to medium-bedded, light gray, skeletal calcarenites, containing clasts of reworked Renfro dolostone and sparse, colonial rugose corals. As is typical of the St. Louis in other places (Dever, 1980), the unit contains large elliptical nodules and ball-and-pillow structures of medium gray to pale green dololutite. Unit B consists of thin-bedded, light gray, fossiliferous calcarenites and calcilutites with interbedded greenish-gray shales; chert nodules occur locally; brachiopods, bryozoans, and crinoid debris are common. Unit C at the top is composed of massive, medium- to thick-bedded fine-grained calcarenite to calcilutites; irregular chert nodules, sometimes containing colonial rugose corals, are common. The dark gray or brownish-gray color is a product of melanization, and along with rare subaerial exposure crusts and erosional truncation is a product of subaerial exposure and pedogenesis on an unconformity below the Ste. Genevieve Member (e.g., Ettensohn and others, 1988). At the north end of the exposure, unit C is up to 5 ft (1.5 m) thick, but toward the south it is truncated below the Ste. Genevieve to less than 2 ft (< 0.6 m). Colonial rugose corals in the St. Louis have been identified as *Acrocyathus floriformis* and *A. proliferus*, which are common St. Louis guide fossils (e.g., Butts, 1922).

Interpretation. The three-part, fining-upward St. Louis sequence has been interpreted to be a transgressive sequence (Ettensohn and Dever, 1979; Dever, 1980), with unit A representing mid-ramp skeletal shoals at wave base, unit B representing lower-ramp shallow, open-marine conditions, generally below wave base, and unit C representing deeper, open-marine conditions, well below wave base (Fig. 5). The abrupt alteration of these subtidal carbonates by subaerial diagenesis, pedogenesis, and erosion along an unconformity, without an intervening regressive interval, suggests rapid drop in sea level and exposure. In northeastern Kentucky, this uplift has been clearly associated with basement structures (Ettensohn and Dever, 1979; Ettensohn and others, 1988), but the regional nature and distribution of the unconformity may suggest the importance of regional bulge uplift accompanying a tectophase of the Ouachita Orogeny (Ettensohn, 1993). The dolomitic nodules and ball-and-pillow structures in unit A are similar to soft-sediment deformation associated with seismicity and may be seismites (e.g., Ettensohn and others, 2000).

Ste. Genevieve Member

The Ste. Genevieve Member unconformably overlies the St. Louis and begins with a transgressive lag of reworked, dark, upper St. Louis clasts (Fig. 4). The unit is 28 to 36 ft (8.5 to 11.0 m) thick and thins to the northwest due to erosion from the overlying Warix Run Member. The unit can be separated into two parts by an erosional hiatus with a dark paleosol horizon. The lower part is an intertonguing and internally truncated facies complex of thin-bedded, light greenish-gray calcilutites; massive, dark brownish-gray, clotted, bird's-eye calcilutites; and skeletal-oolitic calcarenites. The calcarenites contain, high-angle, planar-tabular crossbeds, some of which show a herringbone pattern. The complex is 18 ft (5.5 m) thick, and facies are uniformly truncated along a melanized paleosol horizon up to 3 ft (0.9 m) thick with breccias and thin, wispy, subaerial exposure crusts. The upper part of the member begins with breccias eroded from the lower unit and consists of 10 to 18 ft (3.0 to 5.5 m) of crossbedded, skeletal/oolitic calcarenite and interbedded dark calcilutites. *Platycrinites penicillus*, a Ste. Genevieve guide fossil (Butts, 1922), has also been found in the upper unit. The top of the unit is unconformable with the overlying Warix Run, and contains remnant soil teepees, root tubules, breccias, faint crusts, and melanization, all indications of a major paleosol. In northern parts of the cut, the Ste. Genevieve shows several relatively recent solution pits, some of which are lined with flowstone.

Interpretation. Both parts of the Ste. Genevieve are interpreted to represent very shallow, high-energy, tidal sandbar belts of migrating bars and shoals; the calcilutites are interpreted to represent lime-mud accumulation in protected lagoons behind the bars and shoals (Fig. 5). As the bars migrated, some of the lime muds were eroded, giving the complex truncation surfaces in the unit. The unusual, dark brownish-gray, clotted calcilutites from the lower part are interpreted to represent migrating mud-mound facies that formed on erosional highs through the accretion of mud clasts ripped up from nearby lagoons by storms. Similar banks have been described from present-day Florida Bay (Ginsburg, 1972). The peculiar bird's-eye texture reflects early, sparry-calcite infilling of voids between mud clasts. The Ste. Genevieve contains prominent paleosol horizons at its middle and top, which represent episodes of subaerial exposure related to eustatic and/or tectonic causes (Ettensohn and others, 1988; Ettensohn, 1993).

Warix Run Member

This member is very similar to the Ste. Genevieve from which it was formally separated in 1984 (see Dever, 1980; Ettensohn and others, 1984) (Fig. 4). The main difference is the presence of quartz sand and peloids. The Warix Run also typically occupies deep erosional lows cut into underlying units (Ettensohn and Dever, 1979; Dever, 1980; Ettensohn, 1980, 1981, 1992). At this exposure, the Warix Run is separated from the Ste. Genevieve by a green sandy breccia, up to 1 ft (0.1 m) thick, containing reworked clasts of the underlying Ste. Genevieve paleosol; most of the quartz sand is concentrated near the base of the unit. Overall, the unit is a dark brownish-gray, peloidal calcarenite with large, planar-tabular crossbeds. The unit occupies a channel cut into the Ste. Genevieve here and thickens to the north as the channel deepens in that direction (Fig. 4). Accordingly, thickness varies from 3 to 13.5 ft (0.9 to 4.1 m) because of the erosional contact with the Ste. Genevieve. The dark color of the unit is the product of melanization, which together with sparse, wispy exposure crusts, and root tubules, indicates periodic exposure. Contact with the overlying Mill Knob member is gradational. Fossils of any kind are extremely rare.

Interpretation. The unconformity atop the Ste. Genevieve is a major regional unconformity, which probably reflects bulge-related uplift during a tectophase of the Ouachita Orogeny (Ettensohn, 1993, 1994). Unconformity formation was accompanied by deep erosion into underlying units, and the Warix Run represents initial lowstand flooding of these lows (Ettensohn and Dever, 1979; Dever, 1980; Ettensohn, 1980, 1981, 1992). The initial flooding is reflected in the basal, sandy breccia, whereas other parts of the unit represent migrating tidal sand bars and dunes in the high-energy tidal channels (Fig. 5). Combinations of eustatic drawdown and rapid upward accretion of the dunes into sea level apparently left the sands periodically exposed to pedogenic processes.

Mill Knob Member

The Mill Knob Member is composed of about 45 ft (13.7 m) of cyclically alternating shaly calcilutites, oolitic/skeletal calcarenites, and bird's-eye calcilutites or dolostones, locally capped with paleosols (Fig. 5). Bedded or nodular cherts are common. Although every cycle is slightly different, most of the cycles are shoaling upward, and five such cycles are present in this exposure, two of which are capped with paleosols. The upper 5 to 6 ft (1.5 to 1.8 m) of the member is unusual in the presence of a coarsening-upward cycle containing much shale (Fig. 4). This cycle begins with a basal zone that reflects reworking of the underlying paleosol and grades upward into greenish-gray mudstones and shales interbedded with thin calcilutites, which are laminated and contain possible rare mud cracks. The top of this cycle is erosionally truncated and capped with a major paleosol, exhibiting melanization, exposure crusts, breccias, and soil teepees. Complete fossils are uncommon throughout the unit.

Interpretation. Unlike other underlying Slade units, the Mill Knob does not reflect a new transgression, but rather a continuation of flooding begun in the Warix Run and succeeding highstand conditions. The Warix Run and Mill Knob are parts of a single, large, fining- and shoaling-upward, regressive sequence and intertongue locally, although not at this exposure (Fig. 5). As the large tidal channels filled with Warix Run sands, shallow seas apparently expanded outward above and beyond the channels to form a shallow-water, tide-dominated shelf, subject to sea-level variations that produced the shoaling-upward cycles noted here and elsewhere. Rare cycles may begin with nodular, shaly, fossiliferous calcilutites that grade into bedded calcilutites, representing lower-ramp, shallow, open-marine environments, but only one such cycle is present here at the base of the unit. More commonly, a cycle begins with crossbedded skeletal/oolitic calcarenite, representing a tidal sand belt or shoal, and grades upward into a bird's-eye calcilutite or dolostone, representing protected lagoonal and intertidal environments. Occasionally, the upper calcilutite or dolostone is altered by pedogenic (paleosol) features (melanization, breccias, exposure crusts, soil peds, and teepees), indicating complete exposure. The last cycle at the top of the Mill Knob is atypical in its high shale content and coarsening-upward nature, and appears to represent a short-lived transgressive succession, reflecting the transition from paleosol to tidal flat and lagoon. Whether or not sediments representing deeper environments were ever present is uncertain, because the succession was truncated and subaerially exposed along the major regional unconformity that separates lower and upper parts of the Slade Formation. The unconformity is widespread in eastern Kentucky and is probably related to a combination of local tectonism and eustacy.

Tygarts Creek Member

This unit consists of 23 ft (7 m) of light gray to white, oolitic/skeletal calcarenite organized into five shoaling-upward cycles (Fig. 4). Each cycle begins with 0.4 to 0.5 ft (0.1 to 0.2 m) of thin-bedded, fine-grained, argillaceous calcarenite with thin shale partings and grades upward into 3 to 4 ft (0.9 to 1.2 m) of massive, crossbedded, oolitic/skeletal calcarenite. Petrographically, the calcarenites are grainstones, and grainstones in the first two cycles, especially oolitic portions, exhibit local intergranular and moldic porosity containing dead oil; when it is warm, oil oozes out of the exposure from these areas. The upper 1.5 ft (0.5 m) of the unit is a dark, argillaceous, skeletal calcarenite. The Chesterian guide fossil *Agassizocrinus* and a large unidentified crinoid stem, which is indicative of the mid-Chester Gasper Stage (McFarlan and Walker, 1956), are both present in the unit. Complete fossils are rare. In northern parts of the exposure, recent karstic processes have affected the unit.

Interpretation. The unit has been interpreted to represent a mid-ramp, high-energy, carbonate sand belt (Ettensohn, 1977, 1980) (Fig. 5), formed at the point where wave base impinged on the bottom. In this setting, ooids were formed and skeletal debris was comminuted. The agitated, unstable bottoms were not conducive for most benthic fauna, and only a few, heavily constructed, vagile gastropods and crinoids regularly inhabited the sands (Ettensohn, 1975). The cycles apparently reflect episodes of abrupt deepening followed by upward aggradation into wave base, while the dark, muddy, upper part of the unit is a transition into rocks representing deeper, open-marine environments above.

The Tygarts Creek is part of a major regional transgression that inundated the once-exposed Mill Knob surface below, and it is part of a sequence that would normally include underlying units representing tidal-flat and lagoonal environments (Ettensohn, 1977, 1979a, 1980). Those units (Cave Branch Bed and Armstrong Hill Member; Fig. 5) are absent here, perhaps due to erosion accompanying sand-belt formation.

Ramey Creek Member

At this exposure, the Ramey Creek Member is 28 ft (8.5 m) thick and consists of two shoaling-upward cycles (Fig. 4). The basal parts of each cycle contain bluish-gray, fossiliferous shales or mudstones that intertongue with crossbedded, argillaceous calcarenites, nodular calcilutites, or dolarenites. Overlying parts of each cycle consist of massive, medium- to thick-bedded skeletal/oolitic calcarenites, with high-angle crossbeds, some of which are herringbone. The lower body of calcarenite clearly intertongues with the underlying shaly section. The shaly parts of the unit are more fossiliferous than any other unit at Bighill, containing abundant ramose and fenestrate bryozoans, brachiopods, corals, gastropods, crinoids, and blastoids; bioturbation is ubiquitous. Among the most distinctive fossils are the bryozoan *Archimedes*, the brachiopods *Anthracospirifer*, *Composita*, and *Diaphragmus*, the coral *Zaphrentoides spinulosus*, the crinoid *Pterotocrinus*, and the blastoid *Pentremites*. *Agassizocrinus*, which occurs in the upper calcarenite, and *Pterotocrinus* are Chesterian guide fossils.

Interpretation. The Ramey Creek represents shallow, open-marine, outer-ramp deposition just seaward of the carbonate sand belt (Ettensohn, 1977, 1980) (Fig. 5). Deposition occurred in a lacework of tidally influenced shoals, where skeletal/oolitic sands were deposited, and in deeper, intervening basins, where calcareous mud and silt, as well as argillaceous muds, predominated. The argillaceous calcarenites, nodular calcilutites, and interbedded shales and mudstones represent basinal deposition below wave and tidal influence. The presence of crossbedded calcarenites among these lithologies apparently reflects storm-generated backflow currents from the sand belt and intervening shoals. The Ramey Creek contains the most diverse and populous fauna of any Slade member. The increased diversity and abundance of fossils, abundant burrowing, and the increased presence of muds (low sparite/micrite ratios) indicate the deeper (generally below wave base), more stable, offshore nature of Ramey Creek environments.

Maddox Branch Member

The Maddox Branch Member includes 12 to 14 ft (3.7 to 4.3 m) of predominantly dark gray to bluish-gray clay shale and mudstone, which forms a prominent bench or reentrant above the upper Ramey Creek calcarenite (Fig. 4). Lenses and nodular layers of argillaceous calcarenite or calcilutite are commonly interbedded with the shales. Some of the calcilutite nodules are brecciated or contorted, and at this exposure, a crossbedded calcarenite reworked into megaripples is the most prominent interbed. The uppermost 1.5 to 2 ft (0.5 to 0.6 m) of the unit is an argillaceous dolosiltite/dolarenite, which appears to be a part of the overlying Poppin Rock Member; it is burrowed, fossiliferous, and locally absent due to postdepositional erosion. The Maddox Branch is commonly fossiliferous but contains a fauna with less diversity and abundance than overlying or underlying members. The most common faunal elements include fenestrate and rhomboporid bryozoans, the productid brachiopod *Diaphragmus elegans*, and crinoid debris.

Interpretation. The predominance of argillaceous and calcareous muds in the Maddox Branch Member reflects deposition in a deeper, open-marine, outer-ramp environment in quiet conditions well below wave base (Fig. 5). The crossbedded and megarippled calcarenite probably represents a major episode of storm deposition. Brecciation and contortion in some calcilutites appear to have been caused by compaction. The low-diversity fauna dominated by productid brachiopods and delicate bryozoans may reflect restriction by soft muddy bottoms.

The Maddox Branch apparently represents the culmination of the transgression begun at the base of the Tygarts Creek Member (Figs. 4–5), and as a consequence should contain a maximum flooding surface before the shallowing-upward, progradational (highstand systems tract) sequence begins. Although the time of maximum water depth in this sequence almost certainly occurred during Maddox Branch deposition, in this location this time is not represented by a surface of condensation or starvation. In some other exposures, however, this time may be represented by an interval of dark, organic-rich shale. Overlying parts of the unit, then, reflect the beginning of middle Chesterian shallowing and progradation. Accordingly, uppermost dolomitic parts of the unit, which are seldom well preserved, have been interpreted to represent a return to nearer-shore, shallow, open-marine conditions (Ettensohn, 1977, 1980, 1981).

Poppin Rock Member

The Poppin Rock Member includes 22 ft (6.7 m) of bluish-gray, argillaceous, thin- to medium-bedded calcarenite (Fig. 4). Crossbedding and scours are common in the beds, and the tops of these beds typically exhibit slightly reworked bryozoan-brachiopod-crinoid communities. Fenestrate (e.g., *Archimedes* and *Lyropora*), ramose, and rhomboporid bryozoans; the brachiopods *Diaphragmus, Composita,* and *Anthracospirifer;* the coral *Zaphrentoides spinulosus;* and echinoderm debris are common on these bedding planes. The stemless crinoid, *Agassizocrinus conicus,* a middle to late Chesterian guide fossil (Burdick and Strimple, 1982), occurs commonly within the calcarenite layers.

The upper 5.5 ft (1.7 m) of the unit becomes thinner bedded, finer grained, and more shaly; fine-grained calcarenites and calcisiltites predominate. Fossils are more abundant, and bioturbation on upper bedding surfaces can be intense.

Interpretation. The more massive, crossbedded skeletal calcarenites of the lower Poppin Rock Member represent deposition on a carbonate sand belt that was the progradational analogue of the underlying, transgressive Tygarts Creek Member (Fig. 5). The major difference between the two units is the presence of detrital muds and quartz in the Poppin Rock. Each bed in the Poppin Rock represents a migrating shoal, which became stabilized long enough to support a community on its top. The upper, more shaly part of the unit represents a somewhat deeper, more protected transition from the agitated sand belt to a quiet, deeper, back-sand-belt lagoon, represented by immediately overlying parts of the Paragon Formation (Ettensohn and Chesnut, 1979; Chesnut and Ettensohn, 1988).

Paragon Formation

The Paragon Formation is largely composed of Upper Mississippian, shallow-water, marginal-marine clastics, which were formerly included in the Pennington Formation (Fig. 4). Because these rocks are not closely related to or correlative with Pennington rocks in the type Pine and Cumberland Mountain outcrop belts in extreme southeastern Kentucky, all Upper Mississippian clastic rocks above the Slade carbonates on the east-central Kentucky outcrop belt were incorporated into the newly designated Paragon Formation (Ettensohn and others, 1984). The rocks are rarely exposed due to predominance of shale and because large parts of the unit are commonly cut out by postdepositional, Pennsylvanian erosion near the Mississippian-Pennsylvanian transition.

Lower Dark Shale Member

A complete exposure of this unit is present at the top of the southeastern cut, but it is being rapidly covered with slump debris and vegetation. The unit contains up to 16 ft (4.9 m) of greenish-gray to dark gray, silty, fissile clay shale, typically with macerated plant debris (Fig. 4). The unit may be truncated at the top by the clastic/dolostone member and intertongues at its base with the Poppin Rock Member of the Slade Formation. Lower parts of the unit contain argillaceous calcarenite lenses and layers, which may be very fossiliferous and bioturbated. Fossils are very similar to those in the underlying Poppin Rock Member, but are generally more abundant. To the south, this unit has been informally called the Sloans Valley member (Ettensohn and Chesnut, 1979; Chesnut and Ettensohn, 1988).

Interpretation. The shales in this member have been interpreted to represent a protected shelf lagoon behind the Poppin Rock sand belt (Fig. 5). The fossils found in lower parts of the unit formed communities on small sandy shoals that developed in the lagoon as spillover lobes from the Poppin Rock sand belt (Ettensohn, 1977; Ettensohn and Chesnut, 1979; Chesnut and Ettensohn, 1988). Presence of plant debris suggests proximity of terrestrial source areas to the east.

Clastic/Dolostone Member

This unit is up to 17 ft (5.2 m) thick and begins with a fining-upward sequence of sandstone and shale. Basal parts of the unit consist of a thin- to medium-bedded, micaceous, medium-grained sandstone, which weathers to a yellowish-orange or brown color; it typically contains ripples, crossbeds, and shale rip-up clasts, and at this exposure is up to 4 ft (1.2 m) thick. This sandstone grades laterally and vertically into 2.5 ft (0.8 m) of thin-bedded, flaser-bedded, micaceous, fine-grained sandstones with ripples, which in turn grade upward into 6 ft (1.8 m) of dark gray shale and laminated siltstones and fine-grained sandstones with wavy and lenticular bedding; bioturbation is ubiquitous. Sharply overlying the sands is 3.5 ft (1.1 m) of interbedded dark shale and fossiliferous limestone. The limestones are succeeded by 1 ft (0.3 m) of greenish-gray shale and a foot of yellowish-orange dolostone (Fig. 4). The uppermost 13 ft (4.0 m) of the Paragon section just described is only visible at a grassy cut to the south of the main exposure on Burnt Ridge Road.

Interpretation. This succession of variable lithologies has been interpreted to represent a fining-upward, tidal-flat sequence on the shoreward side of the lagoon (Ettensohn, 1977; Ettensohn and Chesnut, 1979; Chesnut and Ettensohn, 1988) (Fig. 5). The presence of thin, fossiliferous limestone units apparently reflects brief transgressive episodes that inundated the tidal flats. North of this area, this member of the Paragon is composed largely of clastics, reflecting proximity to northern source areas; to the south, in contrast, the same interval is largely laminated dolostones, probably reflecting the absence of major clastic influx (Ettensohn and Chesnut, 1979; Ettensohn and others, 1984; Chesnut and Ettensohn, 1988). Apparently, this exposure occurs in a transition area between the two.

Tectono-Stratigraphic Implications

The Mississippian section at Bighill is very typical of Mississippian rocks throughout much of the Appalachian Basin in that it consists of a three-part succession composed of Lower and Middle Mississippian clastics (Borden Formation), Middle and Upper Mississippian carbonates (Slade Formation), and uppermost Mississippian clastics (Paragon Formation). This succession has traditionally been interpreted to represent post-Acadian clastic influx, carbonate deposition accompanying tectonic quiescence, and renewed clastic influx marking inception of the Alleghanian Orogeny (e.g., Perry, 1978; Chesnut, 1991). However, more recent interpretations based on flexural models suggest instead that these rocks are part of a third-order, Mississippian sequence that largely represents an Acadian relaxational response, and that the Alleghanian Orogeny did not begin until Early Pennsylvanian time (Ettensohn and Chesnut, 1989; Ettensohn, 1994, 2001). In contrast, some of the smaller subsequences, like the St. Louis, Ste. Genevieve, and Warix Run-Mill Knob in the lower Slade (Figs. 4–5), have been interpreted to represent eustatic and tectonic events superimposed on the larger relaxational response.

The flexural models predict a distinct sequence of lithologies and unconformities similar to those seen here and in other parts of the Appalachian Basin. Having examined various flexural models, we feel that the viscoelastic models of Quinlan and Beaumont (1984) and Beaumont and others (1987, 1988) seem to most consistently and easily explain the observed sequence. Moreover, the relatively long time involved in developing critical parts of the Mississippian section (~20 m.y.) is most typical of relaxation in viscoelastic regimes (Sinclair and others, 1991, p. 600). These models are briefly described below.

Models

Most flexural models predict that during orogeny, surface and subsurface deformational loading by flakes, blocks, thrusts, nappes, and folds produces a downwarped flexural or retroarc foreland basin cratonward of the orogen and a peripheral bulge on the cratonward margin of the basin due to regional isostatic compensation by the lithosphere (Fig. 6A). As orogeny proceeds and thrust loads shift cratonward, the foreland basin and peripheral bulge continue to migrate cratonward away from the load. Once active orogeny and thrusting cease, however, lithospheric relaxation will cause the bulge to be uplifted and migrate back toward the orogen while the adjacent foreland basin deepens and begins to receive major sediment influx (Fig. 7A); after the basin is largely infilled and adjacent highlands are eroded low, a new phase of relaxation involving lithospheric rebound begins (Quinlan and Beaumont, 1984; Beaumont and others, 1987, 1988) (Fig. 7B). Hence, even during times of orogenic quiescence after active thrusting, sedimentation and bulge-basin re-

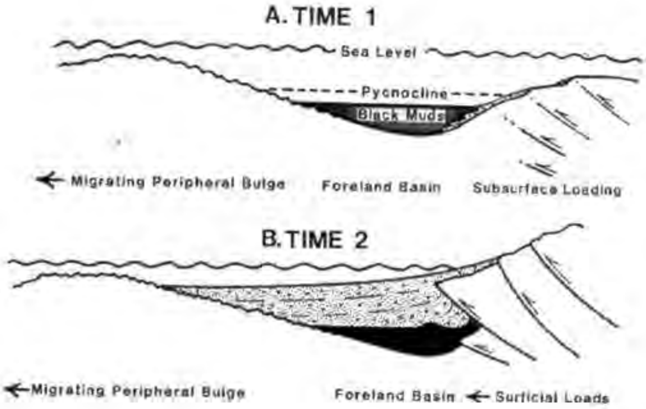


Figure 6. Schematic diagrams showing sedimentologic/stratigraphic responses of the foreland basin during two stages of loading: (A) Rapidly subsiding foreland basin with little clastic influx during subsurface loading—corresponds to Sunbury/uppermost New Albany deposition in this area (see Fig. 8A). (B) Subsiding foreland basin infilled with coarser clastics derived from surficial load—corresponds to Borden deposition in this area (see Fig. 8B). The pycnocline is a zone of thermohaline density stratification with decreasing oxygen content. Dark stipple: black shales; large stipple: coarser clastic sediments; wavy lines: unconformities.

organization continue because of relaxation. Some of this lithospheric reorganization commonly involves reactivation of basement structures or surficial faulting (e.g., Bradley and Kusky, 1986), resulting in local uplift and related facies changes in parts of the basin.

Assuming that deformational loading and relaxation go to completion, each flexural stage will generate a typical sedimentologic/stratigraphic response (Ettensohn, 1994). In following parts of the guide, we will briefly describe the nature and origin of these responses and compare them with the section at Bighill.

Unconformity Development

As convergence begins and a deformational load accumulates on the continental margin, the lithosphere responds by generating a compensating foreland basin and peripheral bulge (Fig. 6A). With cratonward movement of the thrust load in time, the subsiding basin and uplifted bulge migrate in the same direction, and erosion on the uplifted bulge generates a lower bounding unconformity throughout much of the foreland basin (Quinlan and Beaumont, 1984). However, in proximal and central parts of a basin, closer to the locus of active deformation, subsidence may outstrip any effects of bulge uplift, resulting in a conformable contact at the base of the sequence. In parts of the Appalachian Basin to the north and south, this unconformity occurs at the Devonian-Mississippian boundary below the Sunbury Shale and its equivalents (Figs. 5, 8A). However, at our location in west-central parts of the Appalachian Basin, the Devonian-Mississippian boundary occurs in uppermost parts of the New Albany Shale and is apparently conformable (Weir and others, 1971; Ettensohn, 1979b). Although we will not examine this part of the section on the field trip, this transition represents initiation of the fourth and final tectophase of Acadian Orogeny (Ettensohn, 1985).

Foreland-Basin Subsidence and Regional Transgression

As active tectonism and deformational loading ensue, rapid foreland-basin subsidence follows bulge uplift and moveout. Because initial subsidence is largely related to subsurface loading (Karner and Watts, 1983), or loading that never breaks the ocean/sea surface, no

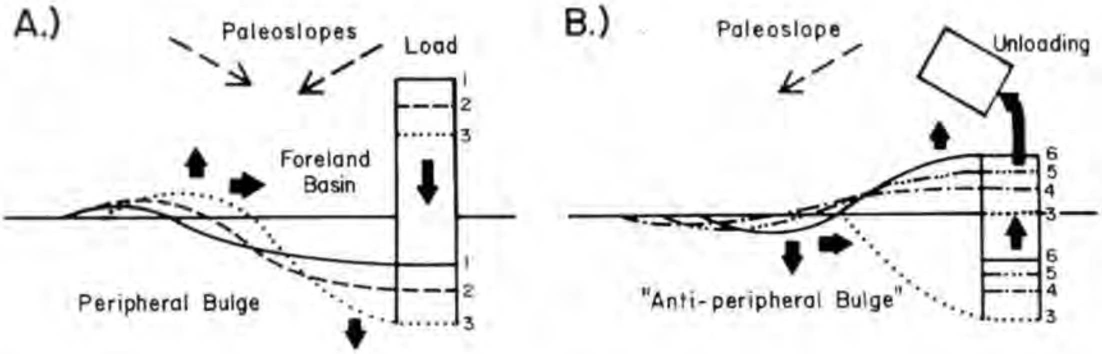


Figure 7. Schematic diagrams showing two types of flexural response to lithospheric-stress relaxation (redrawn from Beaumont and others, 1988): (A) "Loading-type" relaxation when thrust migration ceases, and (B) "Unloading-type" relaxation when erosional unloading generates rebound near unloaded area (see Fig. 8).

major source of orogenically derived sediment is available (Fig. 6A). In the absence of major clastic influx, suspended clay and abundant organic matter from the water column compose most sediment in the early foreland basin, and because subsidence exceeds sedimentation, the water column soon becomes stratified, and organic-rich sediments are preserved as black muds in resulting oxygen-poor environments (Fig. 6A). In the typical central Appalachian, Mississippian section, this stage is represented by the Lower Mississippian, black Sunbury Shale and its equivalents (Figs. 5, 8A), present here in uppermost parts of the New Albany Shale (Weir and others, 1971; Ettensohn, 1979b).

Loading-Type Relaxation and Regional Regression

Once active deformation and thrust migration cease, the deformational load becomes static. The lithosphere responds to the static load by relaxing stress so that the foreland basin deepens and narrows while the peripheral bulge is uplifted and shifts toward the load (Fig. 7A) (Beaumont and others, 1988). If sea level is low at this point, bulge uplift and migration may generate a regional unconformity. Moreover, by this time, emplacement of surface loads allows drainage nets to develop so that much of the static surface load can be eroded and transported to the foreland basin as turbidites, debris flows, deltas, and tempestites, burying basinal black shales below flysch-like sediments (Fig. 6B).

This relaxation in the central Appalachian Basin is represented by turbidites and deltaic deposits in the Borden Formation

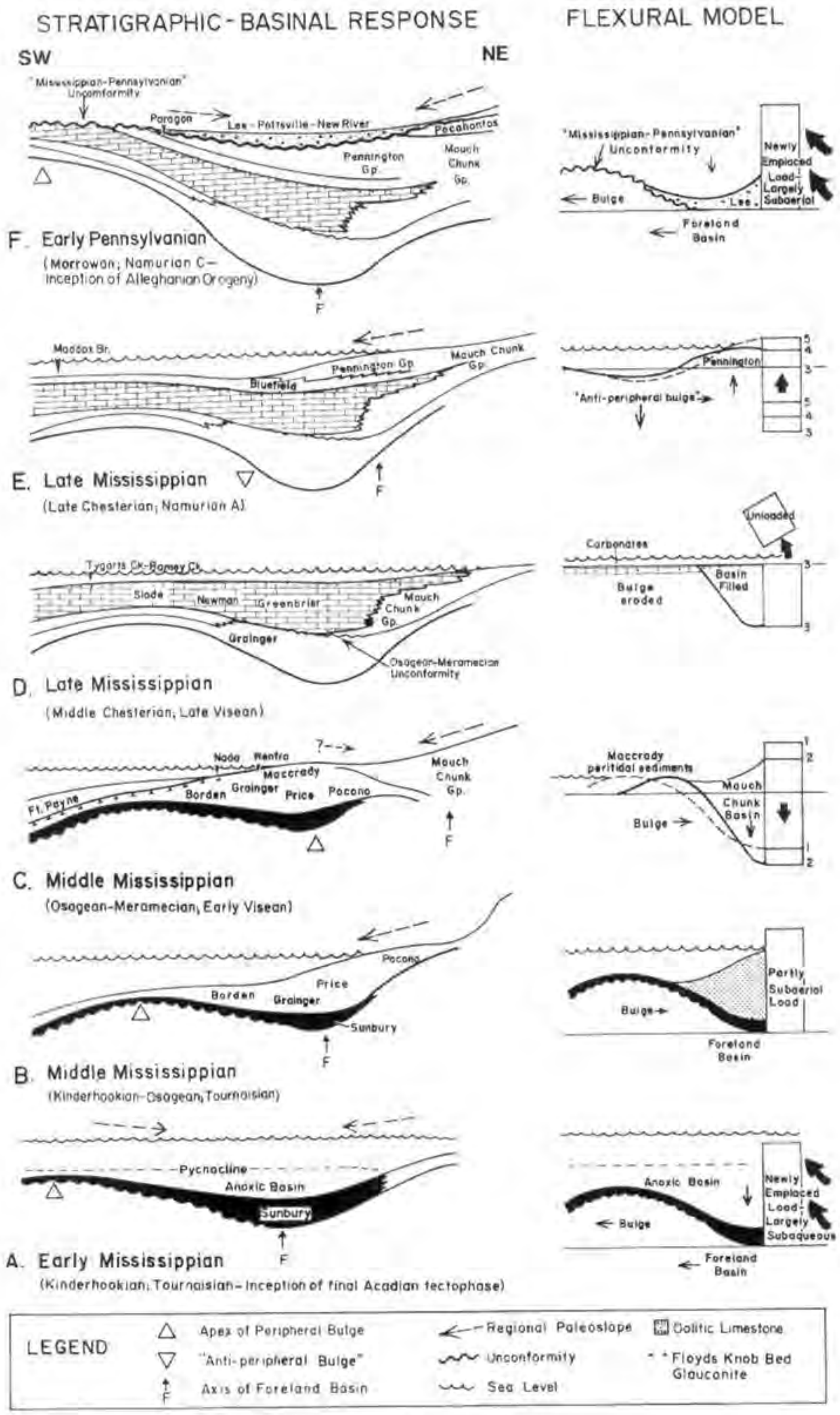


Figure 8. Schematic east–west section across central Appalachian Basin, showing the probable succession of flexural events between last tectophase of the Acadian Orogeny (A) and the inception of the Alleghanian Orogeny (F) and their sedimentary/stratigraphic responses relative to units in the central Appalachian Basin and at Bighill, Ky. (adapted from Ettensohn, 1994).

and equivalents in the Grainger, Price, and Pocono formations, as well as in the lower Mauch Chunk Group in eastern parts of the basin (Figs. 5, 8B). However, eastward bulge migration apparently disrupted deltaic sedimentation (Fig. 8C), and in distal parts of the basin west of the bulge, sediment starvation and delta destruction ensued, as seen in the Nada and in the glauconite-rich rocks of the Floyds Knob Bed (Stockdale, 1939; Kepferle, 1971); in more proximal parts of the basin on and near the bulge, deltaic sedimentation gave way to shallow open-marine and peritidal sedimentation in the Maccrady Formation and in succeeding units like the Renfro (Fig. 8C). In more distal areas to the west and southwest, declining clastic influx gave rise to the deeper-water, cherty Fort Payne carbonates.

The Maccrady, Fort Payne, and equivalents like the Renfro, however, were truncated by a regional unconformity during the Osage-Meramec transition (Fig. 8C). Although uplift on structures has been implicated locally (Warne, 1990), the influence of bulge uplift in unconformity formation is indicated by timing and distribution of the unconformity (Ettensohn, 1994). Nonetheless, delta destruction and unconformity formation are anomalous compared to other flexural sequences at similar stages, requiring an additional means of sea-level lowering—a requirement supporting the mid-Mississippian period of eustatic lowstand noted by Vail and others (1977) and Harland and others (1989). In fact, the sea-level drop and exposure reflected in Maccrady and Renfro tidal flats apparently resulted from the unique coincidence of eustatic lowstand and bulge uplift and culminated in a regional unconformity during the Osage-Meramec transition, represented here by the Renfro-St. Louis unconformity. With the decline in clastic influx and advent of shallow waters in a subtropical setting, widespread carbonate deposition in largely coeval units like the Slade, Newman, Greenbrier and Monteagle limestones supplanted the clastic infilling of the basin that would have normally characterized remaining parts of loading-type relaxation (Fig. 8D).

Anomalies in this phase of the sequence include three unconformities in lower parts of the Slade. Of the unconformities, the early Chesterian, Ste. Genevieve-Warix Run unconformity is the most widespread, and its regional distribution parallel to the Ouachita orogen suggests bulge uplift during a Ouachita tectophase (Ettensohn 1993, 1994; Ettensohn and Pashin, 1993, 1997). The St. Louis–Ste. Genevieve and Mill Knob–Tygarts Creek unconformities, on the other hand, seem to reflect some combination of local structural reactivation and eustatic lowstand (Dever and others, 1977; Ettensohn and others, 1988) (Figs. 4–5).

Immediately following early Chesterian uplift and erosion (Ste. Genevieve–Warix Run unconformity), quartzose sands flooded parts of the central Appalachian Basin, generating local sandstones and arenaceous calcarenites like the Loyalhanna Member of the Greenbrier, the Trough Creek Member of the Mauch Chunk, the drillers' Greenbrier Big Injun and Keener sands, and the Warix Run Member of the Slade Formation. Although these sand-rich units are interpreted to represent tidally influenced, coastal sand-flat environments (Carney and Smosna, 1989; Vest, 2000), their provenance is unknown. Their association with the early Chesterian unconformity and overlying Mill Knob transgression, however, may indicate that they are lowstand deposits with sources to the north and east generated by Ouachita bulge uplift.

Equilibrium Phase

Eventually the foreland basin fills with sediments while adjacent orogenic highlands undergo extensive lowering due to subsidence and erosion, leading to a brief period of near-elevational equilibrium between the filled basin and the eroded highlands (Fig. 8D). This phase is the culmination of loading-type relaxation, and in the resulting, shallow, low-gradient seas, a blanket of shallow-water carbonates spreads rapidly throughout the basin (Fig. 8D). In the Appalachian Basin, this phase peaked in Late Mississippian (late middle Chesterian) time prior to deposition of the lower Bluefield, Maddox Branch, Pencil Cave, or Lillydale shales, when a sheet of very shallow-water, skeletal, and oolitic sands, represented at Bighill by the Tygarts Creek and Ramey Creek members (Figs. 4–5), spread across much of the basin and adjacent craton (Fig. 8D). At this time, Mississippian carbonate deposition attained its greatest extent in the foreland basin.

Unloading-Type Relaxation, Regression, and Cratonward Progradation

Deposition of the carbonate blanket (Fig. 8D) is the culmination of regression begun with loading-type relaxation and is relatively short lived, because the area of the former orogen and foreland basin soon rebounds upward in isostatic response to "unloading." A compensating "anti-peripheral bulge," or peripheral sag, develops cratonward of the rebounding area, deepens, and migrates toward it in time (Fig. 7B) (Beaumont and others, 1988). As a result, shallow-water carbonates from the previous phase are abruptly overlain by transgressive, deeper-water shales or carbonates. This brief transgressive episode is followed by a regressive, cratonward-prograding wedge of marginal-marine and terrestrial, clastic sediments as the peripheral sag fills (Fig. 8E). Because the rebounded area includes parts of the former foreland basin and parts of the already-beveled orogenic upland, most derived sediment is relatively fine grained. Moreover, because this phase of relaxation begins from a state of approximate elevational equilibrium at or near sea level, a single cratonward-dipping paleoslope develops (Fig. 7B), and sediment is deposited in mainly marginal-marine or terrestrial environments.

In the central Appalachian Basin, this phase of relaxation begins with abrupt deepening in a peripheral sag represented by the deeper-water Maddox Branch Member of the Slade, the Pencil Cave or Lillydale shales of the upper Newman Limestone, and the lower Bluefield Formation (Figs. 4–5). The overlying clastics of the Paragon Formation and Pennington or upper Mauch Chunk groups represent the cratonward-prograding wedge of marginal-marine sediments (Ettensohn and Chesnut, 1985) (Fig. 8E). Based on the few places where the Mississippian-Pennsylvanian boundary is apparently gradational (Ettensohn and Chesnut, 1989; Ettensohn, 1994), this marginal-marine sedimentation probably continued into earliest Pennsylvanian time (Pocahontas Formation and equivalents), when it was abruptly ended by truncation along the sub-Absaroka or Mississippian-Pennsylvanian unconformity (Ettensohn and Chesnut, 1989) (Fig. 8F).

"Mississippian-Pennsylvanian" Unconformity

In eastern parts of the central Appalachian Basin, Mississippian and Pennsylvanian sections have been interpreted to be gradational, and the major erosive event reflected in the systemic unconformity apparently began later in Early Pennsylvanian time along a surface that first truncates Lower Pennsylvanian sediments (Englund, 1979; Englund and others, 1979) and cuts progressively deeper into Upper Mississippian rocks to the west and northwest. Although the systemic unconformity is not present in this exposure, on Indian Fort Mountain just northwest of Bighill, Lower Pennsylvanian conglomerates unconformably overlie lower Slade carbonates, and at least 215 ft (66 m) of Upper Mississippian rocks is missing on the unconformity (Weir and others, 1971). Hence, what appears to be a Mississippian-Pennsylvanian unconformity throughout most of its distribution is actually an Early Pennsylvanian unconformity that almost certainly reflects true inception of the Alleghanian Orogeny (Figs. 5, 8F).

Conclusions

The Mississippian section at Bighill (Fig. 4) represents part of a largely Mississippian, third-order sequence defined at the base by Sunbury equivalents in the New Albany Shale and at the top by the Early Pennsylvanian unconformity present elsewhere in the area (Fig. 5). Based on the section and general knowledge of Appalachian Basin, Mississippian stratigraphy, Sunbury equivalents represent the transgressive systems tract at the base, whereas overlying parts of the Borden, Slade, and Paragon Formations represent parts of the succeeding highstand systems tract. In another sense, however, flexural modeling suggests that the typical, three-part, clastic-carbonate-clastic, Mississippian succession is mostly of tectonic origin related to the closing phase of the Acadian Orogeny, such that basal transgressive parts of the sequence reflect a final phase of active deformational loading, whereas overlying regressive parts represent succeeding phases of lithospheric relaxation (Figs. 5, 8). Although not visible at Bighill, Early Pennsylvanian truncation of the Mississippian section on the sub-Absaroka or "Mississippian-Pennsylvanian" systemic unconformity apparently marks inception of the Alleghanian Orogeny (Figs. 5, 8F).

Although the clastic-carbonate-clastic succession is typical for the Appalachian Basin, the middle carbonate section so well developed at Bighill and elsewhere is anomalous in a typical flexural sequence (Ettensohn, 1994). In fact, carbonate deposition like that observed in the Slade Formation apparently interrupted normal accumulation of deltaic clastics during an early phase of relaxation and effectively altered the course of Mississippian sedimentation throughout the Appalachian Basin. This "interruption" is most likely related to a unique coincidence of relaxational bulge uplift and a sea-level lowstand that resulted in cessation of major clastic influx, generating a sediment-starved, deeper-water shelf (Nada, Fort Payne, Floyds Knob Bed), as well as succeeding, very shallow-water conditions and exposure (Renfro, Maccrady) during the Osage-Meramec transition (Fig. 8C). When seas returned during St. Louis transgression, the necessary conditions for major carbonate deposition (absence of major clastic influx, very shallow waters, and presence in an arid, subtropical belt) were in place, and major carbonate deposition expanded throughout the Appalachian Basin and adjacent regions for the next 8 million years, even in the face of perturbations from the Ouachita Orogeny to the south.

By mid-Chesterian time, abrupt deepening and renewed clastic influx, apparent in the Maddox Branch Member and overlying Mississippian units at this exposure (Figs. 4, 5, 8E, 8F), mark the end of major carbonate deposition throughout the basin and the beginning of Mississippian clastic deposition related to unloading-type (rebound) relaxation in eastern parts of the basin. This clastic deposition apparently continued into Early Pennsylvanian time, when uplift and erosion accompanying inception of the Alleghanian Orogeny truncated the underlying section on the "Mississippian-Pennsylvanian unconformity."

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Silurian through Lower Mississippian Geology, Paleontology, and Economic Influence in the Falls of the Ohio Region, Kentucky/Indiana

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Introduction

This field trip will enable participants to observe a number of excellent exposures of Silurian, Devonian, and Mississippian strata in the Falls of the Ohio region near Louisville, Ky. Participants will also have the opportunity to collect specimens of abundant and well-preserved fossil invertebrates for which the Falls of the Ohio region is renowned.

The nature of the outcrops to be visited requires that the field trip itinerary be somewhat flexible. Because stop 2 (the New Albany Shale type locality) and stop 3 (the Falls of the Ohio) are located within the channel of the Ohio River, river pool levels determine the area of each outcrop that is exposed at any given time. Therefore, these outcrops will be visited only if river conditions allow. Conversely, stop 4 (Atkins Quarry) will be visited only if stop 2 and stop 3 are inundated. The final decision concerning outcrops to be visited will be made by the field trip leaders on the day of the trip.

Because a major goal of this field trip is the collection of fossil specimens, participants will be provided with a series of photographic plates illustrating representative fossils of each lithologic unit extending vertically from the Waldron Shale to the New Providence and Kenwood members of the Borden Formation. These plates will not be included in this field trip guide because of limitations on guidebook length.

In order to maximize the time spent in the field observing the strata and fossils of the Falls of the Ohio region, the Falls of the Ohio State Park Interpretive Center will not be visited during this field trip. The Interpretive Center contains excellent fossil displays and exhibits concerning the geologic and human history of the Falls of the Ohio region. Participants are encouraged to visit the center and view its exhibits at another time.

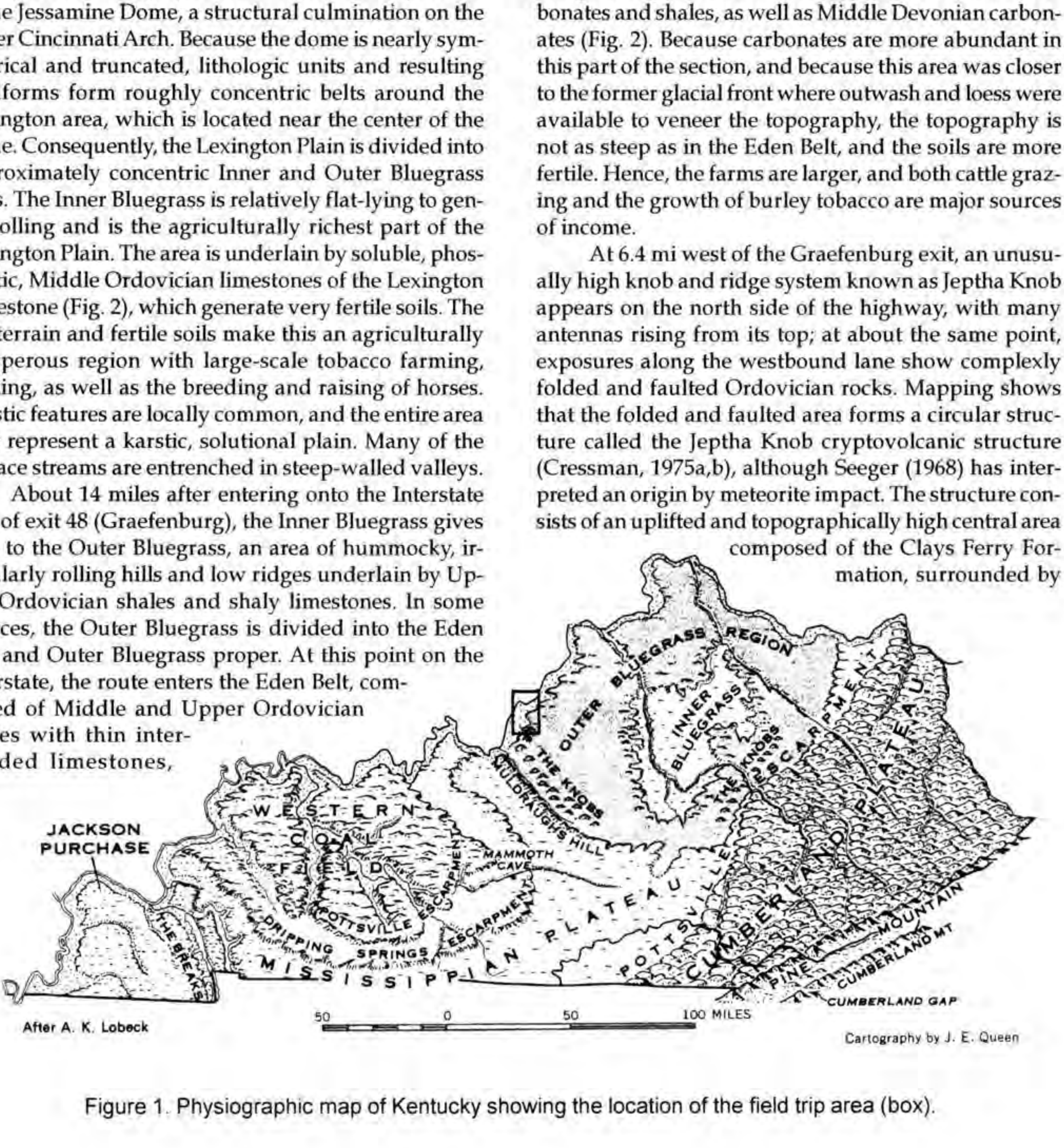
Physiography and the Field Trip Route

The field trip route follows U.S. 60 northwest from Lexington, Ky., to exit 58 on Interstate 64 south of Frankfort, Ky. We enter onto I-64 at the interchange and proceed west to Louisville, Ky. West of Louisville at the junction of I-64 and I-265 (Gene Snyder Freeway) at exit 19, we proceed south on I-265 toward our first stop. At exit 8, we leave the Interstate and proceed south toward Coral Ridge, Ky., on Ky. 1020 (National Turnpike) for 2.5 mi to the General Shale Brick plant, the first stop, where we will examine fossil-bearing Middle Mississippian shales and siltstones from clay pits in the lower Borden Formation.

The route to the Louisville area is present wholly in the Lexington Plain or Bluegrass Section of the Interior Low Plateaus physiographic province (Fig. 1). The Lexington Plain largely coincides with apical portions of the Jessamine Dome, a structural culmination on the larger Cincinnati Arch. Because the dome is nearly symmetrical and truncated, lithologic units and resulting landforms form roughly concentric belts around the Lexington area, which is located near the center of the dome. Consequently, the Lexington Plain is divided into approximately concentric Inner and Outer Bluegrass belts. The Inner Bluegrass is relatively flat-lying to gently rolling and is the agriculturally richest part of the Lexington Plain. The area is underlain by soluble, phosphatic, Middle Ordovician limestones of the Lexington Limestone (Fig. 2), which generate very fertile soils. The flat terrain and fertile soils make this an agriculturally prosperous region with large-scale tobacco farming, grazing, as well as the breeding and raising of horses. Karstic features are locally common, and the entire area may represent a karstic, solutional plain. Many of the surface streams are entrenched in steep-walled valleys.

About 14 miles after entering onto the Interstate east of exit 48 (Graefenburg), the Inner Bluegrass gives way to the Outer Bluegrass, an area of hummocky, irregularly rolling hills and low ridges underlain by Upper Ordovician shales and shaly limestones. In some sources, the Outer Bluegrass is divided into the Eden Belt and Outer Bluegrass proper. At this point on the Interstate, the route enters the Eden Belt, composed of Middle and Upper Ordovician shales with thin interbedded limestones, largely in the Clays Ferry Formation (Fig. 2). Because nonresistant shales predominate, rocks in the Eden Belt have been dissected into sharp, narrow ridgetops and steep-sided valleys. Because of steep slopes and poor, clayey soils, the area is not of major agricultural importance, except for grazing and small-scale farming. Outside the Eden Belt is another belt called the Outer Bluegrass proper, or in this area, the Western Bluegrass. It is developed on Upper Ordovician limestones and interbedded shales of the Calloway Creek, Grant Lake, and Drakes formations, and on its extreme western margins may include Lower and Middle Silurian carbonates and shales, as well as Middle Devonian carbonates (Fig. 2). Because carbonates are more abundant in this part of the section, and because this area was closer to the former glacial front where outwash and loess were available to veneer the topography, the topography is not as steep as in the Eden Belt, and the soils are more fertile. Hence, the farms are larger, and both cattle grazing and the growth of burley tobacco are major sources of income.

At 6.4 mi west of the Graefenburg exit, an unusually high knob and ridge system known as Jeptha Knob appears on the north side of the highway, with many antennas rising from its top; at about the same point, exposures along the westbound lane show complexly folded and faulted Ordovician rocks. Mapping shows that the folded and faulted area forms a circular structure called the Jeptha Knob cryptovolcanic structure (Cressman, 1975a,b), although Seeger (1968) has interpreted an origin by meteorite impact. The structure consists of an uplifted and topographically high central area composed of the Clays Ferry Formation, surrounded by



After A. K. Lobeck

Cartography by J. E. Queen

Figure 1. Physiographic map of Kentucky showing the location of the field trip area (box).

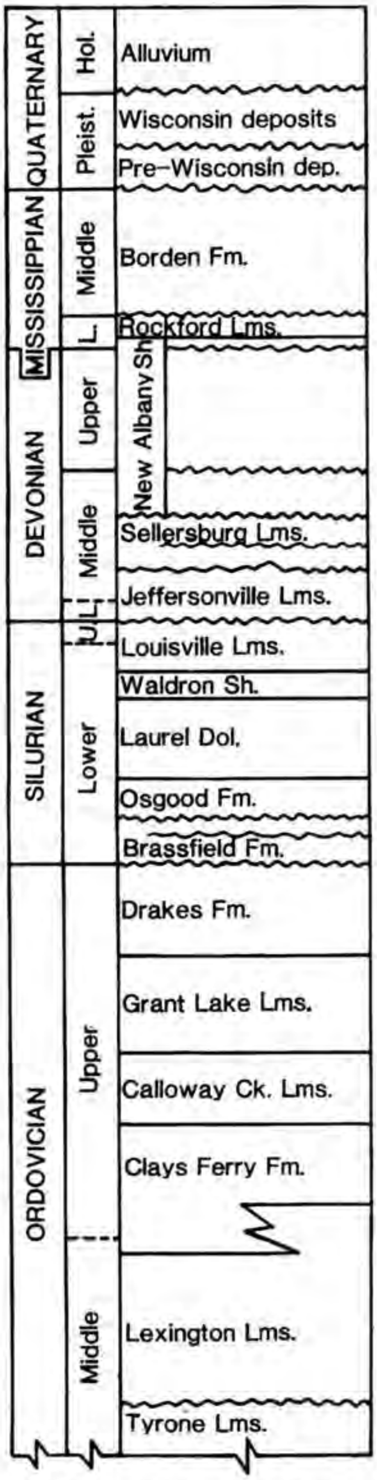


Figure 2. Generalized stratigraphy along the field trip route.

a complexly faulted and folded marginal depression containing younger Upper Ordovician rocks (Cressman, 1975a). The youngest rocks involved in the deformation are part of the uppermost Ordovician formation in the area, the Drakes Formation (Fig. 2), and undeformed rocks of Early and Middle Silurian age unconformably overlie deformed Ordovician rocks (Cressman, 1975a). These stratigraphic relationships indicate that the impact was of latest Ordovician or earliest Silurian age and occurred during development of the regional Ordovician-Silurian unconformity. The preserved structure is approximately 3.2 mi in diameter, and the highway crosses the extreme southern edge of the marginal depression.

The Outer Bluegrass proper continues into the Louisville area, although the degree of dissection is greatly moderated by the more resistant Middle Silurian and Lower and Middle Devonian carbonates underlying the area, as well as by a veneer of Pleistocene outwash, eolian, and lacustrine deposits (Fig. 2). The city itself owes its presence to the Falls of the Ohio, a series of rapids created by a resistant, biostromal accumulation in the Lower to Middle Devonian Jeffersonville Limestone (Fig. 2) in the bed of the river, which will be the subject of stop 3.

South and southwest of Louisville, the relatively low-lying topography in and near the city abruptly gives way to a topography characterized by conical hills and detached ridges known as the Knobs region of the Outer Bluegrass (Fig. 1). The Knobs form a horseshoe-shaped belt that surrounds the Bluegrass (Fig. 1). In this area the Knobs are generally no more than 200 to 300 ft (61 to 91 m) high, and are erosional remnants formed as streams cut into the Knobstone escarpment (or Muldraughs Hill), which defines the outer margin of the Bluegrass in west-central Kentucky (Fig. 1). South of Louisville, the broader bases of the Knobs are generally developed on nonresistant shales of the largely Late Devonian New Albany Shale or the Lower and Middle Mississippian New Providence Shale Member of the Borden Formation with flat resistant caps in upper Borden siltstones (Kenwood and Holtsclaw siltstone members) or silty carbonates (Muldraugh Member, Borden Formation) (Kepferle, 1972, 1974a) (Fig. 2). Some of the intervening valley bottoms and glades are covered with Pleistocene terrace and loess deposits and are broad and flat enough to support farming. Our first stop at the General Shale Brick plant is in the New Providence Shale and Kenwood Siltstone members at the base of one of these knob-ridge complexes south of Coral Ridge, Ky.

Mile
0.0: Begin roadlog at the Hyatt Regency hotel, at the corner of South Broadway and West Vine Street, Lexington, Ky. Proceed south on South Broadway.
0.9: Stoplight. Red Mile Road. Turn right onto Red Mile Road.
2.1: Stoplight. Versailles Road (U.S. 60). Turn left onto U.S. 60. Proceed west on U.S. 60.

12.7: Stoplight. Intersection of U.S. 60 and U.S. 60 Business, Versailles, Ky. Turn right onto U.S. 60.
22.9: Cross under Interstate 64. Turn left onto westbound Interstate 64. Proceed west on I-64.
40.6: Dipping beds along highway are associated with faulting at the Jeptha Knob astrobleme. Jeptha Knob is the hill to the right.
61.9: Exit 19A. Intersection of I-64 and the Gene Snyder Freeway (I-265, Ky. 841). Take exit 19A to Snyder Freeway westbound.
79.8: Exit 8. Intersection of I-265 and National Turnpike (Ky. 1020). Exit onto National Turnpike.
80.0: Turn left at stoplight at bottom of exit ramp and proceed south on National Turnpike.
81.8: Veer left. Proceed south on National Turnpike. Enter Coral Ridge.
82.6: Stop sign. Turn right. Proceed south on National Turnpike.
82.9: Production office of General Shale and Brick, Coral Ridge plant (stop 1).

Stop 1. The New Providence and Kenwood Siltstone Members of the Borden Formation at the General Shale Brick Plant

In this part of Kentucky, the New Providence Shale is the lowest part of the Borden Formation, and exposed parts of the unit at this plant are wholly Middle Mississippian or Osagean (late Tournaisian) in age (Sable and Dever, 1990) (Fig. 2). The unit unconformably overlies Late Devonian parts of the New Albany Shale (Ettensohn and others, 1989), but this contact and lower parts of the New Providence are not exposed here. In this area, upper parts of the New Providence Shale wholly encompass the Kenwood Siltstone (Kepferle, 1972, 1977) (Fig. 3B), but at this plant, upper parts of the siltstone and overlying parts of the New Providence are absent due to erosion. If the first occurrence of a major siltstone is used to define the base of the Kenwood Siltstone (Butts, 1915; Stockdale, 1939; Conkin, 1957; Kepferle, 1971), exposed parts of the New Providence Shale at this plant are 153 ft (47 m) thick, whereas preserved parts of the Kenwood Siltstone are 57 ft (17 m) in thickness (Fig. 4).

The Nw Providence is composed largely of dark greenish-gray to medium gray, silty clay shale with rare stringers of siltstone or limestone. Horizons of sideritic concretions or nodules and phosphorite nodules occur locally, and fossils are abundant at some horizons. Except for some of the contained siltstone units like the Kenwood above, New Providence shales are relatively uniform throughout the distribution of the unit.

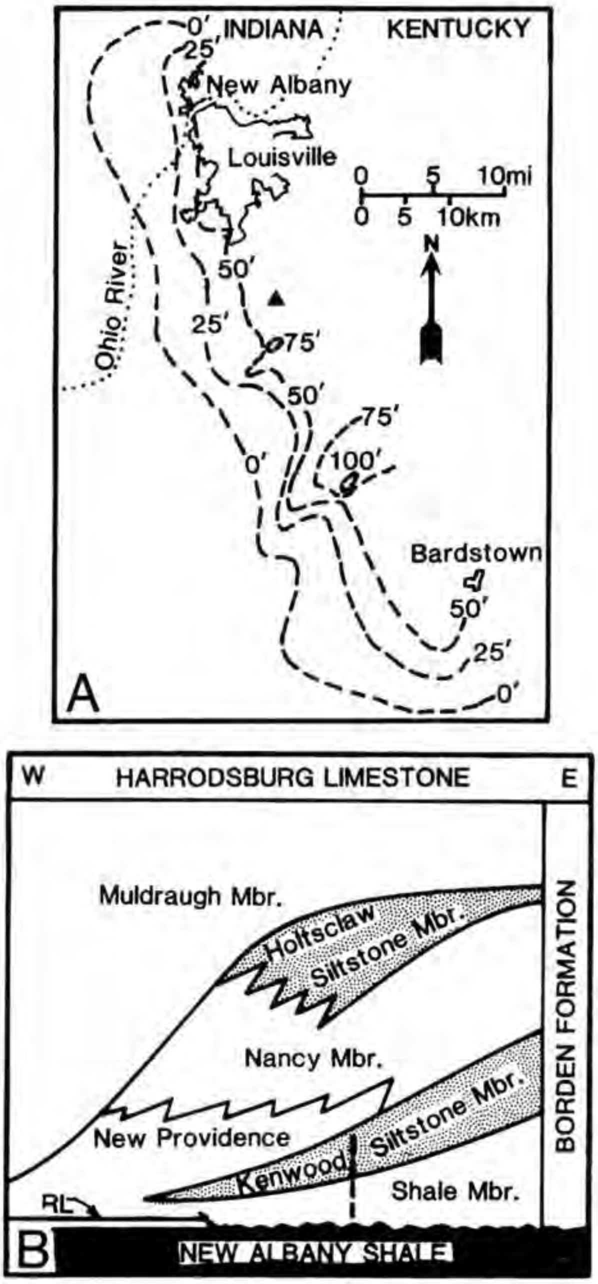


Figure 3. (A) Isopach map showing thickness and lobate geometry of the Kenwood Siltstone Member. Because of updip erosion, only the western terminus of the unit is preserved. (B) Generalized stratigraphic relationships in the ancient Borden Delta front and adjacent units in west-central Kentucky and adjacent parts of Indiana. The vertical dashed line shows the approximate stratigraphic disposition of the Coral Ridge section (adapted from Kepferle, 1971, 1977).

Conkin (1957), however, divided shaly parts of the unit into two subdivisions, the Coral Ridge and Button Mold Knob members (Fig. 4), based largely on their contained faunas. Although the faunas are distinct, the

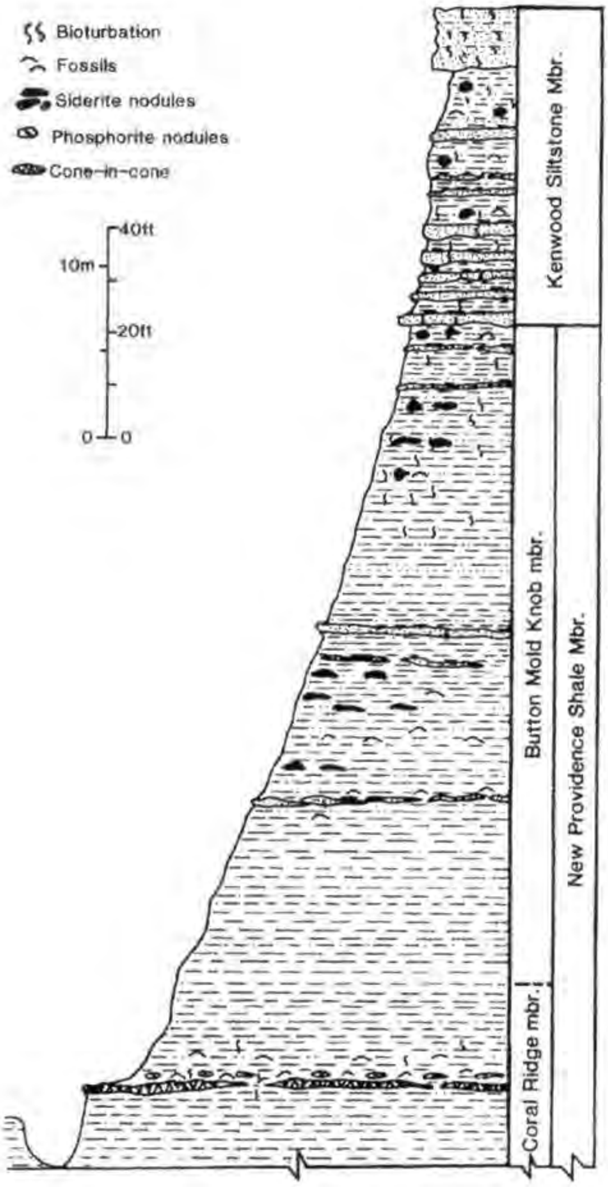


Figure 4. Stratigraphic section at the General Shale Brick plant, Coral Ridge, Ky.

lithologies are difficult to distinguish, and hence use of the two member names in a formal, lithostratigraphic sense has been rare. The lower 15 ft (4.6 m) of the exposed shale is unfossiliferous and probably represents the lower part of Conkin's (1957) Coral Ridge member. The upper part of this member begins at a ferruginous siltstone with cone-in-cone structures and is characterized by depauperate, mollusk-dominated fauna. Several species of ammonoids and gastropods are most common, but brachiopods and pelmatozoan debris are also present. Many of the fossils have been replaced with marcasite, pyrite, or phosphorite. Small phosphorite nodules are abundant, and some of these have been bored. In places, phosphorite-infilled burrows are common. According to Conkin (1957), the upper part of the Coral Ridge member should be about 15 ft (4.6 m) thick and is bounded by another cone-in-cone bed, but at this locality that bed is missing. Although the member distinction has never been widely accepted, the small, low-diversity fauna present above the base of the New Providence continues to be called the Coral Ridge fauna.

Conkin (1957) assigned all overlying parts of the New Providence Shale to the Button Mold Knob member (Fig. 4). Shales in this part of the section are very similar to those at the base of the New Providence, except that siltstone stringers and large siderite nodules become more abundant, especially toward the top of the unit. However, phosphorite nodules and pyrite or marcasite replacement are absent. In the lower two-thirds of the Button Mold Knob, fossils can be extremely abundant and diverse. Species of rugose and tabulate corals, chonetid, productid, and spiriferid brachiopods, fenestrate and rhomboporid bryozoans, gastropods, trilobites, abundant pelmatozoan debris, and the trace fossil *Zoophycus* are present, and Conkin (1957) has called this the Button Mold Knob fauna. In the upper third of the member, this fauna becomes scarce, except for the trace fossils. Those fossils present are usually preserved in large siderite concretions, some of which are septarian and up to 3 ft (0.9 m) in length. Some of these fossils include gastropods, trilobites, brachiopods, nautiloids, conularids, and trace fossils.

Sharply overlying the New Providence Shale is the Kenwood Siltstone Member of the Borden Formation (Butts, 1915; Stockdale, 1939; Kepferle, 1971) (Fig. 4). Among the plant workers, this unit is informally called the "Rosewood," but application of this name to the Kenwood is mistaken, for Butts (1915) originally used the term for all the shales (New Providence and Nancy members of the Borden) overlying the Kenwood. Although siltstone stringers increase in number in upper parts of the New Providence Shale, we have chosen the first major siltstone as the base of the Kenwood Siltstone (Fig. 4). The lower 18 ft (5.5 m) of the member consists of thin-, even-bedded, medium gray siltstones interbedded with silty clay shales like those in the underlying New Providence. Sole marks, crude graded bedding, ripple bedding, plane laminae, and micro cross-laminae are present in some of the siltstones. Small siderite concretions occur locally.

The overlying 24 ft (7.3 m) is largely silty mudstone with thin siltstone stringers and siderite nodules. The upper 11 ft (3.4 m) of the member forms a resistant cliff and is composed of medium gray, fine-grained, micaceous sandstone to siltstone with interbedded silty shale. Sedimentary structures are generally obscure, but scours, plane laminae, micro cross-laminae, swaley crossbedding, and sole marks, which include groove casts and brush marks, are present locally. The unit is highly bioturbated, and examples of *Zoophycus, Scalarituba, Chondrites,* and a large, unidentified meandering trace are common. The only common body fossils are productid brachiopods in some of the more shaly units, and accordingly, Conkin (1957) has placed the Kenwood in the *Productus wortheni* Zone. Work by Kepferle (1972, 1977) has shown that the Kenwood siltstone sequence drops stratigraphically to the southwest (Fig. 3B) and that paleocurrents were generally to the west-southwest (Fig. 3A).

Interpretations. The New Providence-Kenwood sequence is part of the overall coarsening-upward Borden deltaic sequence (e.g., Kepferle, 1977), which represents the flooding of the Appalachian Basin with relaxational clastic sediments following the final Early Mississippian tectophase of the Acadian Orogeny (Ettensohn, 1994, 2001). This clastic wedge, known as the Price-Pocono, Grainger, or Borden Delta, immediately followed basinal, black-shale deposition in south-central parts of the Appalachian Basin. Price-Pocono clastics generally reflect subaerial parts of the delta complex, whereas the Grainger and Borden represent more distal, subaqueous parts of the complex. The delta complex extends more than 480 mi (800 km) along strike in the Appalachian Basin, overlapping large parts of the earlier Catskill Delta complex, but subaqueous lobes of the complex extend westward nearly 360 mi (600 km), crossing the Cincinnati Arch and much of the Illinois Basin (Swan and others, 1965; Lineback, 1966) (Fig. 5). In fact, the field trip site in the Louisville area is on the western side of the Cincinnati Arch and on the eastern flank of the Illinois Basin (Fig. 5). The extent of this complex into the Illinois Basin is unusual compared to earlier Appalachian Paleozoic delta complexes, which were wholly restricted to the Appalachian Basin, and probably reflects subsidence or tilting of south-central parts of the continent due to coeval Ouachita convergence on its southern margin (Etttensohn, 2001).

During Early Mississippian time, this site, along with much of the cratonic interior, was an area of slow, deep basinal sedimentation due to regional subsidence and deepening accompanying the final, Early Mississippian tectophase of the Acadian Orogeny (Ettensohn and others, 1988; Ettensohn, 1998). Because of water depth and other regional considerations, a stratified water column (Fig. 6) was established in which phosphorites and black shales were deposited on the resulting anoxic bottoms (Ettensohn and Barron, 1981; Ettensohn, 1998). This area, however, which was west of the Cincinnati Arch, never received much of the east-

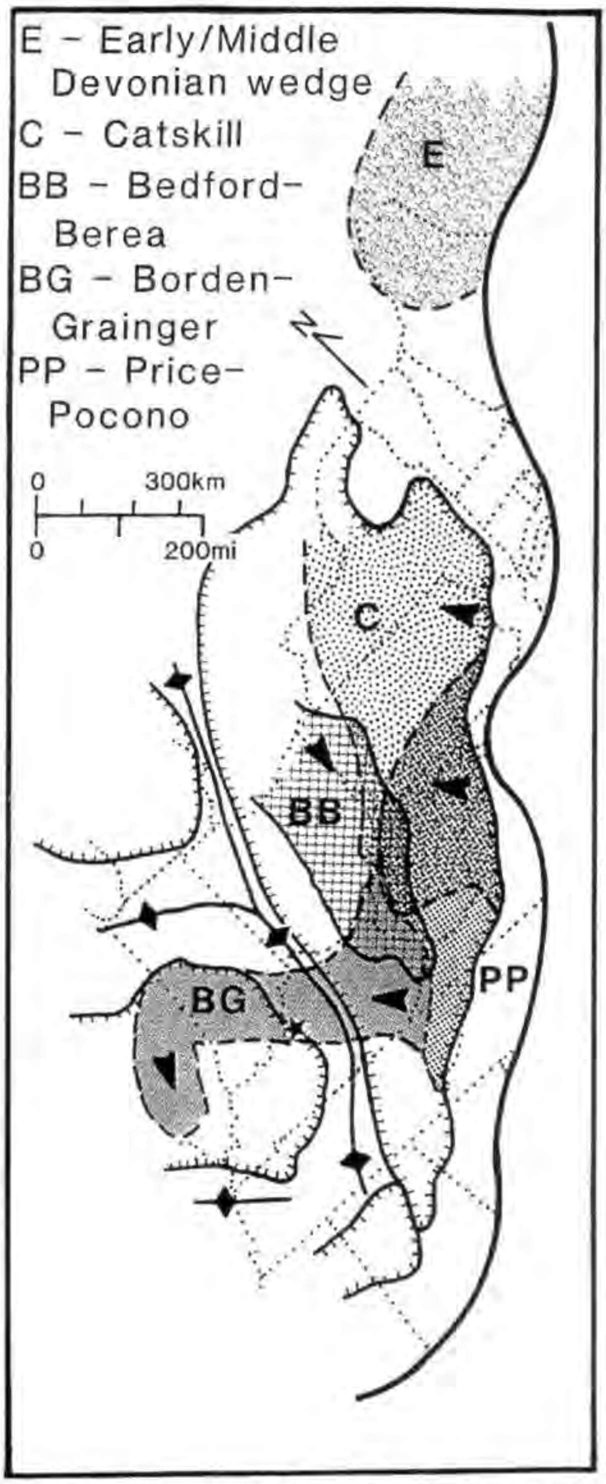


Figure 5. Distribution of Devonian–Early Mississippian, Acadian clastic wedges. Each wedge was part of a prograding delta complex. Arrows superimposed on wedges represent predominant paleocurrent directions. Kenwood Siltstone was part of the Borden-Grainger wedge, and location of the field trip area (star) occurs near the point where the wedge crossed the Cincinnati Arch and migrated into the Illinois Basin.

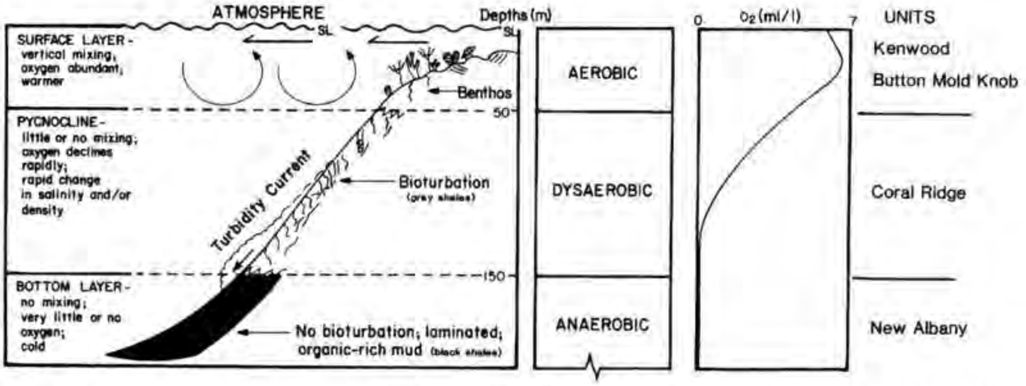


Figure 6. The New Providence and Kenwood members of the Borden are interpreted to represent prodelta and delta-front environments, respectively, that prograded into a basin with a stratified water column. The location of these members relative to water stratification is shown in this schematic diagram.

erly-derived sediment, and Mississippian parts of the section, where preserved, consist of little more than a foot (0.3 m) of sandy black shale and phosphorite nodules at the very top of the New Albany Shale (Ettensohn and others, 1988, 1989). Although the New Albany is not visible at this stop, this locality is part of the area around Louisville in which biostratigraphy indicates that Mississippian parts of the New Albany black shales were eroded during late parts of Early Mississippian (mid-Tournaisian) time, probably due to uplift on the Louisville High (Ettensohn and others, 1989). So when the Borden Delta Front prograded into this region in Middle Mississippian, Osagean time, it was into a moderately deep, stratified shelf area, where erosion and nondeposition had predominated for some time. This stratification is clearly indicated in patterns of oxygen-related biofacies (e.g., Bottjer and Savrda, 1990) (Fig. 6).

Unfossiliferous, laminated black shales like those in the New Albany Shale represent deep, anaerobic, basinal environments (Fig. 6). The overlying bioturbated sediments in "Coral Ridge" parts of the New Providence reflect a prodelta, muddy-shelf environment, where deposition was largely through suspension sedimentation. The low-diversity faunal assemblage of small, less heavily calcified body fossils is typical of a dysaerobic biofacies (Bottjer and Savrda, 1990), suggesting low oxygen levels in dysaerobic parts of the water column. These fossils are commonly associated with horizons of phosphorite nodules, which may indicate the faunas developed during periods of low sedimentation or sediment starvation. Moreover, the abundance of phosphorite in this part of the section probably indicates that upwelling has also been present periodically (e.g., Heckel, 1977; Diester-Haass, 1978), as suggested by Ettensohn and Barron (1981) for underlying black shales. The enhanced productivity that is suggested by upwelling may have also contributed to the periodic oxygen depletion and reducing conditions that are necessary for the deposition of phosphorite and shell replacement by iron sulfides (e.g., Prévôt and Lucas, 1990).

In "Button Mold Knob" parts of the New Providence, the absence of phosphorite and pyrite replacement, as well as abundant bioturbation and a diverse assemblage of heavily calcified body fossils, suggests an aerobic biofacies in oxygenated parts of the water column (Fig. 6). Although the prodelta setting does not appear to have changed, the presence of aerobic conditions must reflect decrease in relative sea level and/or rapid upward accretion of the seafloor. The fauna, however, indicates that at least periodically the seafloor was firm and escaped rapid sedimentation. The excellently preserved, but disarticulated, nature of the fauna, however, may indicate rapid burial and subsequent reworking by storms or bioturbation.

In upper parts of the New Providence and in the overlying Kenwood Siltstone, the fauna becomes scarce, and this may indicate increased sedimentation rates. In the Kenwood Siltstone, this is reflected in a major influx of silt and fine-grained sand. The Kenwood is a wedge of sediment that thins from 100 ft (33.5 m) to nothing across a width of 10 mi and extends along strike for a distance of 50 mi from southern Indiana into north-central Kentucky (Kepferle, 1977) (Fig. 3A). Based on geometry and sedimentary structures, Kepferle (1977) has interpreted the unit to represent a turbidite fan complex at the foot of the delta, fed from two sources. Although complete Bouma sequences are present locally (Kepferle, 1977), most of the preserved beds illustrate only plane laminae (T_{DE}) or cross-laminae (T_{CDE}), indicating distal fan or interchannel deposition.

In the upper part of the Kenwood at this stop, hummocky and swaley crossbeds were also found, suggesting storm influence. The presence of these structures indicates that by the end of Kenwood deposition, bottom aggradation was sufficient to have intercepted storm wave base, which, based on modern analogues, could have been as deep as 230 ft (70 m) (Aigner and Reineck, 1982). This means that sediments originally emplaced as turbidites were periodically reworked by storms on the lower delta slopes (e.g., Pashin and Ettensohn, 1987).

The scarcity of fauna noted above probably reflects rapid sedimentation and soft, unstable bottoms, and these conditions probably explain the fact that productid brachiopods, specialists in soft-sediment dwelling, are the most common fossils. Other fossils are commonly found in siderite nodules and include other soft-bottom specialists and nekto-benthic forms. Their preservation in siderite nodules apparently reflects early diagenesis in organic-rich sediments and some influx of fresh water (e.g., Allison, 1990).

Economic Uses. Brick manufacturing has taken place in the Coral Ridge area since the late 1800's. Attracted to this area by the abundance of soft, plastic clay, its proximity to rail transportation, and the burgeoning Louisville market, the enterprising artisans of that era were poised to take brickmaking from the realm of a cottage industry into that of heavy industry.

In the early 1950's, Coral Ridge Clay Products Company had replaced all of their primitive field kilns with downdraft, periodic kilns and chamber kilns. The handmade, or machine-molded brick, which utilized the soft-mud process, required a predominantly weathered-clay body. Mining was by electric shovel, and the shale was loaded into rail cars and shuttled to the plant. The mining area was where the old plant no. 14 is now situated. Blasting was used frequently to keep the working face loose. The advent of the extruded brick, or stiff-mud process, brought about some basic changes in the raw material requirement and methods of recovery. Larger, heavy equipment has greatly reduced the need for costly blasting, and the self-loading scraper has replaced the dump truck.

The continuous-firing tunnel kiln created a need for a raw material that would dry more rapidly and with less shrinkage, so the harder, less-weathered shale found greater use, but not without expensive trade offs. Utilization of the harder shales and coarser grinding improved the porosity of the unfired units, but introduced a calcium- and iron-carbonate factor not found in the deeply weathered materials. Coarse carbonate particles often result in so-called "lime pops" on the face of the brick, caused by the calcining of carbonate particles during the firing process. These particles expand when exposed to moisture, pushing out a chip in the face of the brick. Finer grinding and screening eliminates most of the pops, but creates a greater tendency for the finished product to effloresce upon weathering. This tendency was overcome by developing a product line that masked the efflorescence.

As the trend toward higher production rates continued, and the need for faster drying of the freshly extruded, or "green," bricks became more acute, the brick makers looked toward the crest of South Park Hills and the hard, silty Kenwood Member of the Borden Formation. Although the high silica content was a problem, the hardness of the Kenwood material provided an element of particle-size stability that improved drying and reduced shrinkage of the green products. Too much silica (more than 10 to 12 percent) often results in cracking of the fired brick due to the alpha-beta quartz transition at 1,067°F due to an attendant volume change between the two phases. Since the bricks are fired at temperatures approaching 2,000°F, the inversion temperature may be crossed several times as the heat is drawn away from the kiln in the cooling zone, thus exacerbating the tendency for cracking to occur.

As the brown, weathered shale became increasingly scarce and the harder shales found greater usage, another problem arose. The unweathered shales contain more sulfide minerals that oxidize in the firing process, sending oxides of sulfur out the exhaust stack. This property would eventually become a greater challenge.

In the middle 1950's, General Shale Brick was operating modern plants at Kingsport, Johnson City, Knoxville, and Chattanooga, Tenn.; and at Richlands and Marion, Va. Looking to expand westward, they acquired Coral Ridge in 1956. Construction of a modern, continuous-firing tunnel kiln began shortly thereafter. By 1958, a second, larger kiln was brought online, and production soared to 61 million bricks per year, which required the mining and preparation of 122,000 cubic yards, or about 165,000 tons per year.

The Louisville plant withstood the fuel crunch of the middle 1970's by the in-house development of a solid-fuel firing system, enabling this and other General Shale plants to take advantage of nearby coal resources.

In the middle to late 1990's, the economy was booming. Most brick producers were selling everything they could make. In that climate, capacity rules. Plans were made to increase production through the construction of a more automated and fuel-efficient plant. Soon thereafter, design work began on the future plant 38. Construction began in spring 1995. More than 400,000 cubic yards of material were moved during the grading phase. The new plant was designed so that a second, parallel kiln could be constructed inside the building with a minimum of modifications. With the older kiln at plant 41 shut down, the two remaining kilns could produce 97.4 million bricks per year.

Currently, all raw materials are mined on site. Approximately 200,000 tons is mined each year. Reserve estimate of on-site materials exceeds 100 years.

Mile

- 0.0: Turn onto northbound National Turnpike.
- 0.2: Turn left. Proceed north on National Turnpike.
- 1.0: Veer right. Proceed north on National Turnpike.
- 2.5: Intersection of National Turnpike and Snyder Freeway. Turn right onto eastbound Snyder Freeway.
- 4.5: Exit 10. Intersection of Snyder Freeway and Interstate 65. Turn onto I-65 northbound. Proceed north on I-65.
- 16.4: Intersection of I-65 and I-64. Exit to I-64 westbound. Proceed west on I-64.
- 18.3: Falls of the Ohio to right.
- 21.3: Sherman Minton Bridge (Ohio River).
- 22.2: Exit 123. Intersection of I-65 and Ind. 62. Exit to Ind. 62.
- 22.5: Stoplight at base of exit ramp. Continue straight.
- 22.6: Stoplight. Turn right onto Ind. 11.
- 22.6: Stoplight. West Spring Street. Continue straight.
- 22.7: Stoplight. East Market. Continue straight.
- 22.8: Stoplight. West Main. Turn left onto East Main.
- 22.9: Stoplight. Pearl Street. Continue straight.
- 23.9: Stop sign. K & IT Railroad bridge to right. Continue straight on East Main.
- 24.0: Turn right onto East 18th Street.
- 24.2: Cross railroad track.
- 24.3: Pass through levee gate, veer right, and proceed west on East Water Street.
- 25.5: Park under K & IT Railroad bridge and walk to outcrops below (stop 2).

Stop 2: New Albany Shale at the Type Locality

When the New Albany Shale (Devonian–Mississippian) was initially described by Borden (1874), nearly 104 ft (31.7 m) was exposed here along the Ohio River and in adjacent parts of Silver Creek. This section was apparently nearly complete, but most of it is now covered, and only 23 ft (7 m) of the Blocher Member remains exposed at and just above river level.

The New Albany Shale unconformably overlies the Beechwood Member of the North Vernon (Sellersburg) Limestone in the Falls of the Ohio area, although the Beechwood is subject to dissolution and is locally absent. The presently used New Albany stratigraphy was developed by Lineback (1968, 1970) and includes five members, which are, in ascending order, the Blocher Member, consisting of dolomitic black shales, dolostones, and dark gray dolomitic mudstones and siltstones; the Selmier Member, consisting of greenish-gray shales with interbeds of dark gray shales and siltstones; the Morgan Trail Member, consisting of fissile, black, pyritic shale; the Camp Run Member, consisting of greenish-gray to olive-gray shales and mudstones interbedded with fissile black shales; and the Clegg Creek Member, consisting largely of fissile black shales with a few greenish-gray shale horizons. Figure 7 is a composite of sections from Floyd, Clark, and Jennings Counties, Ind. Although all five members are present in the western Kentucky subsurface (Woodrow and others, 1988), only the Blocher, Camp Run, and Clegg Creek are exposed at the surface in Kentucky (Ettensohn and others, 1989).

The biostratigraphy of the New Albany was also initially done by Lineback (1968, 1970), but reexamination of conodonts from the shales relative to the *Protosalvinia* zone (see Hasenmueller and others, 1983) now suggests that most of the New Albany units were zoned too high (Ettensohn and others, 1989). Figure 8 shows the revised biostratigraphy and indicates that the Blocher Member is largely late Middle Devonian (Givetian) in age, the Selmier and Morgan Trail Members are early Late Devonian (Frasnian) in age, and that the Camp Run and Clegg Creek Members are largely later Late Devonian (Famennian) in age, although the upper few feet of complete Clegg Creek sections are earliest Mississippian (Tournasian) in age. *Protosalvinia* is a possible alga, which is found in a distinct biostratigraphic marker horizon in the black shales throughout most of the eastern United States (Hasenmueller and others, 1983). The lithostratigraphic, biostratigraphic, and structural relationships of the New Albany Shale in Kentucky and adjacent states are shown in Figure 8.

Unlike other parts of the New Albany Shale, the Blocher Member (Campbell, 1946; Lineback, 1968) is largely Middle Devonian in age and is composed largely of calcareous or dolomitic black shales; many of these shales are massive and not very fissile. Total organic carbon content in these beds generally ranges from 5 to 10 percent, but in the more fissile black shales in the upper part of the unit, total organic carbon content may approach 15 percent (Robl and Barron, 1988).

Thin beds of dolostone, gray mudstone, calcareous sandstone and siltstone, and limestone are also present locally, and some of the sandstones and siltstones exhibit flaser bedding, micro cross-laminae, and interference ripples. Burrowing is also present in some of the black shales, dolostones, mudstones, siltstones, and sandstones, and a low-diversity, high-abundance fauna of brachiopods and cricoconarids is present locally in some of the black shales. The unit is everywhere bounded above and below by sandy, pyritic lag or condensation horizons, although similar horizons may be present within the unit. Figure 9 shows that the Blocher

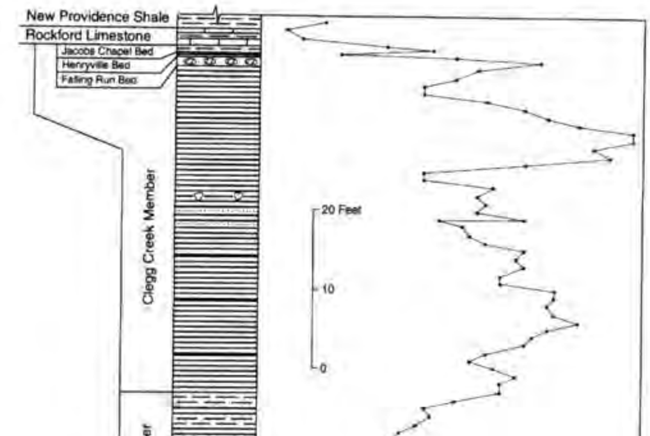


Figure 7. Composite stratigraphic section of the New Albany Shale in the Falls of the Ohio area (Hendricks and others, 1994; modified from Peter T. Goodmann's original drawing).

thickens toward the west and northwest and apparently pinches out on the Cincinnati Arch from Casey County southward, but it locally intertongues with the Duffin facies of the equivalent Portwood Member in east-central Kentucky (Campbell, 1946; Ettensohn and Geller, 1986; Ettensohn and others, 1989).

Prominent, nearly east–west-oriented joints and a subordinate system of north–south-oriented joints traverse this outcrop. On a smaller scale, the shales are broken up by small polygonal fracture sets locally filled with secondary minerals. Although they have the size and appearance of mud cracks, shale radiography indicates that these features are reopened syneresis joints (Harvey and others, 1978).

At this stop, lag horizons are exposed at neither the base nor the top of the Blocher, but partially pyritized siltstone layers at approximately 2.0 ft (0.6 m), 5.0 ft (1.5 m), and 9.0 ft (2.7 m) above present river level are similar. Some of these horizons exhibit well-developed interference ripples. Pyritized burrows and lingulid brachiopods are abundant in some of the less fissile, "crumbly" black shale layers. Thin, calcareous siltstone layers with flaser beds and micro cross-laminae are nearly everywhere common on close inspection.

Mile

0.0: Proceed east along East Water Street, retracing route to East 18th Street.
0.2: Pass through levee gate. Proceed north on East 18th Street.
0.3: Cross railroad tracks.
0.4: Stop sign. East Main Street. Turn left onto East Main Street.
0.5: Stop sign. Vincennes Street. Turn right onto Vincennes Street.
0.6: Stoplight. East Market Street. Continue straight on Vincennes Street.
0.8: Stoplight. East Spring Street. Turn right onto East Spring Street.
1.3: Stoplight. Silver Street. Continue straight (east) on East Spring Street.
1.7: The name of the highway changes to Browns Station Way at the Clark County line. Continue straight (east) on Browns Station Way.
3.6: Stoplight. Randolph Avenue. Turn right onto Randolph Avenue.
4.0: Stop sign. Harrison Avenue. Turn right onto Harrison Avenue. Proceed one block to South Clark Boulevard, and turn left onto South Clark Boulevard. Proceed south on South Clark Boulevard.
4.2: Stop sign. Stansifer Avenue. Proceed south on South Clark Boulevard.
4.5: Turn right onto Sherwood Avenue. Proceed south on Sherwood Avenue.
4.6: Stop sign. Montgomery Avenue. Continue south on Sherwood Avenue.
4.8: Stop sign. Windbourne Street. Continue south on Sherwood Avenue.
5.0: Cross levee. Turn right at bottom of levee onto Riverside Drive. Proceed northwest on Riverside Drive.
5.3: Falls of the Ohio State Park Visitors Center (stop 3).

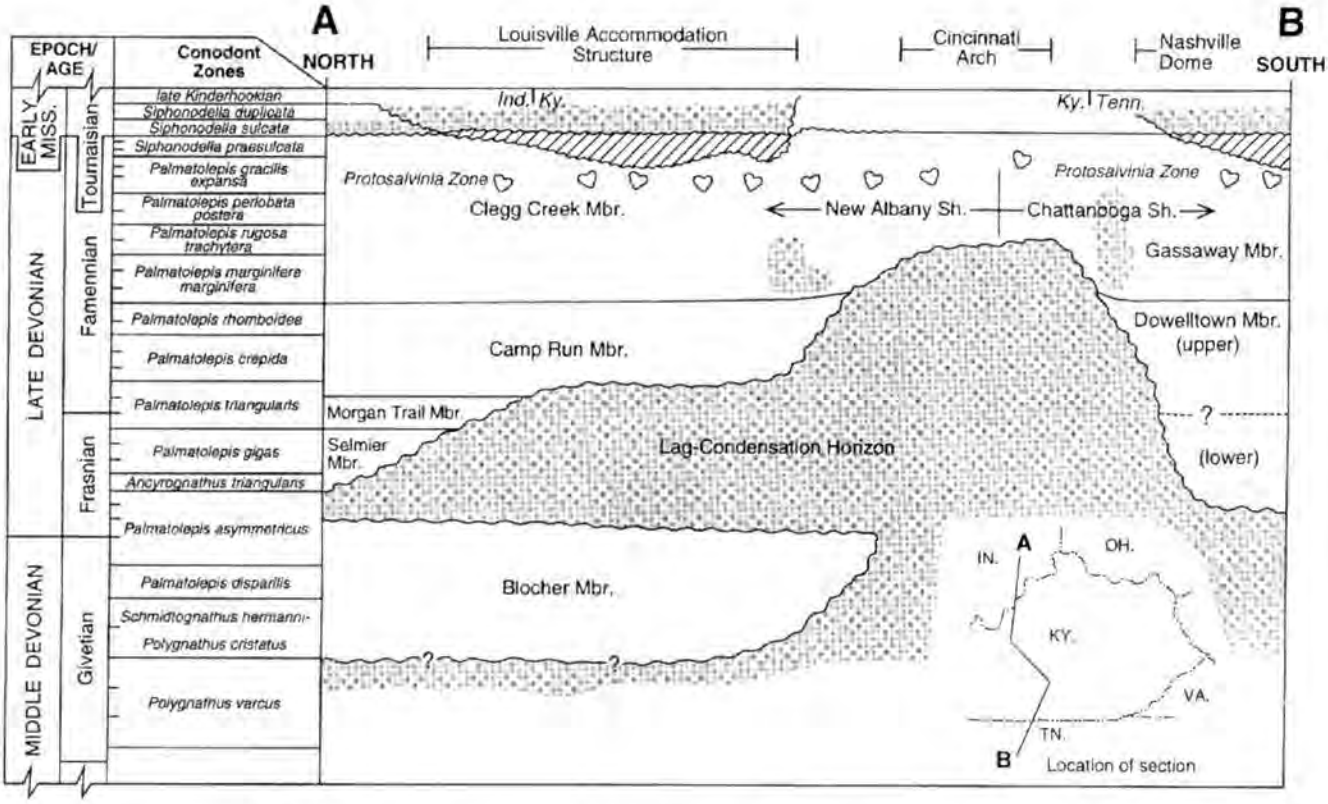


Figure 8. Biostratigraphy of the New Albany Shale in west-central Kentucky and adjacent areas of Indiana and Tennessee. Stippled areas represent lag-condensation zones (i.e., "time-rich" horizons represented by thin, sediment-starved layers or "bone-beds"). Crosshatched areas represent missing section, generally on or near structural features (Hendricks and others, 1994; modified from Ettensohn and others, 1989).

Stop 3: Jeffersonville Limestone at the Falls of the Ohio

Nowhere on earth are fossiliferous rocks of Middle Devonian age as well exposed and as easily accessed as at the Falls of the Ohio. For nearly two centuries, this outcrop has been visited by countless professional and amateur paleontologists who have come to observe, collect, and describe the noteworthy fossil communities exposed in the Devonian limestones at the Falls (Fig. 10).

No other single locality has yielded a greater number of fossil species than the Falls of the Ohio. Since 1820, some 600 species of fossils (including corals, stromatoporoids, brachiopods, crinoids, and other marine invertebrates) have been reported from the Falls.

Although the various fossil species found at the Falls can be found in many areas of North America, nowhere is their vertical and lateral context in the rock layers as easily observed. The vast area of the Falls and the predominantly bedding-plane exposures allow the observation of millions of individual fossil specimens. The fossil communities at the Falls are preserved virtually in situ, allowing rare insights into the paleoecological interactions of the residents of Devonian seas (see Kissling and Lineback, 1967). Cumulatively, these factors make the Falls of the Ohio a paleoecological resource that remains largely untapped.

The Falls of the Ohio is not actually a waterfall as the name implies, but a limestone bedrock ridge that extends across the channel of the Ohio River between Louisville, Ky., and Clarksville and Jeffersonville, Ind. This bedrock ridge formed a series of natural rapids across the river channel prior to the completion of McAlpine Dam and Locks. For many years, the rapids at the Falls of the Ohio were the only natural barrier to navigation along the entire 981-mi route of the Ohio River. In fact, the principal reason the Louisville area was initially settled was because the rapids at the Falls forced boats to unload cargo and passengers. In modern times, the completion of the canal and locks has allowed more cargo to pass through McAlpine Dam than through the Panama Canal (Powell, 1970).

During the Pleistocene, intense floods of glacial meltwater repeatedly scoured the Ohio River Valley, which was subsequently filled with glacial outwash and fluvial and lacustrine deposits. Time and again, the river

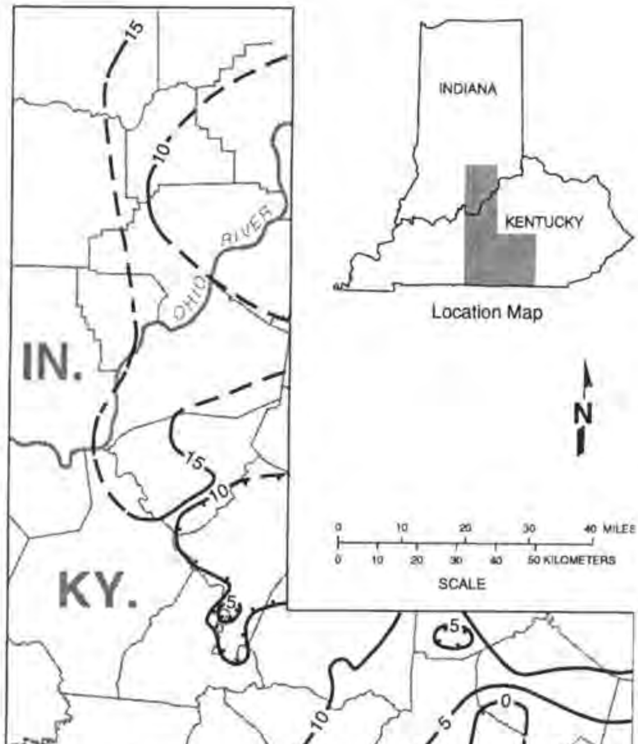


Figure 9. Isopach map of the Blocher Member of the New Albany Shale in west-central Kentucky and adjacent areas of Indiana (Hendricks and others, 1994; modified from Geller, 1985).

meandered in its valley, cutting new channels while eroding preexisting sediments and bedrock. The limestone bedrock ridge that now forms the rapids at the Falls of the Ohio was created by these episodes of meltwater erosion, valley filling, and river meandering.

At the end of the Wisconsinan glacial interval, the limestone bedrock ridge at the Falls was buried by unconsolidated sediments (predominantly glacial outwash). The Ohio River later meandered to a position overlying the ridge. In time, the river cut through the unconsolidated sediments, exhuming the limestone bedrock ridge and its remarkable fossils. Since the Ohio River began cutting a new channel overlying the limestone bedrock ridge at the Falls, approximately 50 ft (15.2 m) of unconsolidated sediment and from 10 ft (3.1 m) to 20 ft (6.1 m) of bedrock have been removed (Powell, 1970). In fact, the erosional processes that first formed the Falls of the Ohio are continuously contributing to its destruction.

The bedrock exposed at the Falls of the Ohio (including the outcrop just west of the mouth of Cane Run Creek) encompasses approximately 1 ft (0.3 m) of Louisville Limestone, a complete section of Jeffersonville Limestone, 35.9 ft (10.9 m) thick, and a thin, largely covered section of the Silver Creek Member of the North Vernon Limestone. The upper Jeffersonville Limestone and the Silver Creek Member of the North Vernon are exposed only along the bluff overlooking the Ohio River downstream from the mouth of Cane Run Creek. Because of limited accessibility, the Cane Run exposures will not be visited.

The Louisville Limestone (Silurian, Wenlockian-Ludlovian) is exposed at the Falls of the Ohio only during periods of low water, usually during the summer and fall. Generally, the Louisville is best exposed along the northwestern margin of the North Flats (Fig. 11). Fossils common in the Louisville at the Falls of the Ohio include chain corals *(Halysites, Cystihalysites,* and *Quepora),* tabulate corals *(Heliolites),* and small mound-shaped stromatoporoids.

The Jeffersonville Limestone (Emsian and Eifelian) unconformably overlies the Louisville Limestone, and was named by Kindle (1899) for the fossiliferous limestone exposures near Jeffersonville at the Falls of the Ohio. However, since the completion of the dam and locks, most of this important outcrop has been permanently flooded. Bedrock is no longer exposed in the river bed at Jeffersonville, and the limestone bedrock ledges that are still accessible are entirely within the cities of Louisville, Ky., and Clarksville, Ind.

Numerous different stratigraphic workers have proposed numerous different biozones of the Jeffersonville Limestone at the Falls of the Ohio (e.g., Oliver, 1960; Perkins, 1963; Stumm, 1964; Conkin and Conkin, 1972, 1976). Of these, the informal fivefold faunal zonation of Perkins (1963) remains the most widely used, paleontologically accurate, and sedimentologically meaningful. Perkins's biozones include the Coral, *Amphipora ramosa, Brevispirifer gregarius,* Fenestrate Bryozoan-Brachiopod, and *Paraspirifer acuminatus* zones, in ascending order (Fig. 12).

In northern Kentucky and southern Indiana, the Jeffersonville Limestone includes a southern limestone facies and a northern dolostone and dolomitic limestone facies (see Perkins, 1963; Droste and Shaver, 1975; Hendricks and others, 1994). The southern limestone facies comprises the five biozones of Perkins (1963) exposed at the Falls of the Ohio. The northern dolomitic

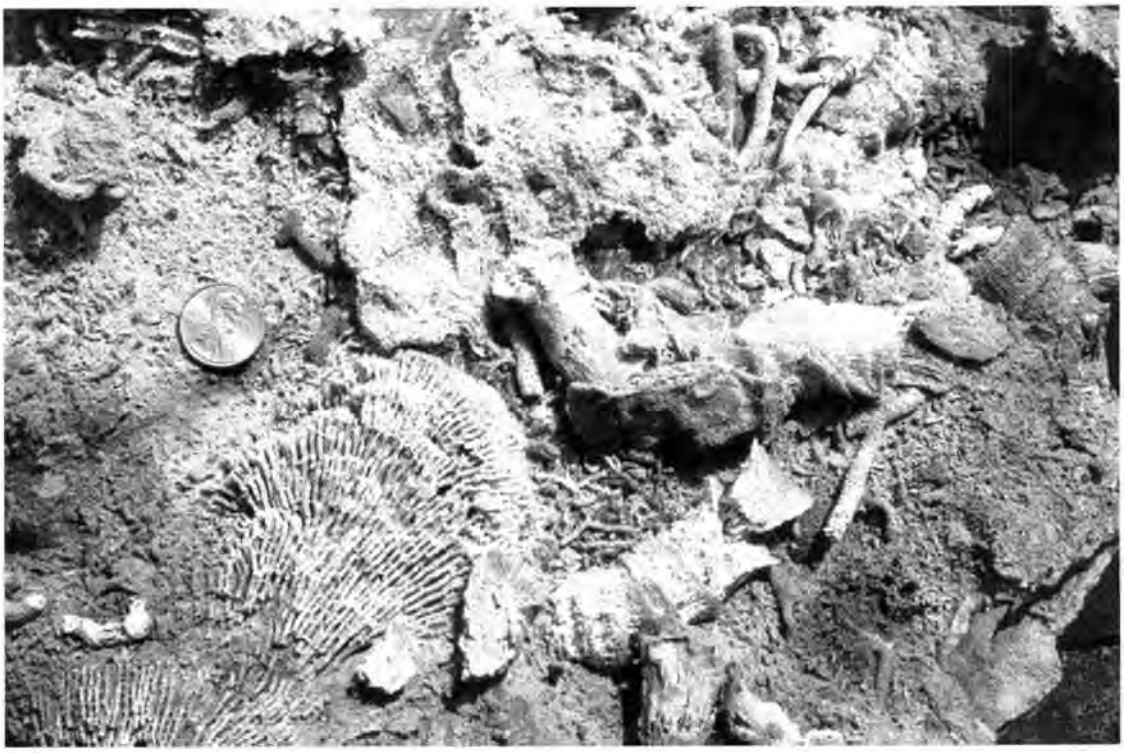


Figure 10. Silicified corals and stromatoporoids from the Jeffersonville Limestone. Coin for scale.

facies of the Jeffersonville Limestone includes the Geneva Dolomite Member, an unnamed member of dolostone and dolomitic limestone (approximately equivalent to the *Amphipora ramosa* Zone), the Vernon Fork Member, and an upper cherty, fossiliferous limestone (the *Paraspirifer acuminatus* Zone). No exposures of the northern dolostone and dolomitic limestone facies will be visited on this field trip. Excellent discussions of the relationships of the various Jeffersonville lithologies can be found in Droste and Shaver (1975) and Perkins (1963).

Stratigraphic nomenclature for the Jeffersonville Limestone is complicated by some workers' use of the various fossil zones in combination with or in place of properly defined lithostratigraphic units such as the Vernon Fork and Geneva Dolomite members. In most cases, the fossil zones were never intended to be used as formal stratigraphic units and are not suggested to be so in this discussion.

At the Falls of the Ohio, the Coral Zone is 10 ft (2.6 m) thick and unconformably overlies the Louisville Limestone (Fig. 12). Its faunas are dominated by abundant and diverse solitary and colonial corals and mat- and mound-shaped stromatoporoids. Coral Zone strata are typically medium to dark gray and grayish-brown, abundantly fossiliferous limestones. Packstones, grainstones, and rudstones are the predominant depositional textures. Solitary and colonial corals, mound-shaped stromatoporoids, and pelmatozoan debris are common to very abundant. Mat-shaped stromatoporoids, brachiopods, and bryozoans are much less common than in overlying zones.

Solitary corals are most abundant in the upper part of the Coral Zone at the Falls. In the North Flats and Lower South Flats (Fig. 11) the upper Coral Zone is a dark, carbonaceous rudstone with many large rugose corals (Fig. 13). Among these is *Siphonophrentis elongata* (also called *S. gigantea),* which attained heights of 4 ft (1.2 m) in some specimens (Perkins, 1963). Many of the larger rugosans in the Jeffersonville assumed a curved growth habit. We presume the coral attached itself to an object such as a shell or another coral as a juvenile and later toppled over when it had outgrown its base. The animal was then forced to grow upward, forming a curved corallum (Thompson, 1982).

Some workers have termed the fossil beds in the Coral Zone at the Falls of the Ohio a fossil "coral reef" (e.g., Conkin and Conkin, 1980). However, no organically bound, wave-resistant, topographically significant composite fossil structure has been reported in the bedrock at the Falls, or anywhere else in Jeffersonville exposures. (A few small bioherms, predominantly *Emmonsia* coral colonies, up to 10 ft (2.6 m) in diameter and from 4.0 ft. (1.2 m) to 5 ft (1.5 m) in height, are present at the Falls and in quarries to the north.) Sediment bind-

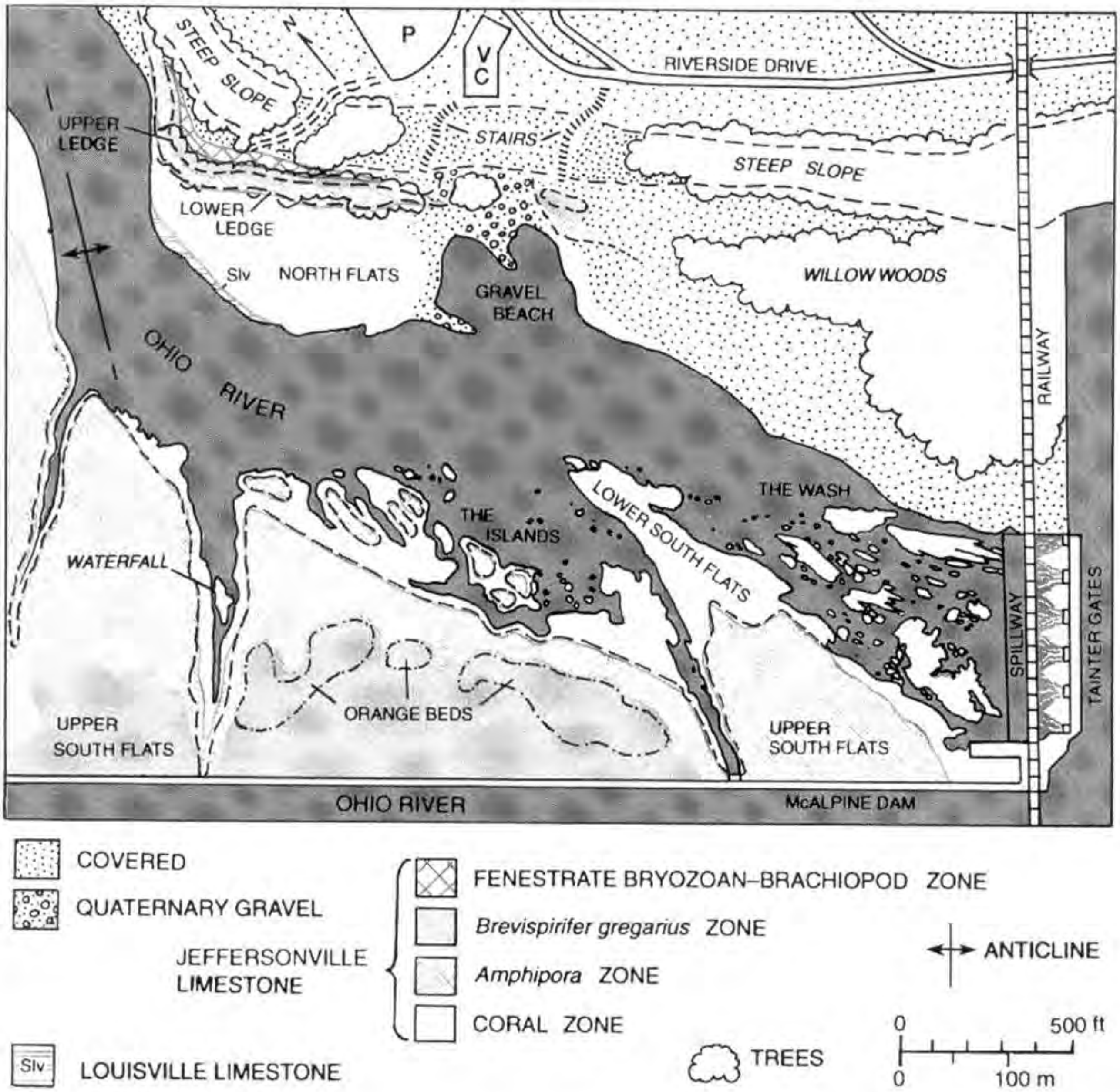


Figure 11. Geologic map of the Falls of the Ohio, showing the areas of outcrop of the various biozones described in the text (Hendricks and others, 1994; modified from Greb and others, 1993).

ing, with consequent biostrome formation, was accomplished to some degree by mat-shaped stromatoporoids, but no wave-resistant structures resulted. Coral Zone communities are more accurately described as representing open-marine, coral-stromatoporoid, level-bottom fossil communities.

The Coral Zone can be traced from outcrops a few miles south of Louisville north to southern Jennings, Jackson, and Lawrence Counties in Indiana (Perkins, 1963). North of the outcrop area of the Coral Zone, the stratigraphic position between Silurian carbonate rocks and the *Amphipora ramosa* Zone of the Jeffersonville Limestone is occupied by the Geneva Dolomite Member.

At the Falls of the Ohio, the *Amphipora ramosa* Zone is 8.7 ft (2.7 m) thick (Fig. 12) and contains abundant small, branching stromatoporoids *(Amphipora;* Fig. 14), mat-shaped stromatoporoids, mound-shaped and branching colonial corals, and rugose corals. Skeletal packstones and grainstones are the predominant textural types. Although solitary and colonial corals are common in the *Amphipora ramosa* Zone, such fossils are

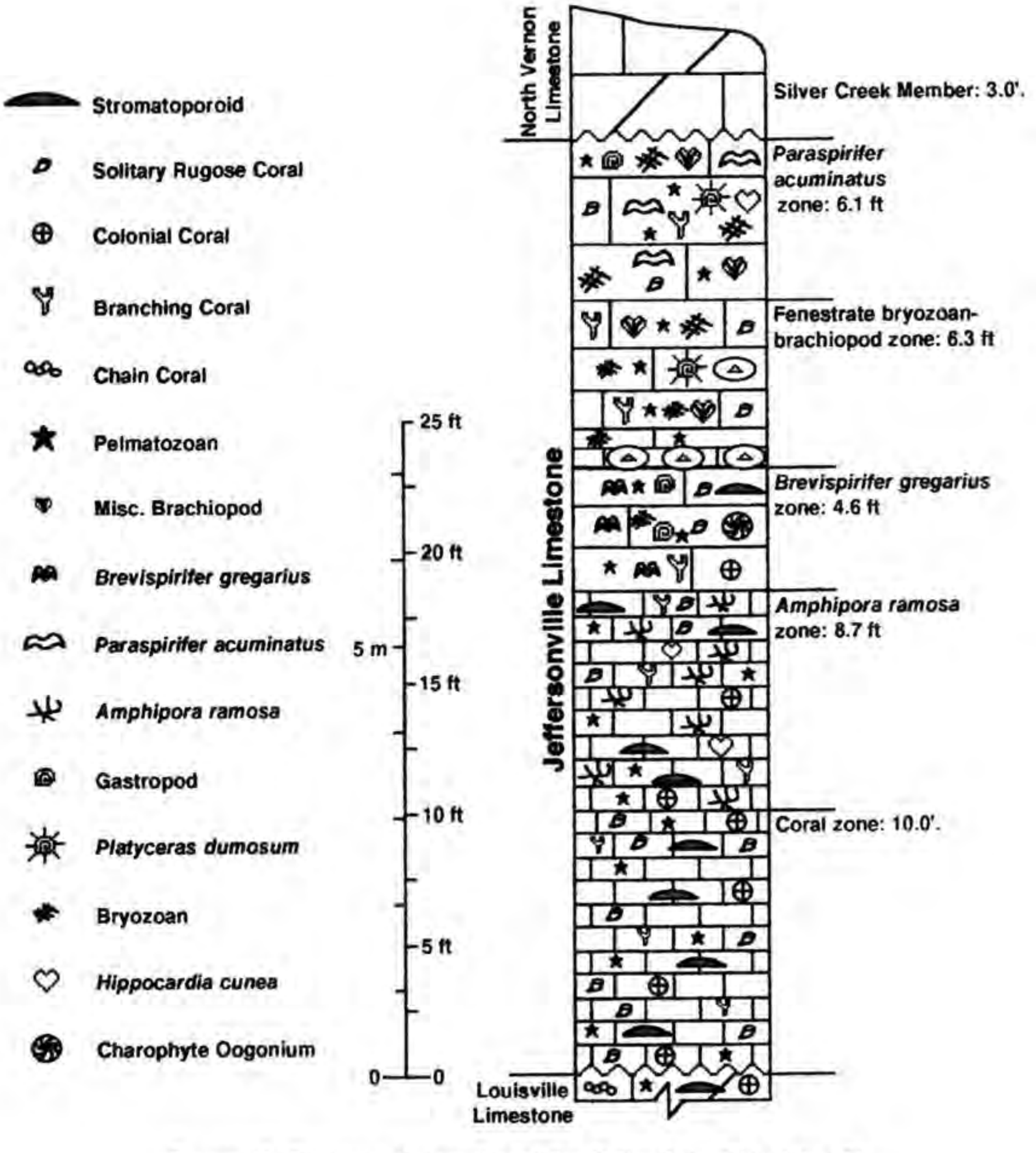


Figure 12. Stratigraphic section at the Falls of the Ohio (stop 3).

considerably less abundant than in the underlying coral zone. Mat-shaped, encrusting stromatoporoids abound, and probably acted locally as sediment-binding agents.

The *Amphipora ramosa* Zone is best exposed in the Lower Ledge in the northern fossil beds and in the Upper South Flats and Islands areas in the southern fossil beds (Fig. 11). Solution cavities have developed in the Islands area of the Lower South Flats, and silicified corals and stromatoporoids stand in relief on the walls.

Rocks in the *Amphipora ramosa* Zone are present throughout the Falls of the Ohio area. North of the Falls of the Ohio in Jennings County, Ind., diagenetically altered rocks in the *Amphipora ramosa* Zone overlie the Geneva Dolomite Member. Such strata commonly include light to medium grayish-brown, fossiliferous, partially sucrosic dolomitic limestones and calcareous dolostones. Packstones and wackestones are probably the dominant sedimentary textures, although recrystallization has obscured many fossils.

The *Brevispirifer gregarius* Zone at the Falls of the Ohio is 4.5 ft (1.4 m) thick (Fig. 12) and includes medium gray, abundantly fossiliferous limestones (packstones and grainstones). In this outcrop, the unit contains very abundant *Brevispirifer,* large snails *(Turbonopsis shumardi),* colonial corals *(Favosites, Prismatophyllum),* solitary corals *(Zaphrenthis;* Fig. 15), charophyte oogonia, and crinoid debris. Hundreds of large *Turbonopsis* snails are preserved in the *Brevispirifer* Zone; specimens are

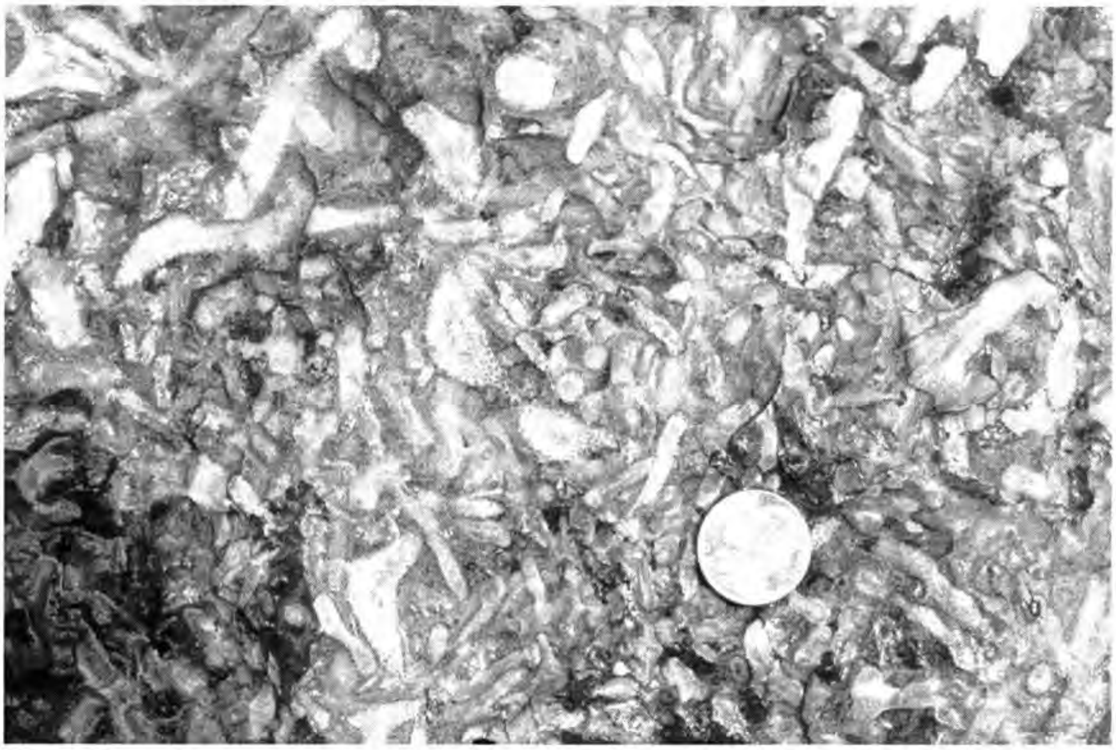


Figure 13. Carbonaceous rudstone with abundant corals from the upper Coral Zone of the Jeffersonville Limestone. Jeffersonville Limestone, Falls of the Ohio. Coin for scale.

abundant in the silicified Orange Beds at the southern Falls (Fig. 11). Often, silicified specimens are preserved as internal molds encrusted by quartz. Other specimens of *Turbonopsis* are found encrusted by stromatoporoids; usually, the entire upper surface of the snail shell was covered, but the aperture of the shell was not. This association may have occurred while the snail was living, and perhaps offered protective camouflage for the gastropod.

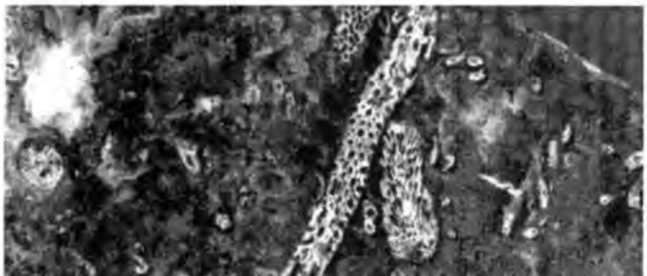


Figure 14. *Amphipora ramosa* and branching tabulate corals in bedrock. Jeffersonville Limestone, Falls of the Ohio. Life size.

Corals are generally smaller and much less abundant than in the Coral and *Amphipora ramosa* zones. Chert is a minor constituent in the *Brevispirifer gregarius* Zone in the Falls of the Ohio area, but to the north, in Scott County, Ind., the unit is quite cherty and argillaceous. The *Brevispirifer gregarius* Zone pinches out rap-

Figure 15. Well-preserved rugose corals *(Zaphrenthis)* from the *Brevispirifer gregarius* Zone. Life size.

idly north of Scottsburg, and its position is occupied by the lower part of the Vernon Fork Member.

The uppermost Jeffersonville Zone that we will see at the main body of the Falls of the Ohio is the Fenestrate Bryozoan-Brachiopod Zone, which is 6.3 ft (1.9 m) thick here (Fig. 12). The unit is best exposed in the wooded area of the Upper Ledge (Fig. 11). Light yellowish-gray skeletal packstones and grainstones are the predominant lithologies, with crinoids, blastoids, bryozoans, brachiopods, and corals being the predominant fossil constituents. Fenestrate bryozoa abound. Among the brachiopods, *Atrypa*, strophomenids, and small spiriferids are common, but *Brevispirifer* and *Paraspirifer* are absent. This zone can be traced from the Falls of the Ohio north to Jennings County, Ind., where the unit is absent and its stratigraphic position is occupied by the upper part of the Vernon Fork Member of the Jeffersonville Limestone.

The *Paraspirifer acuminatus* Zone (Fig. 12) was characterized by Perkins (1963) as being faunally and lithologically similar to the underlying Fenestrate Bryozoan-Brachiopod Zone, but with the addition of the large spiriferid *Paraspirifer acuminatus* (Fig. 16). Like the latter unit, the former includes light gray to yellowish-brown, fossiliferous, bryozoan- to pelmatozoan-rich limestones with packstone and grainstone textures. The *Paraspirifer acuminatus* Zone is the most widespread of all the Jeffersonville Limestone biozones recognized at the Falls of the Ohio, with similar lithologies present everywhere in the southern Indiana Devonian outcrop belt.

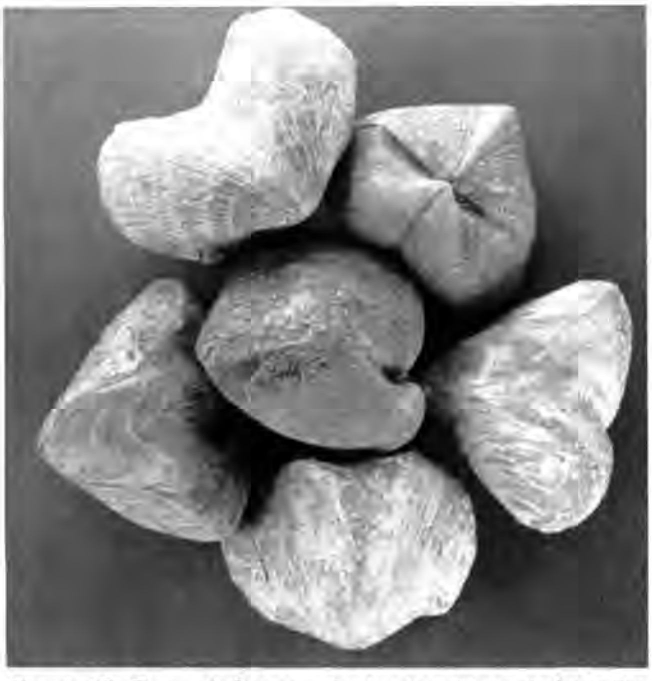


Figure 16. *Paraspirifer acuminatus* brachiopods from the Jeffersonville Limestone. Each specimen is approximately 2 in. (50 mm) across.

Based upon variations in lithology, depositional textures, sedimentary structures, and faunal constituents, Perkins (1963) noted that during Jeffersonville deposition, lithologies associated with all of the five biozones exposed at the Falls of the Ohio were deposited in progressively shallower water from south to north. Although Perkins (1963) believed the Geneva Dolomite to be a separate, older formation than the Jeffersonville, he recognized that the packstones, grainstones, and rudstones of the Coral Zone pinch out to the north and are replaced by the heavily recrystallized Geneva Dolomite. Later, Droste and Shaver (1975) recognized the Geneva to be at least partly correlative to rocks of the Coral Zone at the Falls of the Ohio. Similar stratigraphic relationships are shown in the packstones and grainstones in the *Amphipora ramosa, Brevispirifer gregarius,* and Fenestrate Bryozoan-Brachiopod Zones, which grade north into the laminated, mud-cracked, tidal flat and sabkha dolomicrites of the Vernon Fork Member (Droste and Shaver, 1975; Hendricks and others, 1994).

Overlying the bedrock in the Falls area is some 50.0 ft (15.2 m) of unconsolidated sand, silt, and gravel. These sediments are principally glacial outwash and alluvial deposits (Powell, 1970; Kepferle, 1974b). Large erratics, some up to 5.0 ft (1.5 m) across, are found at the Falls of the Ohio. Several sand and gravel pits operate in the area, and numerous bones of Pleistocene vertebrates, including mammoths, have been unearthed in such pits.

Mile

0.0: Leave Falls of the Ohio State Park; head southeast along Riverside Drive.
0.2: Stop sign. Sherwood Avenue. Continue straight on Riverside Drive.
0.7: Veer left. Pass through levee gate onto Market Street. Proceed straight on Market Street.
0.9: Turn left onto Southern Indiana Avenue.
1.0: Stop sign. West Court Avenue. Turn right onto West Court Avenue.
1.1: Stoplight. Continue straight on West Court Avenue.
1.4: Stoplight. Pearl Street. Continue straight on West Court Avenue.
1.5: Stoplight. Spring Street. Turn left onto Spring Street.
1.7: Stoplight. Eighth Street. Continue straight on Spring Street.
1.9: Stoplight. Tenth Street. Continue straight on Spring Street.
2.0: Stoplight. Twelfth Street. Continue straight on Spring Street.

2.2: Stoplight. Wall Street. Continue straight on Spring Street.
2.6: Stoplight. Eastern Boulevard. Continue straight on Spring Street.
3.0: Stoplight. Dutch Lane. Continue straight on Hamburg Pike. The name of Spring Street changes to Hamburg Pike north of Dutch Lane.
3.4: Turn right onto Quarry Lane.
3.9: Liter's Quarry of Indiana; Atkins Quarry (stop 4).

Stop 4: Atkins Quarry, Jeffersonville, Clark County, Ind. (Optional)

This quarry will be visited only if high Ohio River pool levels prevent the examination of stop 2 (the New Albany Shale type locality) and stop 3 (Falls of the Ohio). The section exposed in this quarry includes, in ascending order, the Laurel Member of the Salamonie Dolomite (called the Laurel Dolomite in Kentucky), the Waldron Shale, the Louisville Limestone, the Wabash Formation, the Jeffersonville Limestone, the North Vernon (Sellersburg) Limestone, and a partial section of the New Albany Shale (Fig. 17).

The Laurel Member of the Salamonie Dolomite is poorly exposed in the lowest part of the quarry. Although approximately 38.2 ft (11.6 m) of the Laurel is present in a core drilled at this site, only the upper 2 ft (0.61 m) of the unit is exposed adjacent to the sump pond. The exposed Laurel includes light gray to light olive-gray limestone with some medium gray to dark gray mottles and bands. Although fossiliferous, identifiable taxa in the Laurel here are limited to pelmatozoan fragments.

Conformably overlying the Laurel, the Waldron Shale (Wenlockian) is 13.2 ft (4.0 m) thick and includes olive-gray to dark-greenish-gray, sparsely to abundantly fossiliferous shale and mudstone, as well as light gray fossiliferous limestones. Long renowned for its fossils (e.g., Hall, 1882), the Waldron contains diverse, well-preserved, open-marine faunas that include many species of brachiopods, crinoids, cystoids, corals, bryozoans, sponges, algae, pelecypods, cornulitids, and trilobites.

Fossils are abundant in the Waldron in some layers, and small lens-shaped bioherms up to approximately 2 ft (0.6 m) across are present. Fossil preservation in the Waldron at this site can be remarkable. Complete crinoid calyxes with all arms preserved and complete trilobites are often found.

The Louisville Limestone (Silurian, Wenlockian-Ludlovian) conformably and gradationally overlies the Waldron Shale and is 56.0 ft (17.1 m) thick in this exposure. The Louisville includes mostly fossiliferous, light gray limestones, although depositional textures and lithologies can vary somewhat. The Louisville is in turn conformably and gradationally overlain by a 17-ft (5.8-m) section of the Wabash Formation (also Silurian, Wenlockian–Ludlovian). The two formations are faunally similar, and the sole lithologic difference between them is the more argillaceous nature (and the more olive-gray color) of the Wabash. Generally, the contact between the two formations is picked at the lowest persistent bed of argillaceous limestone or calcareous shale in the transitional interval between the formations (Droste and Shaver, 1986a–g). Fossils common in the Louisville and the Wabash include chain corals *(Halysites, Cystihalysites,* and *Quepora),* tabulate corals *(Heliolites),* pelmatozoans, and small mound-shaped stromatoporoids.

A complete section of Jeffersonville Limestone, approximately 41.0 ft (12.5 m) thick and lithologically similar to the nearby Falls of the Ohio outcrops, is exposed at this stop. Unconformably overlying the Jeffersonville is some 20.0 ft (6.1 m) of the Silver Creek Member of the North Vernon Limestone (Eifelian), which was named by Siebenthal (1901) for exposures along Silver Creek near the Falls of the Ohio. The Silver Creek Member possesses two basic lithologies: a lower, massive, bioturbated, variably fossiliferous, argillaceous, dolomitic lime mudstone with wackestone and packstone layers; and an upper unit that closely resembles the lower lithology, but with the addition of abundant chert nodules and stringers. Fossils include locally abundant brachiopods, corals (less), pelecypods, and trilobites. The Silver Creek is thickest in central Clark County, Ind., where sections as thick as 26.0 ft (7.9 m) are present (Whitlatch and Huddle, 1932).

The Beechwood Member (Givetian) of the North Vernon Limestone is 3.8 ft (1.2 m) thick and unconformably overlies the Silver Creek in this quarry. The Beechwood is typically an abundantly fossiliferous, usually light-colored, bioclastic (crinoidal) limestone (grainstone), although glauconitic lithologies exist. The base of the Beechwood is commonly marked by a prominent lag zone with quartz sand, phosphatic nodules, and fishbone fragments. Fossils include abundant pelmatozoan debris, corals, bryozoans, and trilobites. The Beechwood Member is the most widespread Devonian carbonate unit in southeastern Indiana and adjacent Kentucky, nearly everywhere underlying the New Albany Shale.

The primary reason for this stop is to enable participants to collect fossils. Excellent silicified specimens of the brachiopods *Atrypa* and *Spinocyrtia* may be collected from eroded outcrops of Beechwood and Silver Creek present at the upper rim of the quarry. Also present are large, excellent specimens of the coral *Favosites turbinatus* and small auloporid coral colonies.

Mile
0.00: Leave Atkins Quarry.

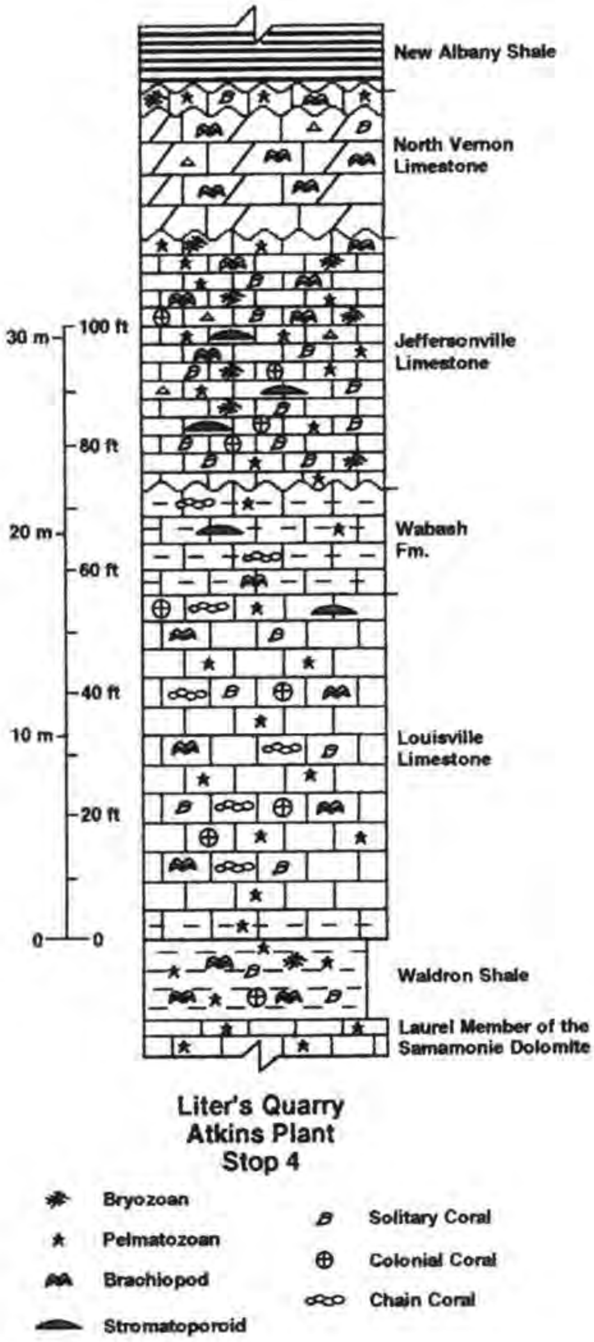


Figure 17. Stratigraphic section at the Liter's Quarry of Indiana, Atkins plant (stop 4).

0.50: Stop sign. Turn right onto Hamburg Pike.
1.85: Stop sign. Truckers Boulevard. Continue straight on Hamburg Pike.
2.25: Stoplight. New Albany–Charlestown Road. Continue straight on Hamburg Pike.
3.51: Stop sign. Coopers Lane. Continue straight on Hamburg Pike.
4.42: Stoplight. Railroad tracks. Turn right onto Hamburg Pike.
4.80: Cross Silver Creek.
7.05: Sellersburg city limits.
7.67: Stoplight. Turn right on Ind. 31.
7.90: Stoplight. Turn right onto Utica Street.
8.00: Stop sign. New Albany Street. Continue straight on Utica Street.
8.35: Cross railroad tracks.
8.45: Stop sign. Cross railroad tracks.
8.78: Sellersburg Stone Company Quarry. Scale house and office on left (stop 5).

Stop 5: Sellersburg Stone Company Quarry, Sellersburg, Clark County, Ind.

The purpose of this stop is to examine the formations present and to collect representative fossil specimens. Numerous outstanding fossils may be found in Waldron Shale spoil piles and in the residuum developed on the upper surfaces of the Jeffersonville and North Vernon limestones.

The section exposed in this quarry (Fig. 18) is similar to that exposed at stop 4, and includes, in ascending order, the Laurel Member of the Salamonie Dolomite, the Waldron Shale, the Louisville Limestone, the Wabash Formation, the Jeffersonville Limestone, the North Vernon (Sellersburg) Limestone, and a partial section of the Blocher Member of the New Albany Shale (Fig. 18). However, several prominent stratigraphic variations exist between the two sections. These include (1) a thicker section of the Wabash Formation and a correspondingly thinner section of Louisville Limestone, (2) a thinner section of the Jeffersonville Coral Zone and a correspondingly thicker section of the overlying biozones, particularly the *Amphipora ramosa* and the *Brevispirifer gregarius* zones, and (3) the presence of the Speed Member of the North Vernon Limestone.

The Speed Member (Eifelian) of the North Vernon Limestone is 1.8 ft (0.5 m) thick in this section. The Speed unconformably overlies the Jeffersonville Limestone and is in turn overlain conformably by the Silver Creek Member. At this location, the Speed Member of the North Vernon Limestone is a medium to dark gray, abundantly fossiliferous limestone (packstone) with many platy bryozoans, button corals *(Hadrophyllum)*, trilobites, and pelmatozoan fragments.

The Speed is not present at the Falls of the Ohio, presumably because of nondeposition (Droste and Shaver, 1986f). Throughout the southern Indiana Devonian outcrop belt, the Speed is generally less than 5.0 ft (1.5 m) thick. The Silver Creek and Speed occur in facies relationship and are conformable where both are seen in the same exposure (Droste and Shaver, 1986e).

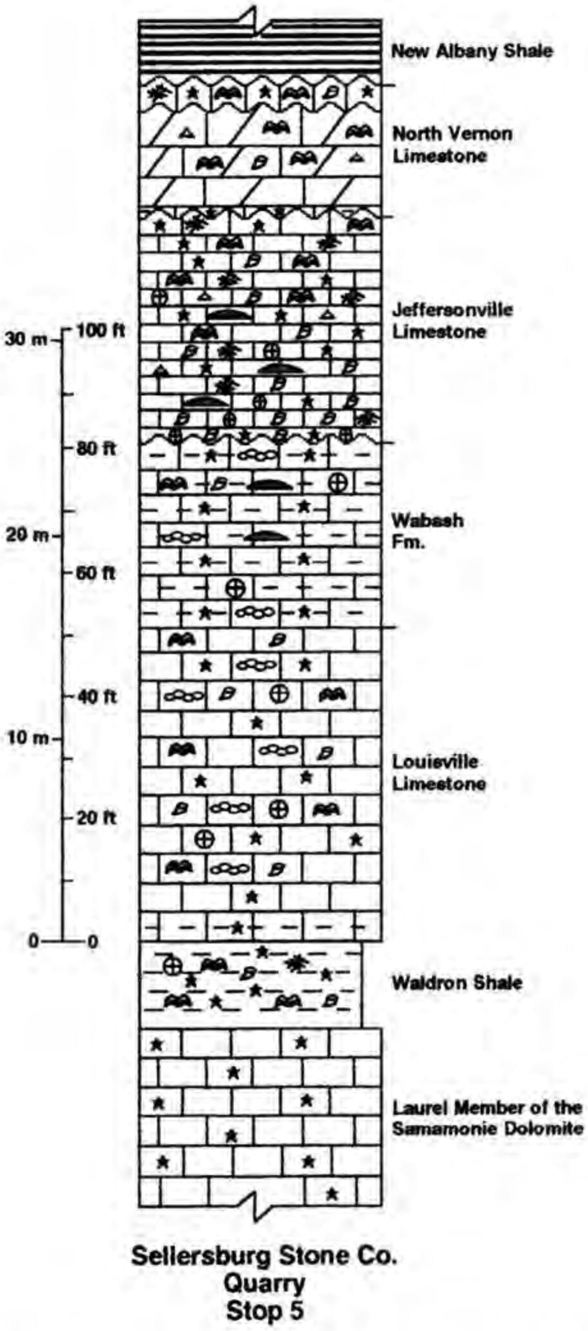


Figure 18. Stratigraphic section at the Sellersburg Stone Company quarry (stop 5).

This stop concludes the field trip.

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The Middlesboro Impact Structure and Regional Geology of the Pine Mountain Thrust Sheet

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Introduction

Welcome to the 2002 combined annual meeting of the Geological Society of America's Southeastern and North-Central Sections. This field guide is intended to provide groups visiting the Middlesboro, Ky., impact structure with a summary of previous investigations of the area, as well as updates on current research by the authors.

The field trip is divided into two parts. Day 1 introduces participants to the regional geologic setting upon which the Middlesboro impact structure is superimposed. During day 2, participants will visit sites within the impact itself. Although divided into 2 days, this field trip can be compressed into 1½ days, depending upon the time requirements and precise interests of your group.

Detailed driving directions are included between each stop, but because many of the stops are in an urban setting, human activities could alter them.

This guide only introduces the basics of the impact cratering process. It is recommended that the reader refer to books such as *Traces of Catastrophe* (1998) by Bevan French or *Impact Cratering: A Geologic Process* (1989) by H.J. Melosh prior to this trip. If you desire a more historical perspective of the field area, *The Wilderness Road* (1999) by Robert Kincaid provides an excellent synopsis.

By the end of the trip, you will be well introduced to the formation and features of the Middlesboro impact structure and its geologic setting.

Regional Geologic Setting

Pine Mountain Thrust Sheet

The Middlesboro impact structure is situated in the southern Appalachians near the junction of the Kentucky, Tennessee, and Virginia borders (Fig. 1). Middlesboro is a circular, approximately 5 km (3 mi) diameter, alleviated, geomorphic basin drained by Yellow Creek northward into the Cumberland River.

The Middlesboro structure is superimposed on the Pine Mountain Thrust Sheet, a large (125 x 25 mi) northeast–southwest-trending overthrust block (Fig. 2) that exposes Upper Devonian to Middle Pennsylvanian strata (Fig. 3). This overthrust was produced by lateral compressive forces during the late Paleozoic assembly of the North American, European, and African continents to form the supercontinent of Pangaea. This collision, known as the Alleghanian Orogeny, was the final

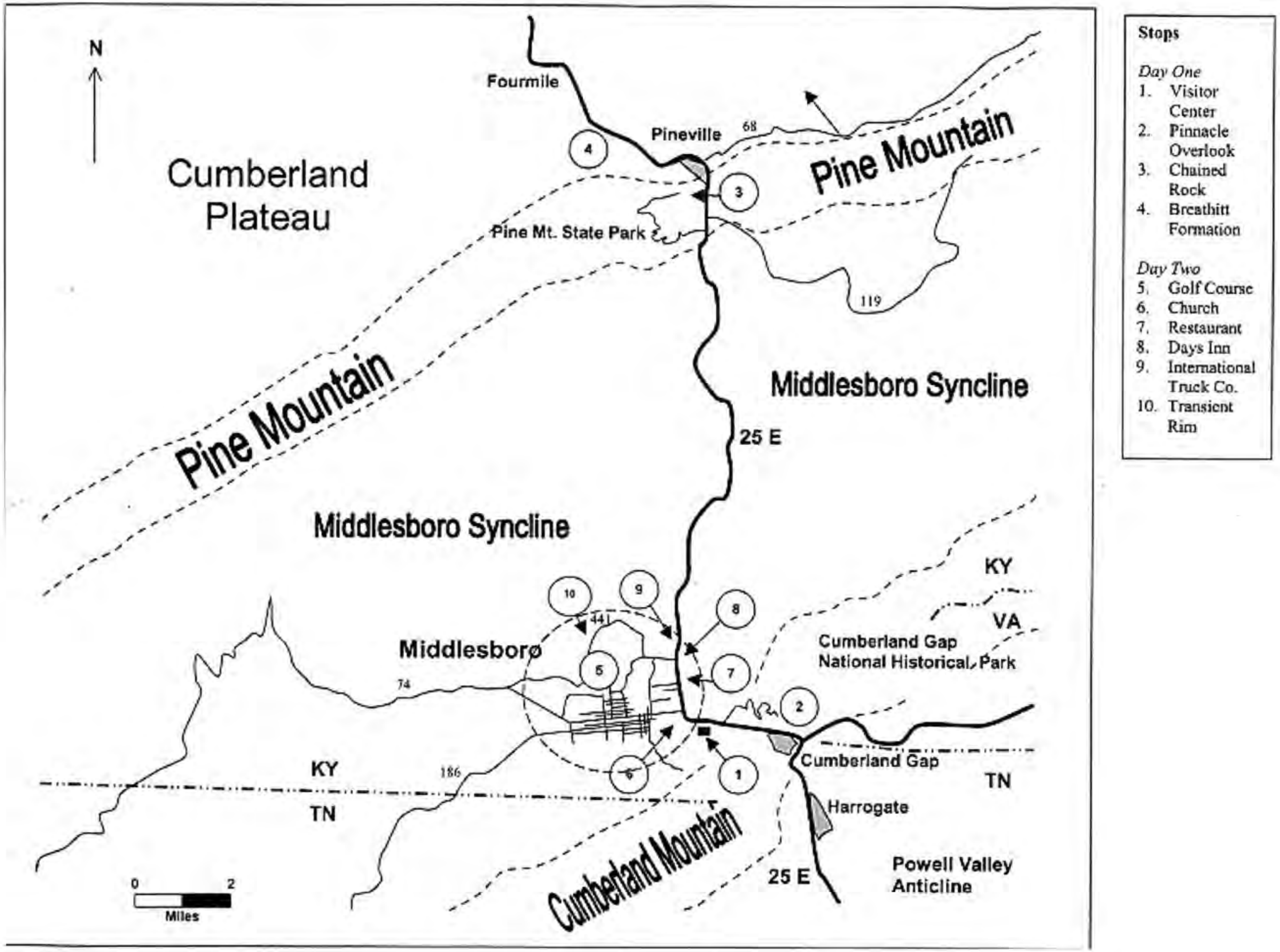

Figure 1. Major stops for this field trip.

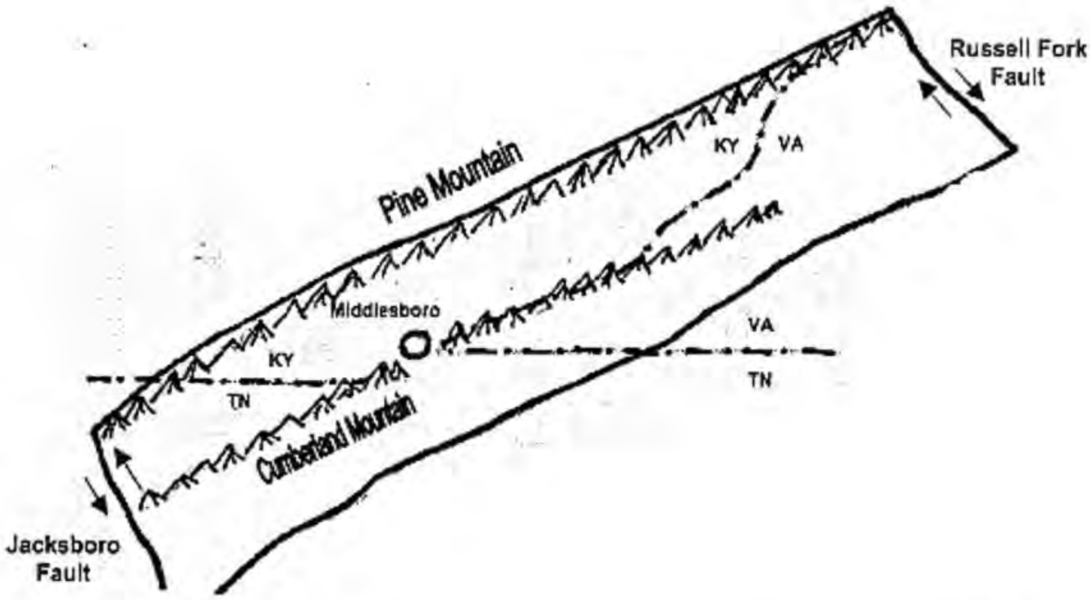

Figure 2. Prominent features of the Pine Mountain Overthrust Sheet and the location of the Middlesboro impact. Modified from McGrain (1975).

stage in forming the Appalachian Mountains along with a series of imbricate thrust blocks, thrust to the northwest. The major detachments developed in the sedimentary cover rocks, with the least competent lithologies, including shales of the Rome Formation (Middle Cambrian) and Chattanooga Shale (Upper Devonian). Eventually these faults ramped upward, steeply crosscutting younger strata and creating large folds in some areas.

The Pine Mountain Thrust Sheet is bounded by faults on all four sides (Fig. 2). The northwest leading edge is the Pine Mountain Thrust; the southeastern trailing edge (Virginia and Tennessee) is the Hunter Valley Fault. The Jacksboro wrench fault in northern Tennessee defines the southwestern end of the block and indicates about 11 mi of movement. The Russell Fork wrench fault (Kentucky and Virginia) on the northeastern end indicates about 4 mi of westward movement. Within the thrust sheet, between the Pine and Cumberland Mountains, is the Middlesboro Syncline, with surface exposures of the Pennsylvanian Breathitt Formation. The Middlesboro impact is situated just southeast of the synclinal axis. Farther southeast, beyond Cumberland Mountain, are exposed lower Paleozoic strata of the Powell Valley Anticline.

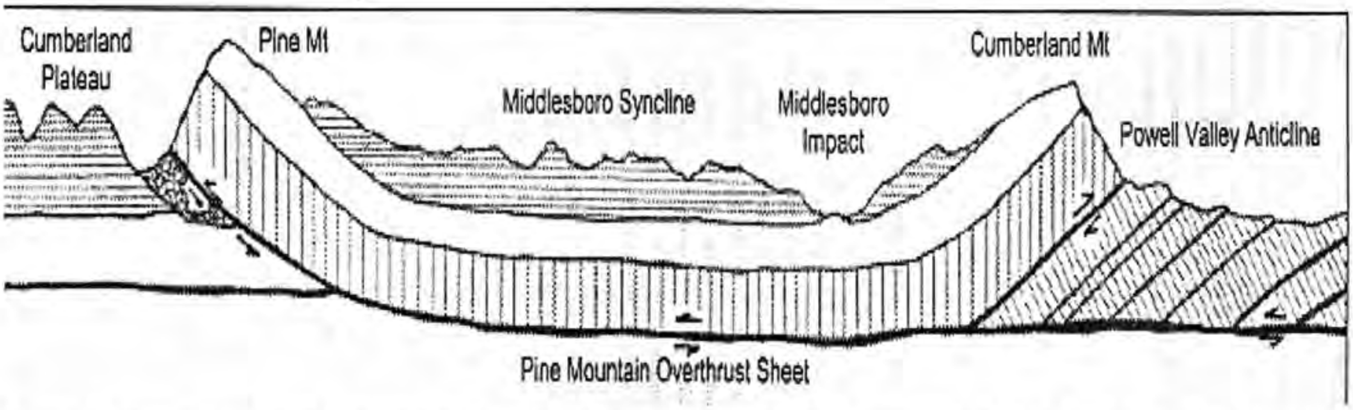

Figure 3. Generalized (not to scale) northwest–southeast cross section through the field area, showing prominent structural features between the Cumberland Plateau and Powell Valley.

Local Stratigraphy

The stratigraphy within the thrust sheet ranges from Upper Devonian Chattanooga Shale to the Mississippian Grainger, Newman, and Pennington Formations to the Pennsylvanian Lee and Breathitt Formations. The rock units of primary concern for this field trip are the Lower Pennsylvanian Lee Formation and the Lower to Middle Pennsylvanian Breathitt Formation (Fig. 4).

The Lee Formation, whose type area is nearby Lee County, Va., consists of sandstone, shale, siltstone, mudstone, coal, limestone, and conglomeratic units that were deposited in marginal-marine and fluvial settings during Late Mississippian to Early Pennsylvanian time. In the field area, the Lee Formation is easily identifiable by its conglomeratic units ranging from 940 to 1,780 ft in thickness. Quartz pebbles are present throughout as thin, graded, or crossbedded lenses. These units are well exposed along Cumberland and Pine Mountains.

The overlying Breathitt Formation consists of Lower to Middle Pennsylvanian sandstones, shales, siltstones, mudstones, and coal beds that were deposited in marginal marine and/or terrestrial depositional settings. The Breathitt Formation is well known for its abundance of *Stigmaria* and *Calamites*, as well as assorted fern and other carbonized leaf impressions.

An Introduction to Impact Cratering

In order to meaningfully observe and interpret the Middlesboro impact structure, one must first gain a basic understanding of the impact process and evidence that has been used to identify impact craters on Earth.

Impact craters are circular or elongate topographic depressions that result from the collision or near collision of a projectile or bolide (meteoroid, asteroid, or comet) with a planetary surface (such as Earth's). Projectile velocities typically range between 5 and 40 km/s (3 to 25 mi/s). During impact, a tremendous amount of energy is released, dependent upon projectile mass and speed and the target body's gravitational acceleration. This energy produces extremely high pressures and temperatures instantaneously. The resultant shock wave has the ability to deform rocks and minerals, producing features uniquely characteristic of impact. These include planar deformation features (PDF's) in quartz grains, shatter cones, melt breccias, and high-pressure polymorphs of quartz (coesite and stishovite).

The impact-cratering process is generally divided into three stages: collision, ejection/excavation, and post-impact modification (Fig. 5). The effects of the collision stage were described in the previous paragraph. Following collision, a bowl-shaped depression called the

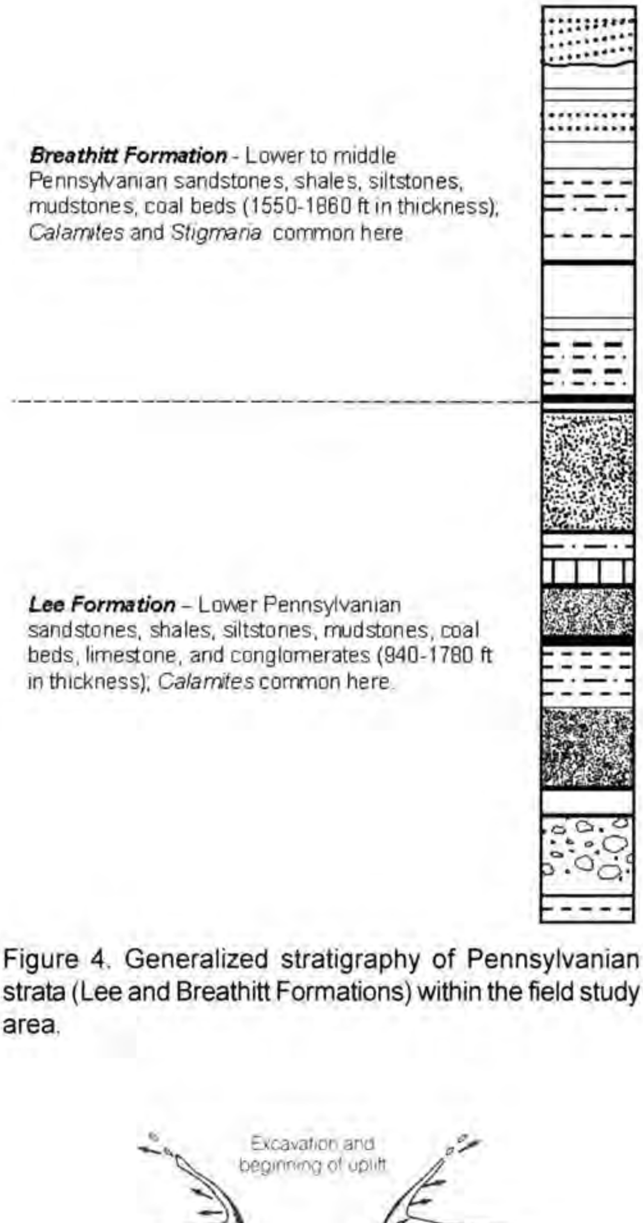

Figure 4. Generalized stratigraphy of Pennsylvanian strata (Lee and Breathitt Formations) within the field study area.

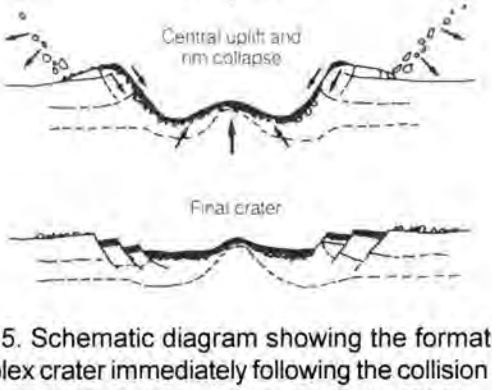

Figure 5. Schematic diagram showing the formation of a complex crater immediately following the collision stage of the impact-cratering process (Melosh, 1989).

transient crater is excavated. Some of the excavated material is ejected into the atmosphere, while the remainder falls back into the crater or lands adjacent to the rim. During the ejection stage, rim material is thrust up, out, and away from the center of impact, with some strata overturning to form an "ejecta flap." Seconds, minutes, hours, and even days following impact, during the modification stage, the transient crater rim collapses along arcuate normal faults to produce an enlarged diameter for the final crater. Weathering and erosion serve to modify the crater form following impact. Highly modified, ancient impact craters are often referred to as "astroblemes."

Impact craters are generally classified as simple, complex, or multi-ring basins. Simple craters are bowl-shaped depressions whose strata dip radially away from the center of impact. Complex craters have a similar overall morphology, but have a terraced rim and a central core of uplifted material. Size transition from simple to complex craters is based on crater diameter and usually occurs at 5 km (3 mi) diameter for terrestrial impacts. This transition is dependent upon the mass and velocity of the incoming projectile and the gravitational acceleration of the target body. Multi-ring basins generally have even larger diameters and are characterized by a central peak surrounded by a series of concentric rings, giving them a "bull's-eye" appearance. An oblique impact (< 30° from horizontal) produces another crater form, one that is oval shaped with an asymmetrical distribution of ejecta.

Until recently, impact cratering was poorly understood, and many scientists doubted its importance as a process for modifying planetary surfaces. During the 1960's, research into nuclear explosions, travel to the Moon in the Apollo Program, and work with suspected terrestrial impact craters revealed it to be a common modifying force in the solar system. Today, impact craters have been identified on virtually every solid solar system surface, including Mercury, Venus, Mars, Phobos, Deimos, the moons of Jupiter, Saturn, Uranus, and Neptune, and even asteroids. Here on Earth, approximately 150 impact craters have been identified on land, while approximately the same number are suspected on the ocean floor.

Middlesboro is one such site that has been identified as an impact crater. There are also two other suspected impact structures, Jeptha Knob and Versailles, in the state of Kentucky (Koeberl and Anderson, 1996).

The Middlesboro Impact Structure

History of Middlesboro

Middlesboro Basin has long held both historic and scientific significance for this part of the southern Appalachians. It initially served as a stopover for settlers migrating westward through the Cumberland Gap. Middlesboro's lowland topography provided abundant water, but was also known for its natural wetlands and quagmires that hindered travel along the Wilderness Road.

Prior to the late 19th century, Middlesboro consisted of a series of scattered dwellings and trading posts. The 1890's brought the exploitation of coal reserves in surrounding Pennsylvanian strata, which, in turn, led to a booming local economy. As a result of an influx of English investment money and new workers, the town of Middlesboro was established in 1889 by coal baron Alexander Arthur and named after the town of Middlesborough, England. The prosperity of Middlesboro continued until the economic crash of 1893 and a major fire that destroyed part of the town. Slowly the economy recovered, and Middlesboro retains its mining-based economy today.

Early Scientific Investigations

Before the turn of the 20th century, geologists began to take an interest in the southern Appalachians and the conspicuous Middlesboro Basin. N.S. Shaler of Harvard University conducted the first geologic survey of the region and simultaneously ran a geologic field school for students from 1875 to 1880 (Kincaid, 1999). Other early investigations examined possible origins of the Middlesboro Basin. Ashley (1904) and Ashley and Glenn (1906) revealed strata within Middlesboro that were "greatly disturbed by folding and faulting" within a broad, flat, alluviated basin. Both researchers attributed the disturbed strata to "stresses that produced the formation of the Appalachian province" (Ashley, 1904). They hypothesized that development of the basin resulted from the erosion of weakened strata and subsequent ponding of water within the basin. Rich (1933) agreed with the conclusions of Ashley and Glen, but added that Middlesboro may have resulted from the collapse of a small dome, followed by gravitational settling and ponding.

Later geologic mapping in the Middlesboro North (Englund and others, 1964), Middlesboro South (Englund, 1964), and Kayjay/Forkridge quadrangles (Rice and Maughan, 1978) led Englund and Roen (1962) to propose an impact origin for Middlesboro (Fig. 6). Their hypothesis was based on the presence of a circu-

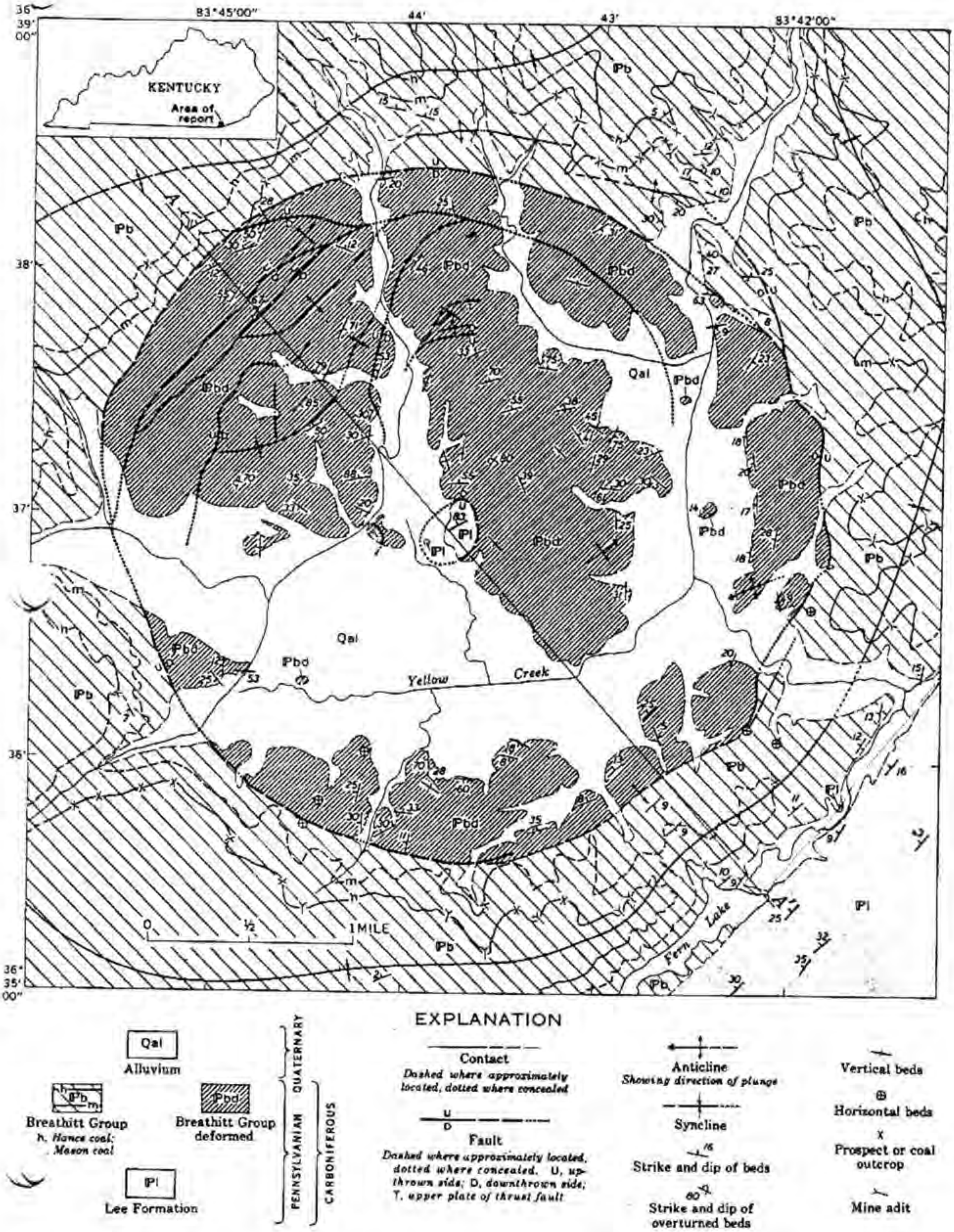

Figure 6. Early geologic map of the Middlesboro structure by Englund and Roen (1962).

lar basin, intensely deformed rock, normal faulting with arcuate trends around the basin, overturned beds, shattered quartz grains, and a central core of uplifted material. Such observations were consistent with an impact model for Middlesboro, but could also be explained by other non-exogenic processes, such as cryptoexplosion.

Evidence confirming an impact origin was not long in coming, however. In 1966, Robert Dietz discovered shatter cones within the central uplift area, and later petrographic analyses of sandstone specimens led to the identification of shocked quartz (Bunch, 1968; Carter, 1968), confirming the impact hypothesis. Magnetic and gravity surveys (Seeger, 1970, 1974; Steinemann, 1980) also have added further support for an impact origin.

Although these early studies have identified Middlesboro as an impact crater, detailed mapping and petrologic analyses (Milam, 1998; Milam and Kuehn, 1999, 2002) are only now revealing the true mechanics and morphology of this impact.

Day 1: Regional Geology

Field trip begins at the Cumberland Gap National Historical Park Visitor Center along U.S. 25E, south of Middlesboro, Ky. (Fig. 1). Hours are 8 A.M. to 5 P.M. daily year-round, except December 25 and January 1. This stop provides water/restroom facilities.

Stop 1. Cumberland Gap National Historical Park Visitor Center

Our trip begins with a visit to the Cumberland Gap National Historical Park Visitor Center. The Visitor Center houses cultural, historical, and natural history exhibits that will provide context for the remainder of an otherwise scientific trip.

The geology of this region and the human saga have been intricately related for thousands of years. Northeast–southwest-trending mountains, such as Cumberland Mountain and Pine Mountain, have served to control patterns of human migration, settlement, and commerce. Native Americans and settlers of European descent crossed these mountains at low points, where they had been dissected by natural wind or water "gaps." Between 1790 and 1810, approximately 250,000 settlers from Virginia and other eastern states crossed through Cumberland Gap on their way to Kentucky and Tennessee. Later, Cumberland Gap was also of strategic value for funneling supplies and troops during the Civil War. The gap remained an important transportation route until as recently as 1995, when the Cumberland Gap Tunnel, a 4,600-ft, twin-bore tunnel, was opened. The tunnel penetrates Cumberland Mountain southwest of the gap and was designed to better accommodate the growing demands of vehicle traffic along U.S. 25E in the area. The National Park Service is currently restoring the old Wilderness Road through the Cumberland Gap to its nearly original, historic appearance. Project completion is scheduled for the spring of 2002. Despite impressive, modern engineering feats like the tunnel, natural gaps still serve as important transportation corridors in the southern Appalachians.

Turn right from the Visitors Center parking lot and proceed east along Pinnacle Road for 3.6 mi (Fig. 1). This is a winding road unsuitable for trailers and large vehicles over 20 ft in length. Park in the lot where the road ends and take the short hike to the Pinnacle Overlook. During inclement weather, the overlook can be very windy.

Stop 2. Cumberland Mountain/ Pinnacle Overlook

This stop in Virginia affords a view of Cumberland Mountain, Powell Valley, and at least the southern half of the Middlesboro impact structure, depending upon the time of year and amount of foliage (Fig. 7).

Most natural features within view are a part of the Pine Mountain Thrust Sheet (also known as the Cumberland Overthrust Block), a large northeast–southwest-oriented thrust sheet, which extends through adjacent parts of Kentucky, Tennessee, and Virginia (Fig. 2).

Pinnacle Overlook is situated atop Cumberland Mountain, an exposed section of northwest-dipping, Devonian- to Pennsylvanian-age rock. Cumberland Mountain forms the northwestern limb of the Powell Valley Anticline, whose axis of older, lower Paleozoic strata lies within the valley viewed to the southeast from the overlook.

A brief hike around the overlook reveals graded and crossbedded conglomeratic sandstones of the Lee Formation (Fig. 8). These coarse-grained sandstones contain very well-rounded quartzite pebbles, up to 4 cm (1.5 in.) in diameter, deposited during Late Mississippian–Early Pennsylvanian time (Rice, 1984). The Pennsylvanian *Calamites* flora is also present within this unit. We will see this prominent ridge-forming unit exposed again along Pine Mountain, and anomalously within Middlesboro proper.

A look to the northwest reveals the Middlesboro Basin, within which is situated the town of the same name (Fig. 7). The Middlesboro Basin is a circular, alluviated basin containing intensely deformed strata, mostly of the Breathitt Formation. It is drained by Yellow Creek, which flows northward into the Cumberland River and is surrounded by adjacent high hills that provide up to 610 m (2,000 ft) of local topographic relief.

Figure 7. Westward view of the Middlesboro Basin from Cumberland Mountain, showing prominent landmarks. White dashed line demarcates the approximate outer boundaries of the modified Middlesboro impact.

Figure 8. Crossbedded conglomeratic sandstone of the Lee Formation along Cumberland Mountain near Pinnacle Overlook, Cumberland Gap National Historical Park.

Surrounding Middlesboro and visible to the northwest are the exposed flat-lying strata of the Pennsylvanian Breathitt Formation. These strata underlie the deeply incised plain around Middlesboro and occur within the Middlesboro Syncline. Also visible are current coal-mining activities in the region.

Retrace the route down Cumberland Mountain along Pinnacle Road (Fig. 1). Go past the Visitor Center and follow the signs to U.S. 25E north. Take U.S. 25E north for 10.6 mi until reaching a turnoff on the left (west) for Pine Mountain State Resort Park. After 3.4 mi, you will enter Pine Mountain State Resort Park. Continue for 4.6 mi, following the signs to reach the Chained Rock Overlook parking lot. Hike the 0.5 mi trail to the Chained Rock Overlook. (Caution: This stop has very steep drop-offs and is very dangerous for climbing. No handrails are present.)

Stop 3. Pine Mountain/Chained Rock Overlook

High atop Pine Mountain, one can now view the leading edge of the thrust sheet to the north (Fig. 3). At Chained Rock Overlook (Fig. 9) we are approximately 2,200 ft above sea level and 1,200 ft above the town of Pineville, Ky. Chained Rock takes its name from the fact that a large slab of Lee conglomerate is literally chained to Pine Mountain here. Local history has it that in the early 1900's, residents from Pineville, concerned with the threat the boulder posed to their town, attached a chain to the ominous rock, thereby anchoring it permanently. The effectiveness of this preventative measure is certainly open to debate.

The gap visible just below and to the northeast (Fig. 10) was produced by the downcutting of the Cumber-

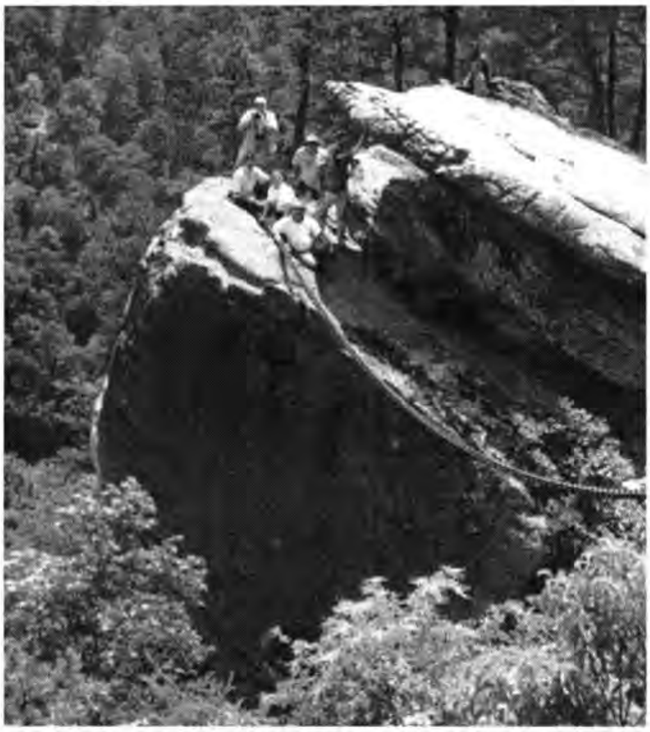

Figure 9. Chained Rock Overlook, Pine Mountain State Resort Park, looking northeast toward Pineville Gap. Notice the southeast-dipping strata of the Lee Formation.

land River through Pine Mountain as uplift occurred. In fact, this is the only point in Kentucky where a modern-day stream breaches Pine Mountain along its entire length (McGrain, 1975).

This leading edge of the thrust sheet exposes southwest-dipping Devonian to Pennsylvanian strata throughout the escarpment. Here, Pine Mountain is capped by conglomeratic sandstones of the Lower Pennsylvanian Lee Formation. As is the case at Cumberland Mountain, the resistant conglomeratic units of the Lee Formation are prominent ridge formers. Additional exposures just above Chained Rock Overlook provide a vantage point for viewing the entire structural setting from the Cumberland Plateau to Cumberland Mountain farther south.

Retrace your entry route, exiting Pine Mountain State Resort Park, and return to the intersection with U.S. 25E (Fig. 1). Turn left and continue north along U.S. 25E for 3 to 4 mi, passing through the town of Pineville, Ky., along the way. Pull off the highway at the spectacular exposures of Breathitt Formation at mile marker 16. (Note: This site receives heavy traffic, and extreme caution should be used when viewing this roadcut.)

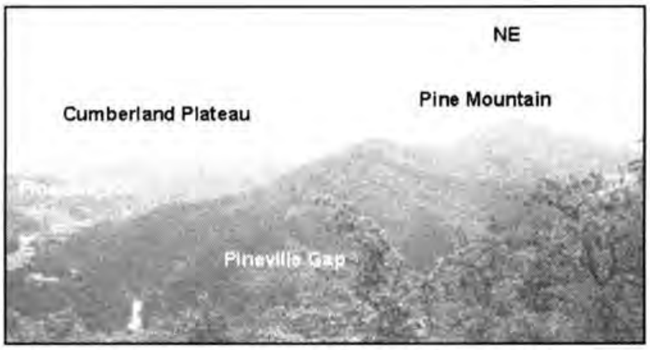

Figure 10. View of the leading edge of the Pine Mountain Thrust Sheet along Pine Mountain from Chained Rock Overlook. The Cumberland Plateau is visible along the horizon farther to the north.

Stop 4. North of Pineville, Ky.

On the south side of the highway, one can view horizontal exposures of the Lower to Middle Pennsylvanian Breathitt Formation within the Cumberland Plateau. Note the variety of lithofacies (sandstone, siltstone, shale, and coal) and the extent of their lateral continuity (Fig. 11). The Breathitt Formation immediately overlies the Lee Formation in the field area (Fig. 4). These strata represent deposition in marginal marine/terres-

Figure 11. View of the flat-lying stratigraphy of the Breathitt Formation within the Cumberland Plateau, northwest of Pineville, Ky., at stop 4.

trial environments. It is important to get a sense of the undeformed appearance of these units prior to tomorrow's trip in Middlesboro Basin, where the same units are heavily disturbed.

Day 2: Middlesboro Impact Crater

From the Cumberland Gap National Historical Park Visitor Center, turn left out of the parking lot and follow the signs to U.S. 25E North to Middlesboro (Fig. 1). One-half mile after entering U.S. 25E, just inside the city limits of Middlesboro, turn left at the first stoplight onto Cumberland Avenue. Continue for 1.3 mi, passing through the downtown area, until reaching 27th Avenue. Turn right (go north). Continue for seven blocks until reaching Circenster Avenue and turn left (go west). At the next intersection, turn right (go north) onto Haywood Road. Take the next left (west) into Middlesboro Country Club. Park in the parking lot next to the clubhouse. Hours are 10:00 A.M. to 8:00 P.M. (winter), 9:00 A.M. to 10:00 P.M. (summer), and 8:00 A.M. to 10:00 P.M. weekends. (Note: Permission must be obtained from the manager prior to viewing exposures, and collecting is not allowed.)

Stop 5. Central Uplift / Middlesboro Golf Course

We are now standing near the center of the Middlesboro impact structure (Fig. 12). Englund and Roen (1962) first noted the presence of conglomeratic sandstones of the Lee Formation here (Fig. 13), and suggested that this area was a centrally uplifted core of material bounded by "steeply inclined normal faults" (yet to be confirmed) common in complex craters. They also noted that "shattered" quartz grains with "parallel arrangement of fractures" were present in the conglomerates here. Bunch (1968) and Carter (1968) later identified shocked quartz containing planar deformation features (PDF's) in these rocks, providing confirmation of an impact origin for Middlesboro.

It was at this site that Robert Dietz (1966) noted the presence of "concave striations suggestive of shatter coning" in an outcrop to the northeastern end of the parking lot adjacent to the clubhouse (Fig. 13). Whether or not this exposure is *in situ* is uncertain. A couple

Figure 12. View of the central uplift area, now the Middlesboro Country Club golf course, with Cumberland Gap visible in the background to the southeast.

Figure 13. Outcropping (or boulder?) of conglomeratic Lee Formation to the north of the clubhouse at Middlesboro Country Club golf course, displaying striations originally described by Robert Dietz (1966).

hundred meters away to the northwest, Dietz reported finding boulders that were "intensely shatter coned." Unfortunately, these boulders no longer exist, due to further landscaping of the golf course, but additional samples of Lee conglomerate can be viewed in a cobble field approximately 31 m (100 ft) north of the clubhouse.

Looking across the golf course, one can easily recognize problems associated with study of the central uplift area. For one, this area has been intensely landscaped, limiting preexisting exposures. Second, a veneer of Quaternary, Breathitt-derived terrace gravels covers most of the hills visible to the northeast and west. Exposures of bedrock are very limited, and shatter cones have been over-collected, so they are no longer present at the surface. It was not until 1999 that the authors located a single sample of coarse-grained siltstone from Middlesboro containing approximately 10 shatter cones (Fig. 14) in the possession of Dr. Nicolas Rast of the University of Kentucky (Milam and Kuehn, 1999).

Also that year, new samples of Lee conglomerate were collected from the central uplift area and have since undergone petrographic analysis (Milam and Kuehn, 2002). These samples display intense shattering and fracturing of the fine-grained conglomeratic sandstone, possible melt textures, sheared quartzite pebbles, planar fracturing, and planar deformation features. These textures are providing new insight into the impact cratering process and, specifically, central uplift formation (Milam and Kuehn, 2002). Additional field work has allowed us to locate and delineate additional surface exposures of the Lee Formation (Fig. 15). Structural data taken from petrofabrics around the crater rim, however, suggest that the bulk of the central uplift may actually be present farther to the northeast. Now that we have examined the central uplift, we will travel along the rim examining exposures.

Return to the parking lot and retrace your route back to Cumberland Avenue (Fig. 1). Turn left (heading east) onto Cumberland Avenue and travel for 1.2 mi and turn right (south) onto the last road on the right before U.S. 25E. Continue for 0.1 mi to the parking lot of the Faith Missionary Baptist Church. Exposures are behind the church. This is a heavily weathered, sloping site that is not easily visible from the parking lot. A better view can be obtained by cautiously climbing the slope. (Note: Permission must be obtained from the proper church officials before viewing this site.)

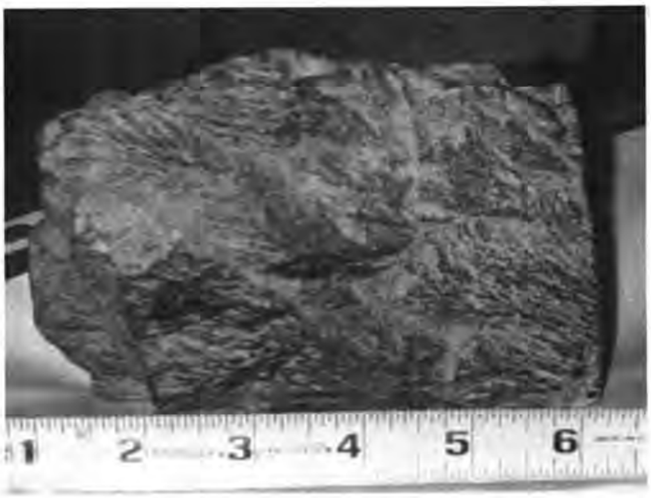

Figure 14. Shatter cones collected from the central uplift area of the Middlesboro impact structure.

Stop 6. Transient Crater Rim/ Faith Missionary Baptist Church

Now we are near the rim of the transient crater that formed initially at Middlesboro (Fig. 16). This exposure preserves the ejection and modification stages of impact. At the top of the site you will notice a series of primarily reverse faults in sandstones, siltstones, and shales from the Lower Pennsylvanian Breathitt Forma-

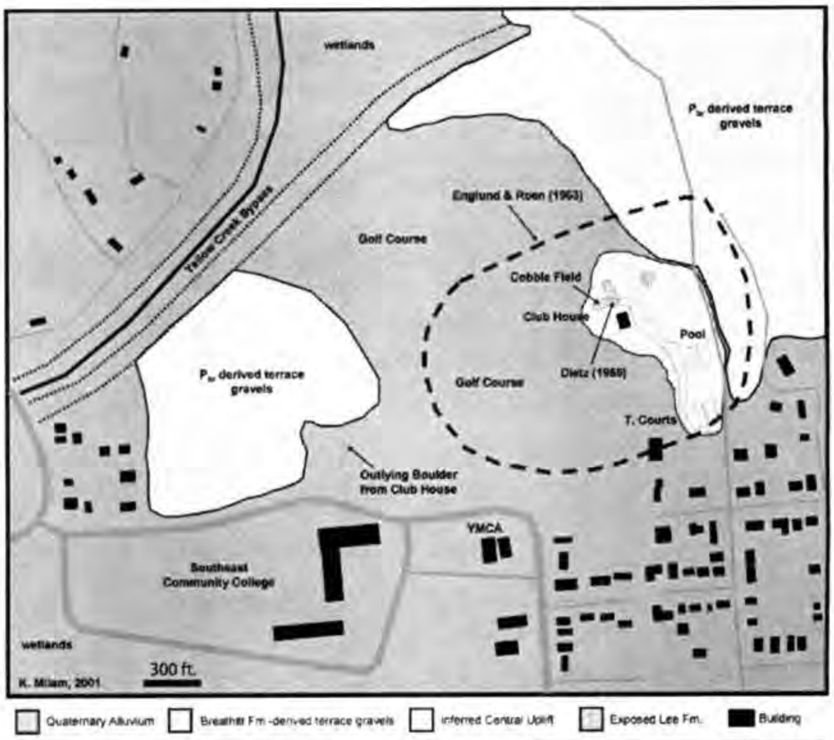

Figure 15. Map of the inferred central-uplift location, showing exposures of the Lee Formation.

Figure 16. Exposure of Breathitt Formation near the transient crater rim near Faith Missionary Baptist Church.

tion (Fig. 17) with interspersed normal faults. Bedding here strikes northeast and dips to the southeast, away from the central uplift. Notice the drag folds associated with the reverse faults (Fig. 18). Approximately 10 ft farther down section are monoclinal folds oriented according to similar stress fields. Fault planes and fold axes have northeast strike and northwest dip orientations. The principal stress placed on these strata appears to have come from the northwest, the direction of the central uplift area.

This site thus preserves an instant in time during crater formation when material was being thrown from the transient crater, and strata near the rim were being pushed up, out, and away from the center of impact (Fig. 18). Some of the material was ejected, whereas the rest was thrust up along high-angle reverse faults (such as at this site). Following the ejection stage, large blocks of material slumped back into the basin along arcuate normal faults. The hill containing this exposure is likely one such block, but only future excavations to the south will reveal this. The unique preservation at this site has allowed us to identify this as the approximately southeastern boundary of the Middlesboro transient crater.

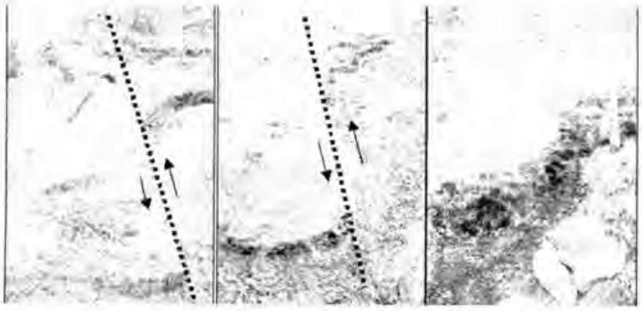

Figure 17. Examples of high-angle reverse faults and folds present at stop 6.

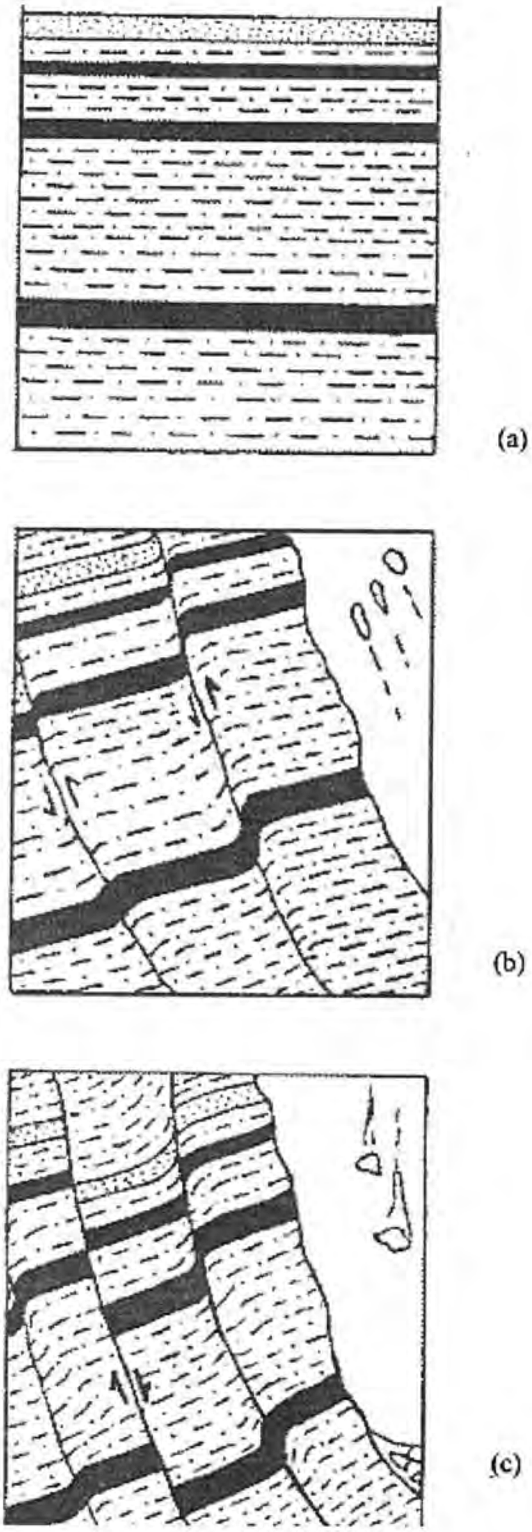

Figure 18. Diagram demonstrating the formation of the transient crater rim and subsequent collapse near stop 6. (a) Preexisting stratigraphy. (b) Strata being faulted and folded during the ejection/excavation stage. (c) Collapse of the transient crater rim and fallback of ejecta during the modification stage of impact.

Retrace your route back to Cumberland Avenue and turn right (heading east). Turn left at the next stoplight and head north on U.S. 25E. Approximately 0.7 mi on the right is an outcrop behind a restaurant (Lee's Famous Recipe). Park at the rear of the parking lot. Walk around behind the fence to view the outcrop. (Note: Permission must be obtained from the restaurant manager before viewing this site.)

Stop 7. Lee's Famous Recipe

At this stop we will view severely deformed shale, siltstone, sandstone, and coal of the Breathitt Formation (Fig. 19) that appears undisturbed as we trace the exposure to the south. Several faults, small folds, and drag folds are present within this cut.

It is not clear exactly how this deformed block of material relates to the impact model. Were these strata thrust westward over nearly horizontal strata during crater collapse? In that case, we may be viewing the leading edge of an arcuate fault along which a terrace block collapsed during crater modification. Or is this a localized slump feature? Either way, this site demonstrates the varying styles of deformation associated with the Middlesboro impact.

Return to your vehicle and exit the parking lot by turning right (heading north) onto U.S. 25E (Fig. 1). Drive for 0.8 mi and turn right into the parking lot of the Days Inn motel. (Note: Exposures are behind a Hardee's restaurant, Days Inn motel, and Ryan's Steakhouse. Please obtain permission from each facility's manager before viewing the site.)

Stop 8. Modification Stage/Days Inn

The entire hillside is interpreted as a block of Breathitt Formation that slumped basinward during the modification stage of impact (Fig. 20). The lithologies here consist mainly of siltstones and shales, heavy with abundant carbonaceous plant fossils. These rock layers contain small channels of dark-brown fluvial sand (as viewed on the upper southern end of the outcrop). The hill is capped by a thick, coarse-grained, crossbedded, fluvial sandstone that unconformably overlies stringers of coal and their associated underclays. Orientation of bedding is variable here, dipping to the north and southwest.

One of the most noticeable features of this cut is the high fracture density. This fracturing may arguably be associated either with impact or tectonic stresses, but it leads to a variety of environmental concerns in this urban area. At one time, the hillslope actually extended across present-day U.S. 25E. As you may notice, much of this hill has been cut away to accommodate businesses on the eastern side of the highway. Due to the densely fractured nature of the strata and the orientation of the bedding, slumping is quite common here. This situation has been alleviated somewhat by "benching" the slope of the outcrop to control minor rockslides.

Return to your vehicle and turn right (heading north) out of the parking lot (Fig. 1). Continue through the stoplight and 0.2 mi from stop 8; turn left at the International Truck Co. Park in the parking lot. Exposures are behind the buildings. (Note: Permission must be obtained from the manager prior to viewing these cuts.)

Stop 9. Modified Crater Rim/ International Truck Co.

Nearly horizontal strata of the Breathitt Formation are preserved in the southern end of this cut. At the

Figure 19. Exposure of highly disturbed Breathitt Formation behind the restaurant at stop 7.

Figure 20. Hillside exposures of highly fractured Breathitt Formation behind motel at stop 8.

northern end, beds dip away from the center of Middlesboro Basin (to the northeast). This site contains several small reverse faults and a prominent high-angle reverse fault (with 2 to 3 ft of separation) at the northern end of the exposure (Fig. 21). A few of the smaller faults on the southern side contain fault gouge.

The reverse faults at this exposure appear to have resulted from the ejection stage of impact just outside the transient crater rim. Following impact, most of this material collapsed back into the newly formed crater along a normal fault farther to the north and along smaller normal faults within this cut. The identification of key marker beds within this exposure allows us to calculate that this entire block has experienced approximately 244 m (800 ft) of stratigraphic displacement.

Figure 21. View of a high-angle reverse fault near the transient crater rim at stop 9. Other such faults are present within this exposure.

Turn right (heading south) from the parking lot onto U.S. 25E (Fig. 1). Continue for 0.2 mi to the stoplight. Take a right (heading west) at the stoplight onto Ky. 441 (Hollywood Road). Continue on Ky. 441, go for 0.2 mi, taking a right; continue for 0.4 mi and take a left on Belt Line Road. Travel approximately 1.5 to 2 mi, and you should eventually see Yellow Creek Bypass (a stream on the left) until you reach a small cut on the right (north) between Lick Fork and Stevenson Roads. Turn in to the right and park. (Note: This is private property, so permission should be obtained from the current landowner.)

Stop 10. Transient Crater Rim/ Yellow Creek Bypass Site

This last stop of the trip also preserves the ejection stage of impact and lies along the transient crater rim. It displays deformed strata of the Breathitt Formation (Fig. 22). Shale, siltstone, sandstone, and coal of the Breathitt Formation all strike 15 to 35° to the northeast and dip 44 to 68° to the northwest (generally away from the center of the impact).

Figure 22. View of rotated and "upturned" coal, shale, and siltstone bedding of the Breathitt Formation near the transient crater rim at stop 10.

The most interesting feature of this cut is the nearly overturned flap of shale, coal, and underclay. Overturned bedding associated with impacts, in the form of an "ejecta flap," was first recognized at Barringer Meteor Crater, Ariz. (Shoemaker, 1960), and has been shown to be a distinguishing feature of transient crater rims. This site is a rare instance of preservation of the lower half of an ejecta flap at Middlesboro, and allows us to confine the location of the transient crater in the northwest. During the impact ejection stage, this flap of material was inverted, followed by collapse of the crater rim (Fig. 23). During modification-stage collapse, this block of material collapsed along an arcuate normal fault, leading to rotation of bedding and its current orientation. Similar overturned bedding has also been found in the southwestern part of the structure near recent coal-mining operations (Greb and Chesnut, 1998).

End of Field Trip

Afterword

There are several additional exposures within the Middlesboro impact crater that do not fall within the scope of this field trip. New exposures are also created with continuing urban development within this basin. If you wish to view any of these, take the time to drive around the basin. Additional mysteries await the inquiring geologic eye at Middlesboro, Ky.

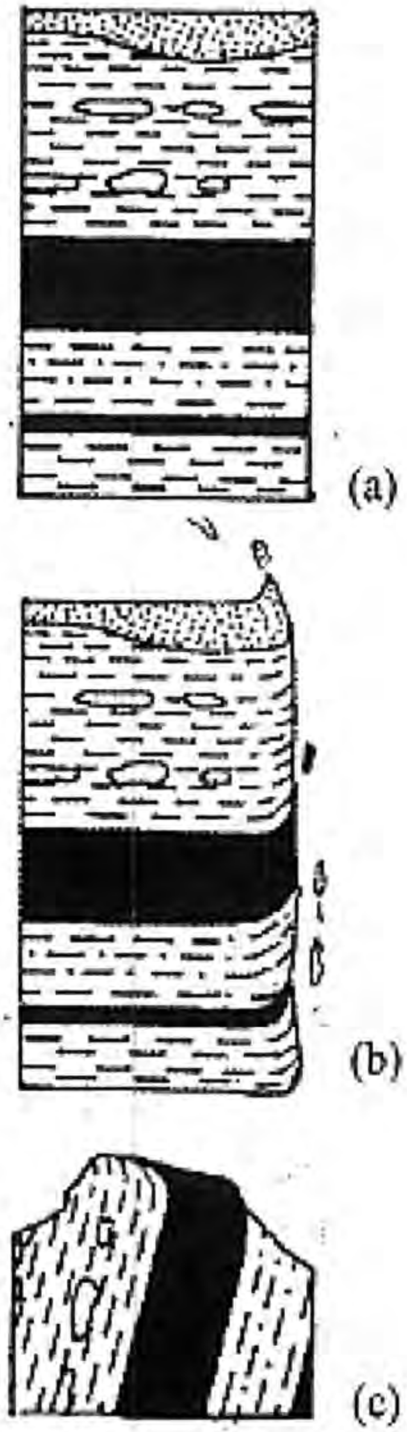

Figure 23. Schematic view of the "upturned flap" shown in Figure 22. (a) Preexisting stratigraphy. (b) Material being excavated along the transient crater rim during the ejection stage. (c) How post-impact modification has rotated strata as the transient crater rim has collapsed back in the basin along normal arcuate faults.

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entrance ramp from the Industrial Park. The Princess No. 6 coal lies 10 m (30 ft) above the No. 5 coal. The Princess No. 7 coal occurs 6 to 11 m (19 to 35 ft) above the No. 6 coal and is exposed toward the base of outcrops at stop 2. The Princess No. 8 coal occurs 10 to 12 m (31 to 38 ft) higher, and is exposed toward the top of the ramp; it will be the focus of stops 1 and 2. The Princess No. 9 coal is sporadically distributed, generally 7 to 12 m (22 to 39 ft) above the No. 8 coal bed. At stop 2, the coal occurs in a scour that lies directly above the Princess No. 8 coal bed. Variability in coal thickness, continuity, and bench architecture along the road will be demonstrated at the first two stops.

Stratigraphic Correlations

Shepperd and Ferm (1962) mapped the strata in this quadrangle (Argillite 7.5-minute) prior to construction of I-64 and Ky. 67 (Industrial Parkway), and before extensive drilling and coal mining of the 1970's. Conemaugh strata were found to occur only on hilltops in the southeastern part of the quadrangle, and no Conemaugh marine units were reported. The Brush Creek coal and overlying marine shale and limestone were recently discovered at this location. The stratigraphic interval between the coal mapped as the Princess No. 8 and the Brush Creek Coal is 88 ft (27 m) (Fig. 23). The lowest red-bed paleosol occurs only 28 ft (8.5 m) above this coal. In Ohio, the lowest red beds occur between the Upper Freeport and the Brush Creek Coals, and the UF-BC interval is 92 ft (28 m) (Sturgeon and Hoare, 1968). These considerations suggest the possibility that the coal at the base of this section (mapped as the Princess No. 8) is the equivalent of the Upper Freeport. Unfortunately, the Upper Freeport and Lower Freeport are not distinguishable palynologically. An alternative explanation could be that the Upper Freeport coal is not present in this area due to limited accommodation along the hinge of the basin. The number of coal beds between the Obryan and Brush Creek Limestones generally increases southward toward Louisa, Ky., based on published geologic quadrangle maps.

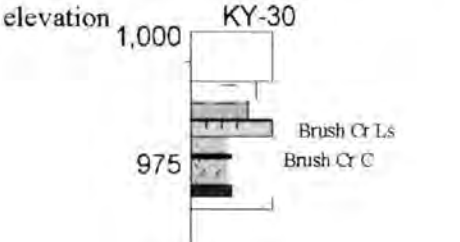


Figure 23. Stratigraphic column produced during geologic mapping from for the Argillite Quadrangle by Sheppard and Ferm (1962).

Stop 1: Princess No. 8 Coal Thickness Variation

Two miles north of exit 179, on the new Industrial Parkway, is an outcrop that exposes strata between the Princess No. 8 coal bed and the lower part of the Conemaugh Formation. The Princess No. 8 coal occurs at road level. The Princess No. 9 coal is absent. The Brush Creek marine zone of the Conemaugh Formation is situated midway up the roadcut, but is poorly exposed here. The Princess No. 8 coal at this stop occurs above two shallow scours (Fig. 24). The coal thins on the margins of the scours and thickens into the scours. Thin leader coals occur at the base of each scour and pinch out onto the margins of the scours. A rooted paleosol beneath the coals (marking the scour) drapes the margin between scours, even where the leader coals are absent. Red coloration within the scours is considered typical of the overlying Conemaugh Formation, but here occurs within the upper Breathitt Group, associated with paleosols. A similar scour, above which the Princess No. 8 thickens downdip and pinches out updip, is exposed between stop 1 and stop 2.

Samples of the Princess No. 8 lower bench and top bench zone were examined palynologically and geochemically from several sample points along each scour (Figs. 25–26). All of the samples are dominated by *Lycospora* and tree fern spores, which is typical of Princess Formation coals in general. Most of the samples are also high in ash and sulfur.

Interpretation

Coal beds can be examined in terms of their architecture. Beds can be divided into benches based on the occurrence of clastic partings or persistent changes in coal lithotypes (Staub, 1991; Greb and others, 2002), and then interpreted based on compositional groups within the benches (Eble and Grady, 1990, 1993; Greb and others, 1999, 2002). Compositional groups utilize

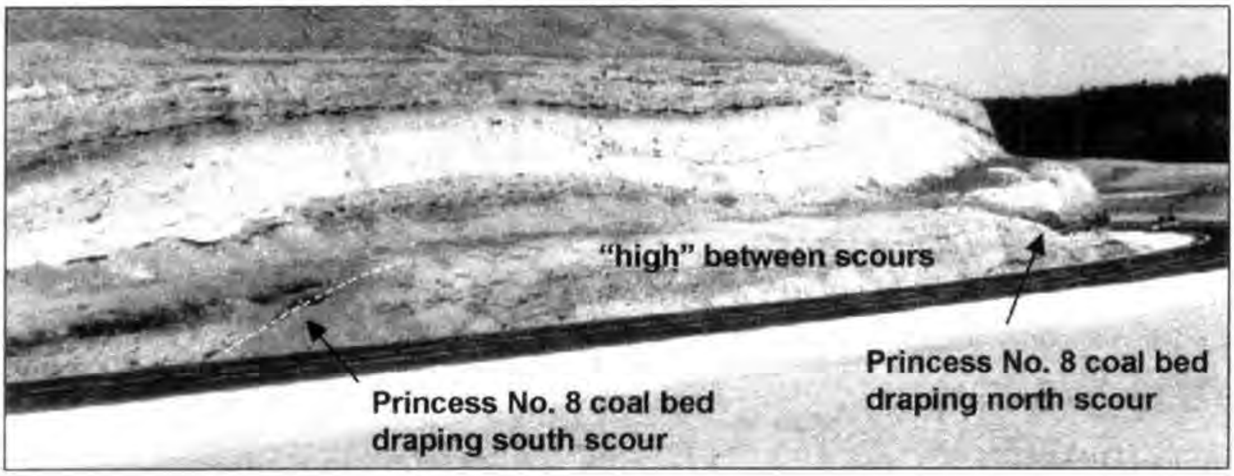


Figure 24. Princess No. 8 coal bed above two scour fills at stop 1.

palynology, petrography, sulfur content, and ash yield to infer original mire environments.

At this location, multiple coal benches occur above each scour and thicken into the scours. Because the number and thickness of coal benches increases into the scours, both can be seen to be a function of local paleotopographic accommodation at the time of peat accumulation. Channel-filling coals have also been noted in younger coal beds (Early and early Middle Pennsylvanian) on the western margin of the basin—another low-accommodation setting (Greb and Chesnut, 1992; Eble and Greb, 1997).

The coal at this location clearly reflects peat accumulation in small mires that were subject to frequent clastic influx, as is shown from the ephemeral nature of the coal and high ash yields. The palynoflora is fairly heterogeneous; no one plant type dominates. It should also be noted that *Lycospora micropapillata* and *L. orbicula* occur in relatively high percentages in many of the samples. Both of these species were produced by *Paralycopodites*, which was a colonizing lycopod tree. Collectively, this probably is the result of rapidy changing edaphic conditions within the mire, related to infilling of the paleotopographic depression..

Stop 2: Accommodation Influences in the Princess Nos. 7 through 9 Coal Interval

Stop 2 is located at the top of the northwest ramp onto Interstate 64. Don't park on the ramp, as we will be heading eastbound after this stop. There are three outcrops at the interchange (Fig. 1). Outcrop A occurs on the eastern side of the Industrial Parkway. Outcrop B occurs on the western side of the Parkway and north

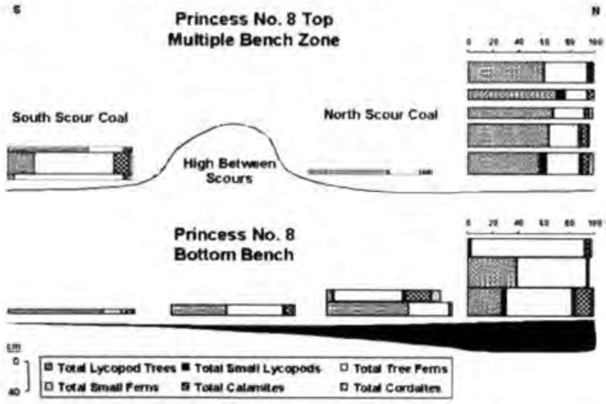


Figure 25. Palynological composition of coals at stop 1.

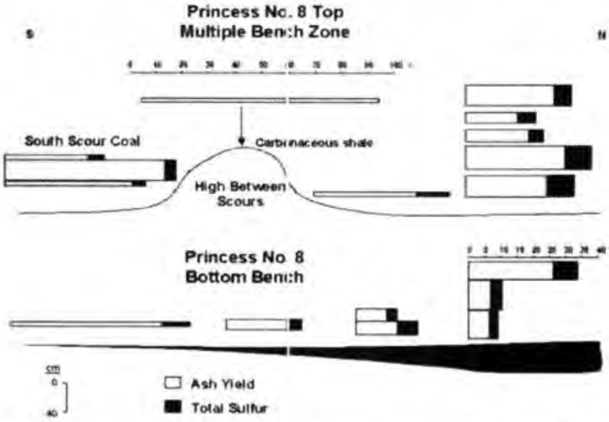


Figure 26. Geochemical composition of coals at Stop 1.

side of the northwest ramp to I-64. Outcrop C occurs on the south side of the ramp (Fig. 1).

Outcrop A. Fault and Heterolithic Paleochannel

The Princess No. 8 coal bed is exposed near the base of the outcrop. On the southern end of the outcrop there is a sharp offset in the coal, and the coal abruptly thickens on the downthrown side of the fault (Fig. 27A). The coal is only thick for a short distance, and then continues northward with little thickness variation. This is the coal that was surface-mined on both sides of the road, which results in the local flat topography. On the north side of this outcrop, a paleochannel cuts down toward the top of the coal (Fig. 27B). The paleochannel consists of laterally accreting and slumped sandstone and shale, which cuts the top of the Princess No. 8 coal bed.

Interpretation. The offset in the Princess No. 8 coal bed (Fig. 27A) is interpreted as a small listric fault. The lower part of the fault is covered, and it is uncertain how much strata was affected by movement along the structure. The local thickening of the coal has the appearance of a small-scale graben (deci-centimeters in width), indicating tensional stress during formation. Thickening of coals along faults has been noted throughout the coal field (Greb and Weisenfluh, 1996; Greb and others, 1999), and is related to the generation of local accommodation space during peat accumulation. A similar type of offset in the Princess No. 5 coal bed was noted by Ferm and others (1971) near Ashland, such that these types of offsets may be common in the Princess District.

Channeling at the north end of the roadcut (Fig. 27B) represents post-peat incision and fill by a small, mixed-load meandering channel. Slumping repeatedly followed lateral accretion, possibly as a result of rapid stage change within the channel. Mixed-load, relatively

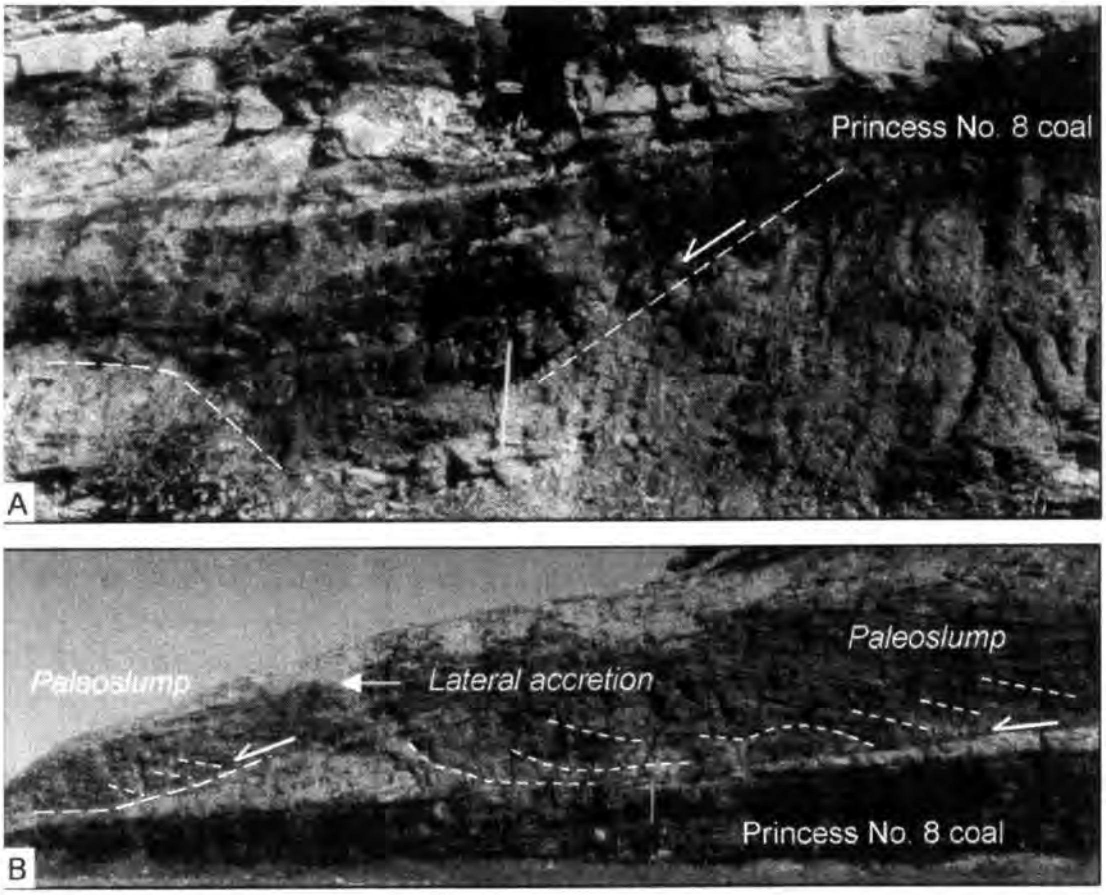


Figure 27. Outcrop A, Stop 2. A. Thick coal on down-dropped side of a small fault toward the southern end of the outcrop. Yard stick for scale (1 yd=0.9 m). B. Heterolithic paleochannel on the northern end of the outcrop exhibiting slumps between lateral accretion surfaces. Yard stick for scale (1 yd=0.9 m).

narrow paleochannels are common at this stratigraphic level.

Outcrop B. Merging Rather Than Splitting Coals

Across the road from outcrop A, there appears to be a southwestward split near the base of the Princess No. 8 coal bed (Fig. 28A). Upon closer inspection, it can be seen that the underclay of the Princess No. 8 coal bed actually cuts across the lower coal "split" (Fig. 28B). The truncation appears gradational because of paleosol development above the scour, but siderite nodules within the underclay of the upper coal can be traced laterally beneath the main coal bench, where the leader coal bench is missing. Also, examination of lithotypes in the leader coal bench are different than those in the base of the main coal benches north of the apparent split, such that they do not appear to split from the same bench.

The Princess No. 8 coal is actually composed of at least three smaller benches, each separated by rash (coaly shale) or gray silty shale. Tracing benches of the coal updip along the ramp of the apparent split shows that each bench thins, but the lower benches thin most. Palynologically, the Princess No. 8 coal at stop 2 is quite similar to the Princess No. 8 at stop 1, being dominated by *Lycospora* and tree fern spores (Fig. 29). The bottom part of the main bench is low in ash and sulfur, as is the

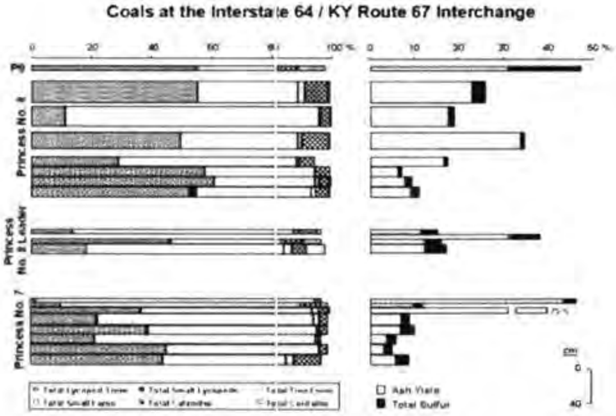


Figure 29. Palynology and geochemistry of coals at stop 2.

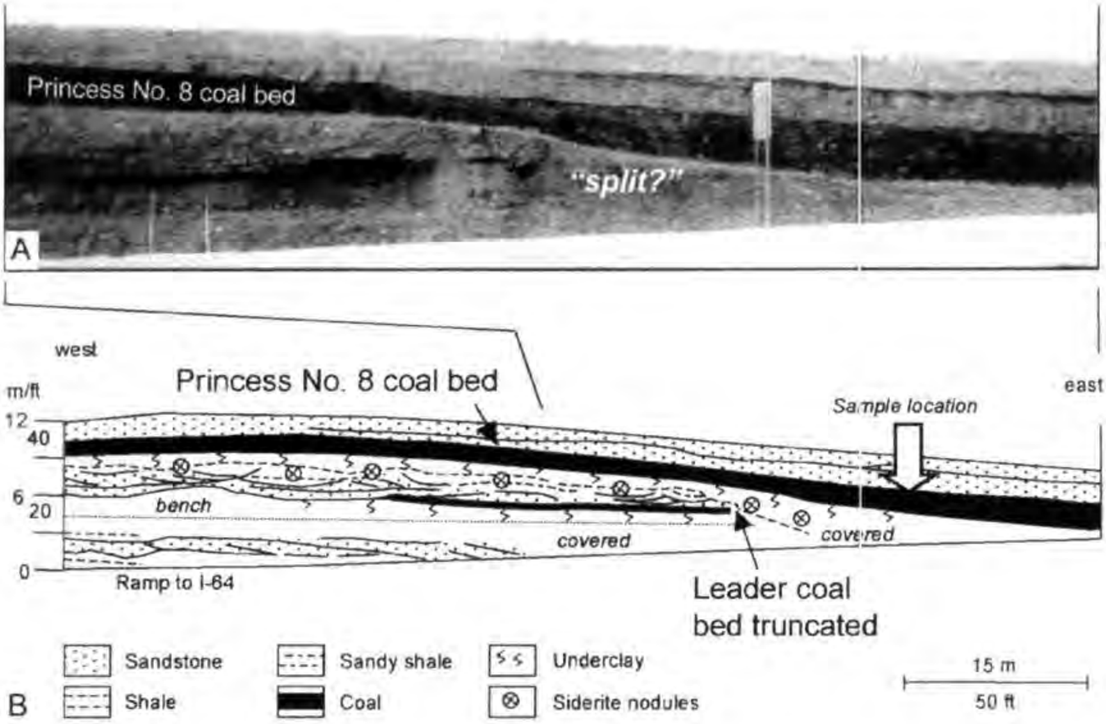


Figure 28. Outcrop B, stop 2. (A) Princess No. 8 coal apparently split along the westbound ramp to Interstate 64. (B) Diagram showing that the apparent split is actually truncation of the Princess No. 8 coal into an underlying coal along a scour beneath the No. 8 coal bed.

underlying leader coal, while the three top benches are high in ash.

Interpretation. Rather than a split in the coal caused by syndepositional clastic influx, this stop highlights an example of truncation and "merge." An exposure surface at the base of the Princess No. 8 coal bed truncated the underlying peat/coal (probably only a local unit) and the Princess No. 8 peat accumulated above the scour. The Princess No. 8 coal thickens down the wedge-ramp clastic interval between the two coals, into a presumed paleotopographic depression, similar to what was seen at stop 1, but here truncating an underlying coal because of locally low accommodation.

The Princess No. 8 paleomire at stop 2 that resulted in the Leader coal was spatially limited and short-lived. Most likely, peat began filling a local depression, prior to being terminated by sediment cover. The subsequent paleomire of the overlying main bench was better developed, and formed fairly thick, low-ash, low-sulfur coal. This bench was no doubt the principal target when this area was being mined. The top three benches of the No. 8 are much higher in ash, which reflects a change from little to no clastic influx during accumulation of the main peat bench to frequent sediment incursion during accumulation of the upperentering benches.

The truncation and merging of coals also shows one possible reason for correlation problems in the Princess Formation in northeastern Kentucky, as well as for coals in other low accommodation areas. In a borehole, this type of truncation and merge would most likely be attributed to splitting of a coal bed. Both coals are underlain by underclays of similar consistency, although more siderite nodules (root-related) occur in underclay beneath the overlying coal. The upper claystone thickens above the scour just as the coal does, and as seen at stop 1. In the Princess Reserve District, the thickest mined coal was often assumed to be the Princess No. 7 coal bed, which has a locally thick underclay. At this location, the Princess No. 8 coal is thick above a well-developed underclay because of local paleotopographic accommodation.

Outcrop C. Scour Fill and Princess No. 9 Coal

At outcrop C, the Princess Nos. 7 through 9 coals are exposed (Fig. 30A). The Princess No. 7 coal bed is exposed toward the base of the outcrop on the ramp to Interstate 64. The Princess No. 8 coal bed is overlain by a lenticular deposit of sandstone and shale, which thins westward. A scour filled with coal and carbonaceous shale occurs on the west-dipping slope of the lenticular deposit, cutting down near the top of the Princess No. 8 coal (Figs. 30A–B). The base of the scour is a nodular, siderite-cemented sandstone (Fig. 30B). The scour is filled with iron-stained (yellow and red) claystones, thin coals, and carbonaceous shales. Coals and coaly shales thicken into the center of the scour (Fig. 30B). The scour fill is capped by at least two horizons of claystones with large elongate siderite nodules and concretions. The claystone is overlain by green- and red-mottled clayey shales, which are truncated by another lenticular sandstone and shale, which thickens westward (Fig. 30A). Because the coals in the scour fill occur at the transition from gray shales and sandstones above the Princess No. 8 coal bed and variegated claystones typical of the Conemaugh Formation at the top of the outcrop, the coals are correlated to the Princess No. 9 coal bed. These coals are restricted to the scour fill at this location.

Palynologically, the Princess No. 9 coal is identical to the underlying No. 8 coal, though higher percentages of *Florinites*, which is cordaite pollen, are seen in the Princess No. 9 (Fig. 29). Geochemically, the Princess No. 9 coal bed is high in ash and sulfur, which isn't all that surprising given the ephemeral nature of the coal and the apparent infilling of a topographic depression at this location. As was mentioned previously, the Princess No. 9 is the last coal in stratigraphic sequence that contains *Lycospora*. The overlying Brush Creek coal is devoid of this genus, and instead is dominated by tree fern spores, as are most Late Pennsylvanian coals. This represents a major change in paleoflora composition that appears to be related to a change in climate from mainly wet to much drier (DiMichele and Phillips, 1994).

The upper lenticular sandstone has a sharp scour base. A thick lag of sideritic nodules occurs on the limb of the deposit. Where the scour cuts into the underlying green silty shale, the lag is apparently truncated by crossbedded, medium-grained sandstones. Sideritic granules and nodules are common along foresets and set boundaries within the crossbedded sandstone. Toward the top of the sandstone, sideritic rootlets and large ironstone masses occur above two crossbed set boundaries.

Interpretation. The two larger lenticular deposits above the Princess Nos. 8 and 9 coals (Fig. 30A) in outcrop C represent meandering paleochannels. The paleochannels are offset, indicating compactional controls on their position. Note also that the paleochannels are relatively narrow. Possible continuations of these paleochannels, or different channels, can be seen across the Interstate to the southeast. Narrow, incised paleochannels are common at several stratigraphic horizons along the Industrial Parkway, possibly reflecting low

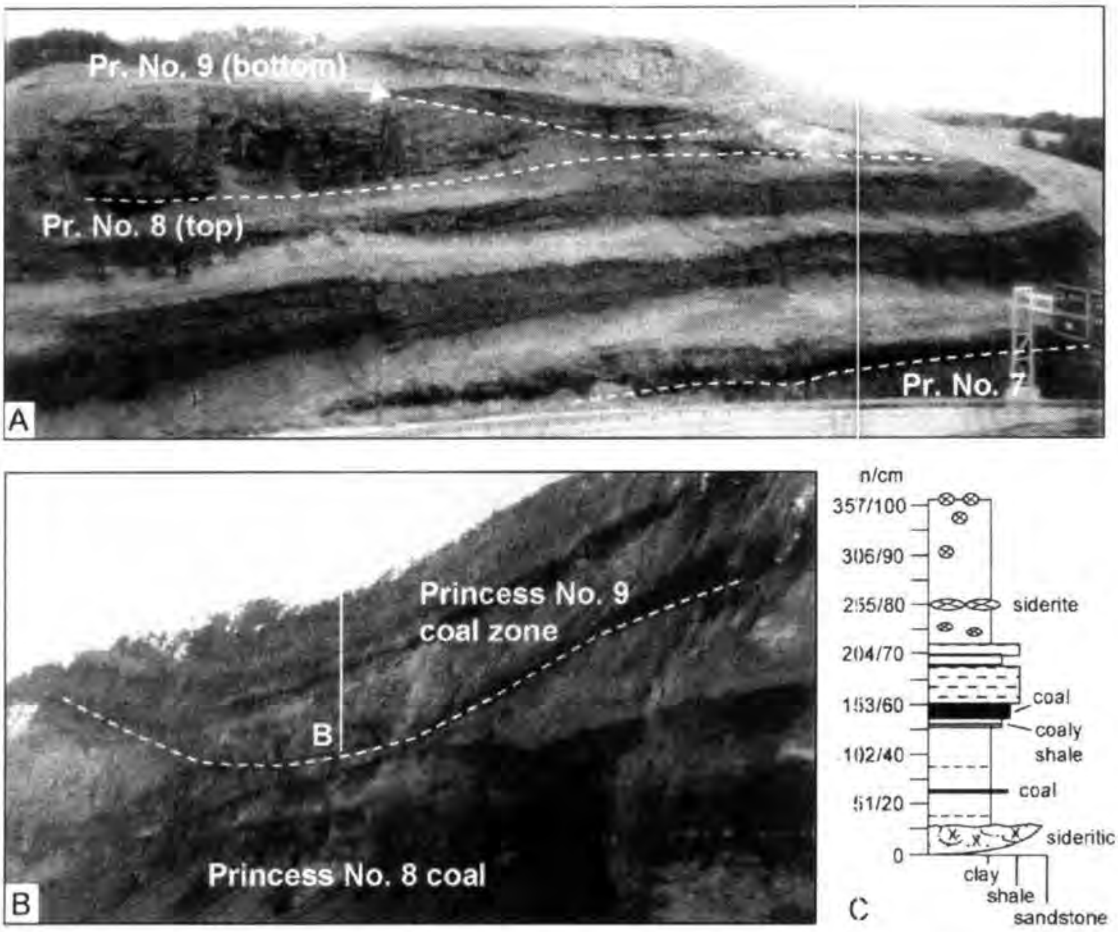


Figure 30. Outcrop C, stop 2. (A) Stratigraphic relationships of the Princess No. 7 (Pr. No. 7), Princess No. 8 (Pr. No. 8), and Princess No. 9 (Pr. No. 9) coals. Lenticular paleochannels above the Princess Nos. 8 and 9 coals are offset relative to each other. (B) Scour cutting toward the top of the Princess No. 8 coal is overlain by thin coals and carbonaceous shales of the Princess No. 9 coal zone. (C) Measured section through the axis of the scour fill (location shown in B).

accommodation and changing paleoclimate influences in this area. An interesting affect of the offset stacking pattern is that the red claystones of the Conemaugh come down closer to the top of the Princess No. 8 coal bed on the dipping slope of the lower paleochannel than was seen at stop 1. On the western margin of the outcrop, those shales are truncated by the upper paleochannel, such that no variegated shales are preserved and the lower boundary of the Conemaugh Formation would be difficult to delineate (without the lateral exposure).

The upper paleochannel (in the Conemaugh Formation) contains abundant sideritic nodules, probably from reworked paleosols beneath. In situ rooting may be represented by the larger concretions toward the top of the sandstone. The occurrence of apparently in situ siderite rootlets at set boundaries toward the top of the sandstone may document seasonal stage fluctuation within the paleochannel, with bar tops being vegetated between lateral dune migrations.

Whereas the merging coal benches in the Princess No. 8 coal at outcrop B were caused by truncation along a gently sloping ramp surface, the coal-filled scour in the upper part of outcrop C fills a narrow depression, similar to what occurs at stop 1, but here completely confined within the scour. As at outcrop B, truncation following Princess No. 8 peat burial causes another coal to come near the top of the underlying coal bed. It is easy to see that with only a little more incision the two coal horizons would have merged. It is certainly possible in this district, or in other areas of low accommodation, that overlying coals might completely replace underlying coal beds along such truncation surfaces, resulting in correlation problems. Downhole, this type

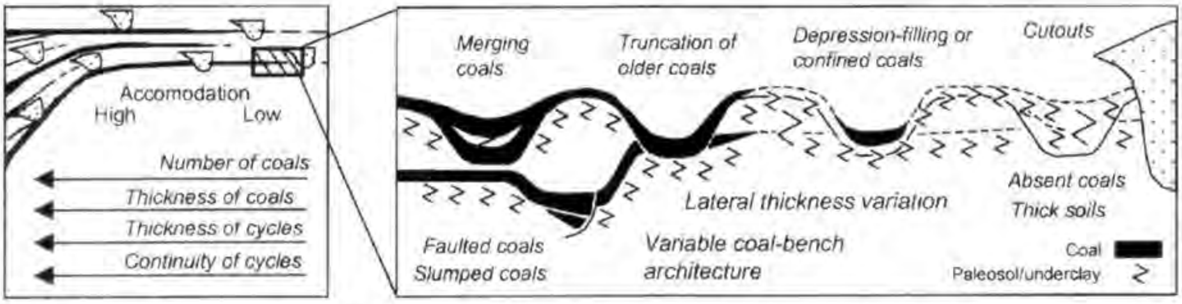


Figure 31. Summary diagram showing coal characteristics in low-accommodation settings.

of truncation would most likely be attributed to thickening of the Princess No. 8 coal, rather than to two separate coals.

At this one stop (outcrops A, B, and C), variability in coal attitude (changing dip and ramps), coal thickness, bench architecture, underclay thickness, coal-clastic cycle (allocycle) thickness, and continuity, can all be seen (Fig. 31). In low-accommodation settings, this type of variation may be common and can be attributed to strong paleotopographic influences on peat accumulation and clastic sedimentation.

Stop 3: Flying J Truckstop—Ky. 180, 0.25 Mile South of the I-64 Cannonsburg Exit (185)

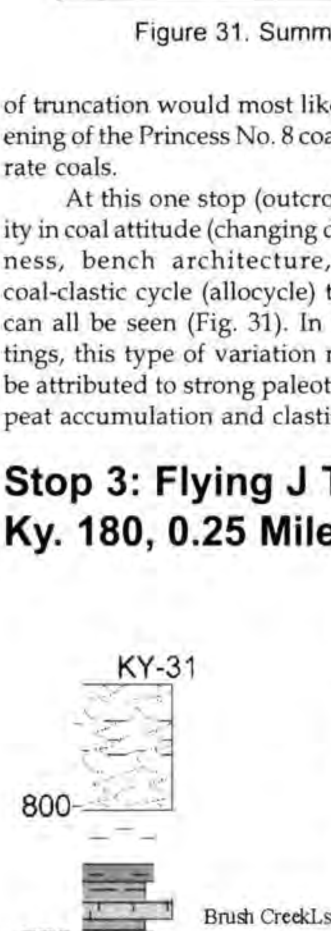


Figure 32. Stratigraphic column for stop 3.

Stratigraphic Correlations

The Brush Creek coal and overlying marine shale are exposed at the north end of this cut, but they are truncated in the middle of the cut by stacked channel sandstones interpreted as part of an incised valley fill (Figs. 5, 32). A coal mapped as the Princess No. 7 was mined in this area at an elevation of about 640 to 650 ft (195 to 198 m) (Boltsfork quadrangle; Spencer, 1964). The Brush Creek coal occurs at an elevation of 772 ft (235 m). This corresponds closely with the unnamed coal 110 to120 ft (33.5 to 36.6 m) above the Princess No. 7 that was used by Spencer as the top of the Breathitt Formation in his general stratigraphic column for the quadrangle. The coal at the base of the section correlates with what was mapped as the Princess 8 coal bed in the Boltsfork quadrangle. It should be noted that this coal comprises the upper portion of a paleosol with variegation (red/purple/green/gray) in the lower part. The position of this coal 55 ft (16.8 m) below the Brush Creek coal, along with the red-bed paleosols that occur in close proximity to it, suggest that it may be equivalent to the Mahoning Coal rather than the Lower Freeport (Rice and Hiett, 1994).

The beginning of the Stephanian was marked by a long-term climate change toward increased aridity in the Appalachian Basin, attributable to orogenesis and associated rain-shadow effects. These changes brought about widespread extinction of floras and the appearance of red-bed paleosols; both have been reported to occur between the Mahoning and Brush Creek Coals in Ohio and West Virginia.

Abundant marine fossils of the Lower Brush Creek limestone and shale occur in a 3.6 ft (1.1 m) interval that begins 5.6 ft (1.7 m) above the top of the Brush Creek coal. The fauna includes chonetid and productid brachiopods, bivalves, gastropods (especially *Pharkodontus*), cephalopods, and crinoids.

Sequence Stratigraphy

The paleosol beneath the Princess No. 8 coal is interpreted as an interfluvial sequence boundary (Sb2 in Figure 11), and only rarely is capped by coal. Fluvioestuarine channel sandstones occupy the interval between this horizon and the Princess No. 7 coal bed along the Interstate 64 westbound Cannonsburg exit ramp. The 23-ft (7-m) shale-dominated interval overlying the coal contains well-preserved plants at the base and coarsens upward, and is interpreted as a lacustrine facies. Base-level cycles in the coastal plain would be capable of producing such a sequence. Coals are known to onlap interfluvial sequence boundaries as water table and base level rise. In this regard, the coal is part of the TST, with the maximum flooding surface represented by maximum lake level (=depth). Lake-filling occurred during HST.

The interval from 33.5 to 63 ft (10.3 to19.2 m) contains individual and stacked paleosols split by what appear to be splay deposits. This is a complex interval that is interpreted as two overlapping interfluvial sequence boundaries. At nearby locations, the tops of individual paleosols in this complex are marked by carbonaceous shale or mudstone.

The Brush Creek Coal accumulated as the coastal-plain water table rose with transgression of the Brush Creek sea. The lower Brush Creek cyclothem and overlying strata are better illustrated at stop 5A . The lower Brush Creek marine unit is TST4 and HST4. It is truncated here by LST7 and TST7, associated with the Buffalo Creek Sandstone (Fig. 11).

Stop 4A: Interstate 64 East, Mile Marker 190.25, 0.5 Mile West of Catlettsburg Exit (191)

Stratigraphic Correlations

The coal at the base of the Interstate 64 roadcut at this stop occurs at an elevation of 567 ft (173 m) and corresponds to the Princess No. 7 coal bed, as mapped by Dobrovolny and others (1963). The section measured here continues up over the top of the I-64 roadcut and up through a second roadcut that existed along Ky. 3. The stratigraphic interval between the Princess No. 7 and the Brush Creek coal is 92 ft (28 m). At stop 1 the coal mapped as the Princess No. 8 was 88 ft (26.8 m) below the Brush Creek coal, so in all likelihood, these are the same coal beds. Palynologic analysis of both beds suggests that they are no older than the Princess No. 8; and the interval below the Brush Creek may be the Princess No. 9 coal bed. Dobrovolny and others (1963) used what is now recognized at the Brush Creek coal as the base of the Conemaugh Group (Fig. 33). The Princess No. 7 (probable No. 8) coal at this location correlates with the Upper Freeport Coal of Wayne County, W.Va., less than 1 mi to the east, as described and mapped by Krebs and Teets (1913) (Martino and others, 1996).

Sequence Stratigraphy

Strata from the Princess No. 7 (=Upper Freeport) to the red-bed paleosol are interpreted as TST1 and HST1 swamps and lakes formed as accommodation space was increased and maximized. Thin, cross-laminated sands are probably fluviolacustrine splays. Rhythmically laminated, shale draped siltstones with thick-thin bundles along with cross-stratified channel sandstones; southeast-directed paleocurrents suggest that estuarine facies are also present (Martino, in review) in nearby outcrops in West Virginia.

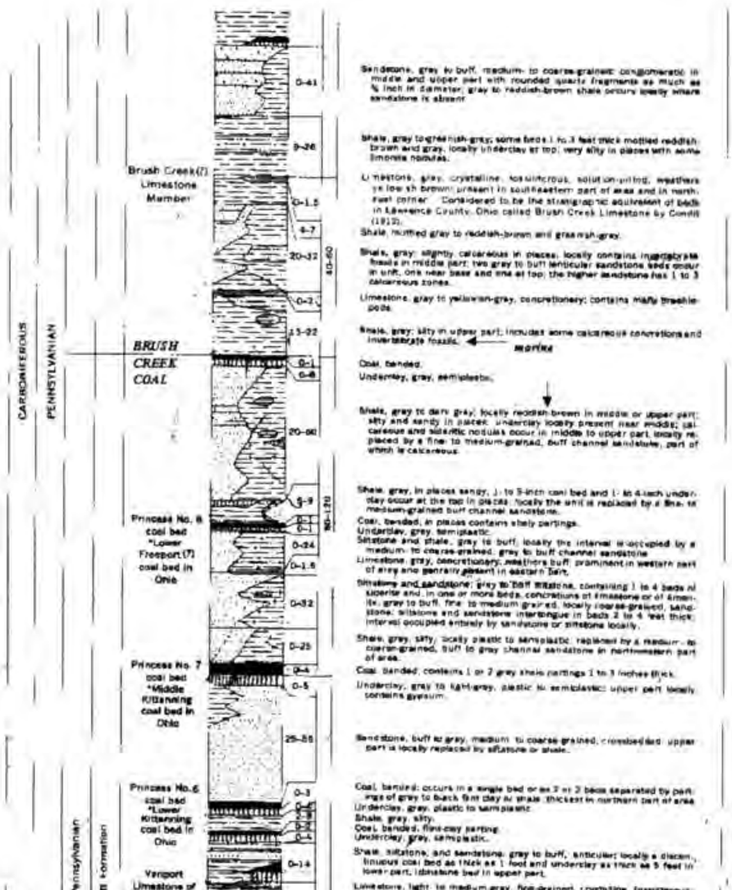


Figure 33. Stratigraphic column produced during geologic mapping of the Ashland quadrangle (Dobrovolny and others, 1963).

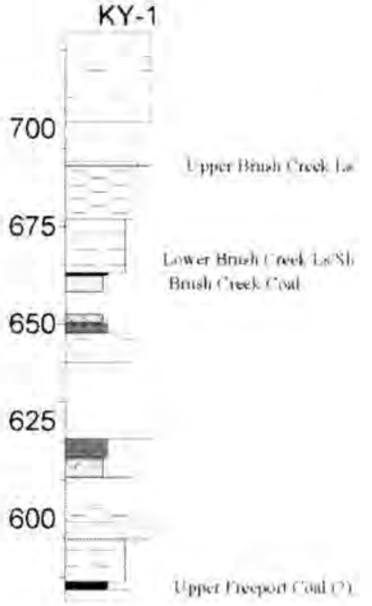


Figure 34. Stratigraphic column for outcrops at stop 4 (see also Figure 5).

Stop 4B: Ky. 23 South Roadcut—Southwest Side of Ky. 23/Ky. 3 Intersection

The paleosol marking SB2 in Figure 11 is accessible in the ditch along Ky. 23 just south of the intersection with Ky. 3. This paleosol occurs at the level of the Mahoning coal and represents a noncalcic vertisol and is capped by flood-basin sands and muds. A second exposure about 1,120 ft (341 m) west along Ky. 3 shows the thick compound paleosol interval below the Brush Creek coal. Paleosols within the lower part of this interval include red-variegated calcic vertisols. The Brush Creek coal in the Ky. 3 roadcut west of this is 7 in. (18 cm) thick. The coal is truncated here by a spectacular conglomerate containing a wide range of locally derived lithologies, including cobbles from the Upper Brush Creek and possibly the Cambridge limestones. This marks the base of the Saltsburg/Buffalo Sandstone IVF (LST/TST7-8; Fig. 5), which is at least 148 ft (45 m) thick at this location. Before the outcrop west of this cut was reclaimed, the unconformity as the base of this unit was observed to ascend at least 40 ft (12 m) into overlying strata. Strata overlying the conglomerate consist of stacked, mudstone-filled channels (Fig. 34). We will see these channel fills at stop 5B.

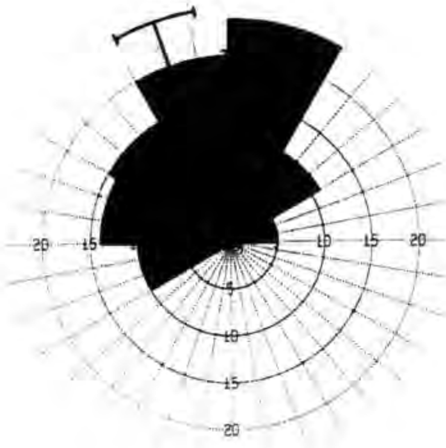
Stop 5A: Ky. 23 South—Mike Marker 9.3, 450 Feet South of Campbells Run Road

The Brush Creek coal exposed at the base of the cut is 15 in. (37 cm) thick and includes bright coal and carbonaceous shale. It is offset by a small fault at the north end of the cut. It overlies a thick paleosol complex and apparently represents drowning of a well-drained landscape in response to rising sea level. The coal is overlain by interlaminated, very fine sandstone and carbonaceous shale with plant fragments and rare pectinid bivalves. A narrow black shale band with intermittent limestone nodules represents the peak of the transgression (mfs) and caps the TST4. Fossils within the shale and limestone are similar to those observed at stop 3, but mollusks predominate, and chonetids and crinoids are rare at this location. The sequence coarsens upward from the black shale band through prodelta and mouth-bar facies, which comprise the HST4. The bench at the top of this cut marks the base of the Upper Brush Creek transgression. This interval is best exposed along Ky. 23 north of Campbells Run Road.

Stop 5B: Ky. 23 South, About 246 Feet North of Campbells Run Road

The Upper Brush Creek limestone is up to 16 in. (40 cm) thick and consists of a discontinuous graded bed of burrowed limestone with abundant very fine quartz sand and silt, and sparse crinoid plates. It occurs 35 ft (10.7 m) above the Brush Creek coal. The Upper Brush Creek marine zone (TST/HST 5) is about 26 ft (8 m) thick and coarsens up into sandstones with HCS, trough cross-stratification, and parallel lamination. Burrows including *Teichichnus* are common. The marine zone is capped by a hackly mudstone with micritic limestone nodules that may represent a paleosol, but is poorly exposed here.

Three stacked fluvioestuarine channel fills of the Buffalo-Saltsburg IVF systems make up the upper 23 ft (7 m) of the section here (LST/TST 7 and 8, Fig. 11). Incision removed important stratigraphic markers, including the Wilgus coal, Cambridge limestone, and Lower Bakerstown coal. The channel fills contain lateral accretion surfaces and abandoned channel mud plugs. Cross-stratification indicates paleoflow was toward the north-northwest (Fig. 35). Most of the sedimentologic features of the channel fills are consistent with meandering river systems. The local occurrence of clay-draped foresets, burrowing sand layers that



Calculation Method ... Frequency
Class Interval .... 30 Degrees
Filtering .... Deactivated
Data Type .... Unidirectional
Rotation Amount ...... 0 Degrees
Population 101
Maximum Percentage ... 23.8 Percent
Mean Percentage ...... 11.1 Percent
Standard Deviation ... 7.92 Percent
Vector Mean .... 341.12 Degrees
Confidence Interval .. 10.3 Degrees
R-mag 0.66

Figure 35. Paleocurrent data for the Saltsburg and Buffalo Creek Sandstones in the Huntington-Ashland area. These sandstones are interpreted as incised valley fills.

show thickening and thinning cycles are suggestive of tidal influence in an upper estuarine setting. IVF's cut during lowstands and filled during rising sea level typically contain fluvial facies that grade upward and downdip into estuarine facies (Fig. 10).

Stop 6: On Ramp to Ohio 52 at the North End of the West Huntington Bridge Over the Ohio River

This roadcut exposes the Cambridge marine unit (TST/HST6) at the base, which is capped by a thick paleosol (Sb7, Fig. 11). The Cambridge marine zone is more extensive in Wayne County than previously thought (Martino and others, 1996). Its underlying calcic vertisol is locally capped by the Wilgus coal and its equivalent. The single-story channel fill that overlies the Cambridge is 33 ft (10 m) thick and represents the Saltsburg Sandstone (LST/TST8). It contains large-scale northwest-dipping lateral accretion surfaces. Internal trough and planar cross-strata indicate flow toward the east-northeast. Clay-draped foresets and rhythmically laminated mudstone plugs suggest this is a fluvio-estuarine channel fill. The base of the Ames marine unit occurs about 82 ft (25 m) above the Cambridge. The Ames marine unit and bounding paleosols will be seen at stop 7.

Stop 7: Ohio 52 West, Mile Marker 0.3

The Pittsburgh Reds, a calcic vertisol sequence that is up to 16 ft (5 m) thick, is exposed at the east end of the cut. It is interpreted as an interfluvial sequence boundary (Sb8). Little relief occurs in association with the overlying splay sandstone, a 13-ft-thick (4-m-thick), very fine sandstone that contains plant fossils and burrows. It is separated from the Ames Shale by a compound paleosol (Sb9). Pedogenic carbonate (Bk, K horizons) at shallow levels are characteristic features of aridosols and indicate well-drained, semiarid conditions. The upper part of the soil is gleyed with a thin carbonaceous shale at the top. These characteristics are best explained by a rising water table that preceded transgression of the Ames sea. Marine fossils are abundant in the lower 12 in. (30 cm) of the Ames marine zone (mainly the brachiopod *Neochonetes grannulifer*, which readily weather out of the shale). A thin biomicrite about 12 in. (30 cm) above the base may represent the transgressive peak (mfs). It contains *Neochonetes*, *Derbya*, crinoid plates, and bryozoans. The rest of the marine zone is silty and/or sideritic, suggesting more rapid deposition, dilution, and perhaps high turbidity. Within the upper 20 in. (50 cm), wave ripples and HCS occur. The Ames marine zone is 23 ft (7 m) thick and is capped by an 8-ft-thick (2.5-m-thick) calcic vertisol (Sb10).

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Middle and Upper Pennsylvanian Stratigraphy, Sedimentology, and Coal Geology in Eastern Kentucky

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Introduction

This field trip will highlight roadcut exposures in northeastern Kentucky along the new Industrial Parkway (Ky. 67, exit 179) and along U.S. 23 (Fig. 1). This area is part of the Princess Coal Reserve District, in the northern part of the Eastern Kentucky Coal Field (Fig. 1). Most of the Princess District is situated north of a structural hingeline on the margin of the central Appalachian Basin. However, the bulk of eastern Kentucky's coal resources and mining occurs south of the hingeline. North of the hingeline, only coals of the Princess Formation (which are exposed at or near the surface) have been mined. Most of the Princess Formation coals are variable in thickness and coal-bench architecture. Coals in older formations south of the hingeline, in general, exhibit greater continuity in thickness and architecture. On this trip, the impact of tectonic accommodation will be discussed relative to coal distribution and sequence development in the Princess Coal Reserve District. The impact of paleoclimatic changes from the Middle to Late Pennsylvanian will also be highlighted. Differences in ash yield, sulfur content, and palynology accompany the Middle to Late Pennsylvanian transition as well. Thick claystones, formed through pedogenic processes, become more abundant in the Princess and overlying Conemaugh Formation, than in older deposits. Some of these paleosols are local resources of refractory grade clay. The importance of recognizing these interfluvial sequence boundaries in low accommodation settings will be another focus of the trip.

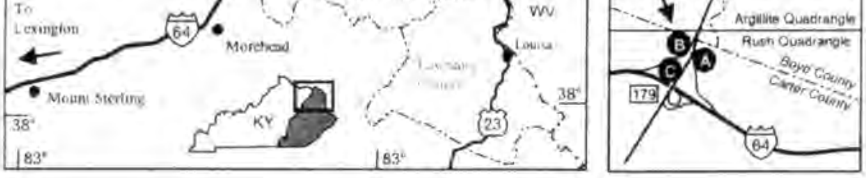


Figure 1. Location map of field stops. Detailed map shows locations of stops 1 and 2 on the Industrial Park road.

Regional Stratigraphy

Chesnut (1992a, 1996) elevated the Breathitt Formation to group status and divided the Middle Pennsylvanian coal measures into formations based on previously described, widespread, marine-shale members (Fig. 2). Many of the same marine units have also been used to revise correlations in surrounding states (Blake and others, 1994), and as key marker horizons for correlating coal beds between marine zones (Rice and Hiett, 1994; Rice and others, 1994; Martino, 1996). The bases of these marine zones are defined by regional marine flooding surfaces, and thereby can also be used to define genetic sequences (Greb and others, in press). Each genetic sequence is composed of five to six coal-clastic cycles (the interval from coal to coal), of similar scale to classic "cyclothems."

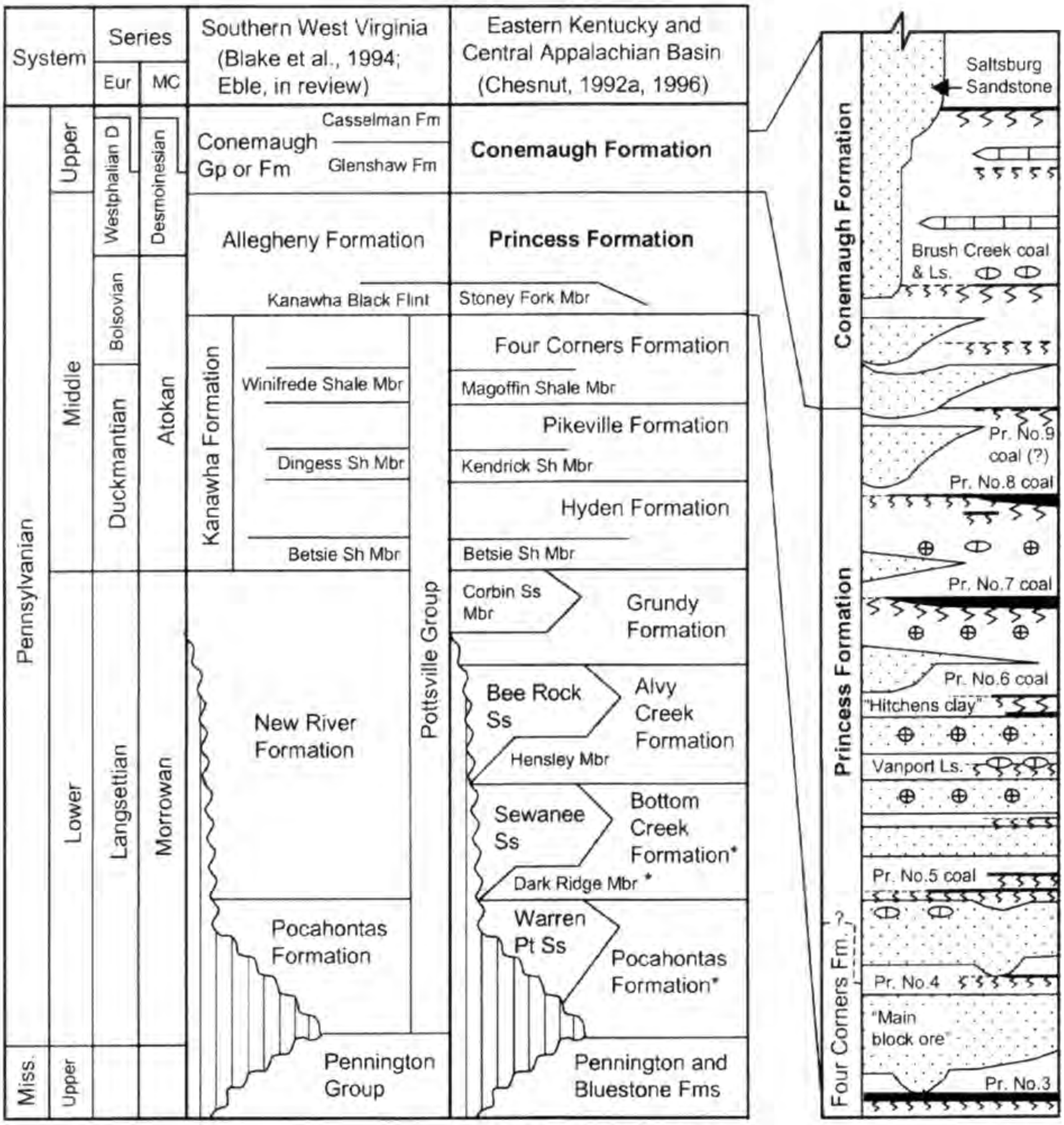
The Princess Formation is the stratigraphically youngest formation in the Breathitt Group (Chesnut, 1992a, 1996), and is generally less than 150 m (500 ft) thick. The base of the formation is the Stoney Fork Member, a marine shale (Fig. 2). Of the marine shales in the Breathitt Group, the Stoney Fork is perhaps the least persistent. This is especially true in the Princess Reserve District, where the unit is truncated or pinches out beneath sandstones above the Princess No. 3, or possibly Princess No. 4 coal beds (Fig. 2). The Stoney Fork may be equivalent to the Main Block Ore, an ironstone bed recognized between the Princess No. 4 and No. 3 coals in some parts of the Princess District (Fig. 2, Chesnut, 1992a), but this correlation is uncertain. Neither the Stoney Fork Member, Main Block Ore, or Princess No. 4 coal bed is a reliable marker horizon in the Princess District. Because of the lack of identifiable stratigraphic markers, the Princess Formation can be difficult to distinguish from underlying Breathitt Group formations in the Princess District. For practical mapping purposes, the contact can be placed above the Princess No. 3 coal bed.

The Princess Formation contains the Princess Nos. 4(?), 5, 5a, 5b, 6, 7, 8, and 9 coal beds (Fig. 2). Several of these beds are well exposed along Interstate 64, and are shown in section by Chesnut (1992b). On the drive to stop 1 (Fig. 1), the Princess No. 3 coal bed (in the upper part of the underlying Four Corners Formation) is exposed near road level between mile markers 174 and 175. Several thin coals, possibly equivalent in part to the Princess No. 4 coal bed (zone), occur above the Princess No. 3 coal bed between mile markers 176 and 177. The Princess No. 5 coal occurs as two beds in the Princess District, separated by clastics. The Princess No. 5 coal zone is exposed near road level in several outcrops between mile markers 177 and 178. Stops 1 and 2 of this trip will focus on new roadcuts exposed on the Industrial Park (Ky. 67) at exit 179 (Fig. 2). The Princess No. 8 coal bed will be seen at stops 1 and 2. The Princess Nos. 7 and 9 coal beds will be seen at stop 2.

The top of the Princess Formation is the top of the Princess No. 8 or No. 9 coal bed, or where absent, the base of the Conemaugh Formation in northeastern Kentucky (Fig. 2). The Conemaugh Formation is characterized by red and green shales and claystones, siltstones, sandstones, coals, and limestones. The base of the Conemaugh Formation is defined at the top of the Upper Freeport coal bed (Rice and Hiett, 1994), a coal that is not extensive in the Princess Reserve District. In addition, there is some question as to whether or not the Upper Freeport is equivalent to the Princess No. 8 or No. 9 coal. For practical mapping purposes, the top of the Princess Formation is generally defined at the first occurrence of green and red claystones, which are more typical of the Conemaugh Formation than the underlying Breathitt Group. The base of the Conemaugh Formation can be observed at stops 1 and 2 (Fig. 1), although it is mostly covered at stop 1. The Brush Creek coal and limestone horizon in the lower part of the Conemaugh (Fig. 2), will be seen at stops 3 and 4. Sandstones and paleosols within the Conemaugh will be seen at stops 4 through 7 (Fig. 1). Stops 6 and 7 will be in southeastern Ohio, across the river from Kentucky. Nearby, in West Virginia, the Conemaugh is elevated to group status and consists of the Glenshaw and Casselman Formations (Fig. 2). Stops in the Conemaugh on this field trip will be in the Glenshaw Formation equivalent in Kentucky.

Regional Tectonics

The central Appalachian Basin is a sub-basin of the Appalachian Foreland Basin (Fig. 3A). The central Appalachian Basin formed as a series of foreland basins, initially above the Rome Trough, which is a possible Precambrian aulocogen, and then enlarged in response to collisional tectonics along the eastern margin of North America during the Taconic, Acadian, and Alleghenian/Hercynian Orogenies (Tankard, 1986; Chesnut, 1991, 1994). The northern boundary of the Rome Trough is defined at the surface by the Kentucky River Fault System (Fig. 3A). South and subparallel to the Kentucky River Fault System, is the Irvine–Paint Creek Fault System (Fig. 3A). Faults in both systems exhibit overall down-to-the-south orientations. Stratigraphic thickness changes across the Kentucky River and Irvine–Paint Creek Faults have been used to infer that the structures acted as a hingeline (Fig. 3B) on the northern margin of the basin during the Middle Pennsylvanian (Ferm and Cavaroc, 1969; Donaldson, 1974; Horne, 1979; Powell, 1979, Donaldson and Shumaker, 1981; Donaldson and Eble, 1991). Lower Pennsylvanian strata (Grundy and lower formations in Fig. 3B) thin from more than 600 m (2,000 ft) in southwestern Virginia to less than 10 m (33 ft) in the Princess Reserve District (Fig. 2). Temporally, the rate of thickness change



* not preserved in Kentucky

Figure 2. Stratigraphic column for the Eastern Kentucky Coal Field, highlighting the Princess Formation, Breathitt Group, and Conemaugh Formation.

from the northern margin of the basin to the southern depocenter decreases from the Lower to Upper Pennsylvanian (Greb and others, in review), although the hingeline was still active during deposition of the Princess Formation. Northwestward thinning of Pennsylvanian strata resulted in thinning of all orders of sequences, pinchout and truncation of coal beds, and substantially fewer coal resources north of the hingeline than to the south.

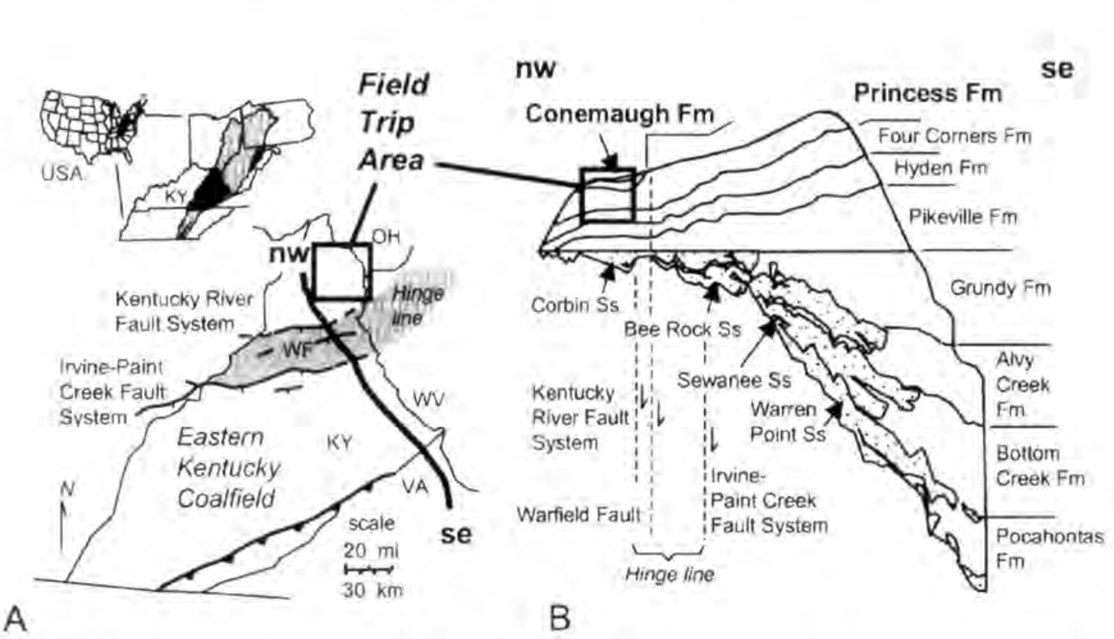


Figure 3. Structure of the Eastern Kentucky Coal Field. (A) Major structures of the Eastern Kentucky Coal Field, with the "hingeline" on the northeastern margin of the basin highlighted. (B) Cross section showing thickness changes of formations from the northern part of the coal field southeastward. Betsie Shale datum (modified after Chesnut, 1992a; Greb and others, in review).

Cyclothems

Cyclothems refer to vertically repetitive successions of strata, including coals, clastics, and carbonates. Pennsylvanian cyclothems were first investigated in the Illinois (Eastern Interior) Basin (Udden, 1912; Wanless and Weller, 1932). Similar groupings were also noted eastward into the Appalachian Basin (Wanless and Weller, 1932; Wanless and Shepard, 1936; Wanless, 1939). In general, Appalachian Basin cyclothems differ from their western counterparts in having fewer carbonates and a greater percentage of clastic deposition (Wanless and Shepard, 1936; Wanless, 1975; Heckel, 1986, 1995; Heckel and others, 1998). The best developed "cyclothems" in the basin are in Upper Pennsylvanian strata. The Brush Creek cyclothem will be seen at stops 3 and 4 (Fig. 2).

Late to Middle Pennsylvanian (Desmoinesian) and younger cyclothemic deposition has been attributed to tectonic controls (e.g., Weller, 1930), delta switching (e.g., Ferm, 1970), glacio-eustacy (e.g., Wanless and Shepard, 1936), and combinations of glacio-eustacy and tectonics (e.g., Klein and Willard, 1989). Eustatic controls are most commonly inferred (e.g., Heckel, 1995; Heckel and others, 1998; Ross and Ross, 1985). Using a mean duration for the Late Pennsylvanian, Heckel (1986) estimated that Midcontinent cyclothems and bundles of cyclothemic sequences fell within Milankovitch orbital parameters of 44 to 393 ka. Durations of 400 ka have been inferred for Appalachian Basin cyclothem-scale units (Chesnut, 1992a, 1994, 1996), and have been analyzed as fourth-order sequences (Aitken and Flint, 1994, 1995).

On this field trip, variability in the extent of coals and underclays will be shown to illustrate potential problems with correlation of fourth-order sequences (cyclothem-scale units) in low accommodation settings. The importance of recognizing persistent paleosols in the absence of coals will also be demonstrated.

Coal and Clay Resources

As mentioned previously, there are fewer coal resources in the Princess Reserve District than in coal districts to the south. Resource mapping by Brant (1982), using data collected during the geologic mapping program in Kentucky, indicates that the Princess No. 3 coal bed is the only coal with mineable thickness across most of the Princess Reserve District. The Princess No. 3 coal bed was estimated to contain 1 billion tons of original resources, and accounted for 30 percent of the resources of the district. The Princess Nos. 5, 6, 7, and 8 coal beds were each more pod-like and only locally thick. The Princess No. 5 coal bed was projected to have had original resources of 416,000 short tons; the Princess No. 6 coal bed had 224,000 short tons, the Princess No. 7 coal bed had 359,000 short tons, and the Princess No. 8 coal bed had 134,000 short tons of original resources (Brant, 1982). Much of the tonnage for these coal beds was in the thinnest category, from 14 to 21 in., which is only mineable by surface methods. Coal has been mined in the district since it was first settled (Spencer, 1964). Peak production from the Princess Formation in the district was 18.5 million tons in 1986 (Carey and others, 2001). In the 1980's, Addington Resources Inc. surface-mined much of the area around stops 1 and 2 (Fig. 1); this was the last coal mining in the district.

Underclays beneath the Princess Nos. 6 and 7 coal beds are locally thick and have been mined for use in brick and tile. These clays are thicker than most of the underclays south of the hingeline; this is possibly related to low accommodation north of the fault, and to paleoclimatic changes in the late Middle and Late Pennsylvanian (most coals mines south of the hingeline are Middle and Late Pennsylvanian in age). The clay beneath the Princess No. 6 coal bed is called the Hitchins clay bed. It may be several meters thick, but is characterized by variable composition and thickness (Dobrovolney and others, 1963; Spencer, 1964; Carlson, 1965; Ferm and others, 1971).

Coal Thickness Variability and Correlation Problems

Brant's (1982) isopach maps of the Princess Nos. 6, 7, and 8 coal beds illustrate the sporadic thickness of these units. Interestingly, in the Ashland, Boltsfork, Rush, and Webbville quadrangles, thick parts of these coal beds commonly occur in elongate pods oriented in east–west directions, parallel to the trend of the structural hingeline, although north of the major faults. In a previous field guide for the Princess Reserve District area, Ferm and others (1971) illustrated the variable distribution and thickness of claystones and coal beds in the vicinity of Ashland, Ky. Thinning of coal-clastic cycles northward, and truncation or pinchout of coal beds, claystones, and other marker horizons, all contribute to correlation problems within the district. Historically, any thick mined coal was called the Princess No. 7 coal bed, especially where the coal was underlain by a thick underclay. As will be seen at stops 1 and 2, however, the Princess No. 8 coal bed also can be thick, and locally has a thick underclay. Where underclays were not well developed, coals were numbered from the Princess No. 3 coal bed up, or the Conemaugh Formation down. Since many of the Princess Formation coals are absent across parts of the district, miscorrelations are possible. Variability in these units will be shown on this field trip to highlight the types of correlation problems that can occur in low accommodation settings.

Conemaugh Stratigraphy and Depositional Environments

The Conemaugh Formation of Kentucky is elevated to group status in adjacent West Virginia, where it is divided into the Casselman Formation (88 m, 290 ft thick) and the underlying Glenshaw Formation (73 m, 240 ft thick; Fonner and Chappel, 1987). The Glenshaw Formation constitutes the lower 73 m (240 ft) of the Conemaugh Group in the southern part of the Dunkard Basin (Martino and others, 1996). The current stratigraphic framework for the Glenshaw is based on key beds, including laterally persistent coal seams and marine units (Figs. 4–5). Four widespread marine units have been distinguished, including, in ascending order, the Lower Brush Creek, Upper Brush Creek, Cambridge, and Ames (Arkle and others, 1979; Merrill, 1986; Martino and others, 1996), but only the "Brush Creek" and Ames were used by geologists that mapped in the Princess Coal District.

The Glenshaw Formation contains channel sandstones, red and olive mudrocks, and coal that have been interpreted as having accumulated in an alluvial coastal plain with a northwest paleoslope (Arkle, 1974; Donaldson, 1979). Shallow marine and deltaic facies have been interpreted for fossiliferous olive-gray mudrocks and limestone and burrowed sandstones in the middle and uppermost parts of the Glenshaw (Donaldson, 1979; Martino and others, 1985, 1996; Merrill, 1986, 1988). Glenshaw facies and interpreted environments are shown in Table 1 (Martino, in review).

Paleosols

Field recognition of paleosols is based on the presence of soil horizons, soil structure, and/or root traces (Retallack, 1988). Glenshaw paleosols are very distinctive in outcrop due to their easily weathered, hackly, variagated appearance and horizonization (Martino, 1992). The paleosol type and degree of development (Table 2) are important in assessing their paleoclimatic and sequence-stratigraphic significance.

Strong soil development results in obliteration of relict bedding, whereas in very strong development the clayey (Bt) horizon is significantly greater than 1 m and is usually associated with major geological unconformities (Retallack, 1990; Fig. 6, Table 2). Most of the strongly developed paleosols in the Glenshaw exhibit features associated with vertisols and aridosols. Vertisols usually are associated with low-relief terrain and subhumid to semiarid climates (18–152 cm rainfall/year) with a pronounced dry season. Aridosols develop in semiarid to arid regions and commonly have shallow calcareous horizons (Retallack, 1990). Histosols

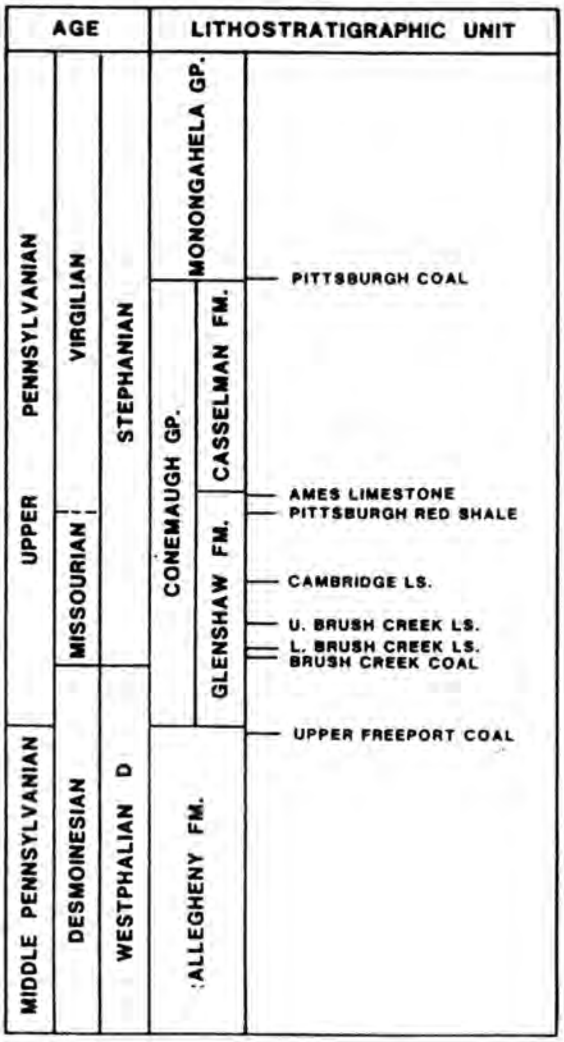


Figure 4. Stratigraphic framework for the Glenshaw Formation in the southern portion of the Dunkard Basin (from Martino and others, 1996).

are distinguished by thick surface organic (O) horizons and are represented by coals and carbonaceous shales where the precompaction thickness was at least 40 cm. The local, pod-like geometry of many Glenshaw coals suggests a rolling or undulatory topography.

Compound paleosols occur where individual paleosol units become vertically stacked into a paleosol zone. Two kinds of paleosol zones occur within the Glenshaw Formation: (1) stacked paleosols of the same type, and (2) stacked profiles representing two different types of soils. The first type is evident in multiple-bedded coal seams with rooted shale or sandstone splits. The second type of paleosol zone is commonly represented by an aridosol or vertisol that is capped by a histosol. These instances represent two separate phases of soil development and reflect a rise in water table, which in many cases was associated with rising sea level, as indicated by shallow-marine roof rock.

The most obvious impact of climate on rocks of the Princess and Conemaugh Formations is a change in color, with the appearance of pedogenic redbeds signaling a shift toward drier, better-drained soils. Sea-level fluctuations took place throughout the Pennsylvanian, but during the Lower and most of the Middle Pennsylvanian, precipitation levels were sufficient to maintain high levels of soil moisture. A long-term shift to drier climates in the central Appalachian Basin began toward the end of the Middle Pennsylvanian and continued into the Late Pennsylvanian. Increasing relief of the Appalachian Mountains and rain-shadow effects have been suggested as a likely cause for this long-term trend (Opdyke and DiVenere, 1994). Superimposed on this long-term change were short- and intermediate-term climate cycles (10,000's to 100,000's of years) that have been attributed to astronomical factors involving the orbital eccentricity of the earth and cyclic variation in axial tilt and precession. These types of cycles have been invoked to explain the vertical juxtaposition of calcic vertisols and histosols (Cecil, 1990; Cecil and others, 1994). A link between climate and sea level is widely perceived to be important, but various workers differ in whether highstands were wetter (Busch and Rollins, 1984; Busch and West, 1987; Heckel, 1995) or drier (Cecil, 1990; Cecil and others, 1994). Within the Glenshaw Formation, noncalcareous red-mottled vertisols appear at the level of the Mahoning coal, while calcic, red-mottled vertisols first occur a few meters below the Brush Creek Coal.

Glenshaw Sequence-Stratigraphic Model

Previous workers have interpreted 11 fifth-order allocycles to be within the Glenshaw Formation in Ohio and Pennsylvania (Busch and Rollins,1984; Busch and West, 1987; Fig. 7). Recent work in eastern Kentucky and West Virginia suggests that nine of these allocycles are distinguishable in the southern Dunkard Basin and can be incorporated into a sequence-stratigraphic framework (Martino, in review; Fig. 8).

In siliciclastic basins, sequence boundaries are typically represented by laterally continuous, basin-wide, or interbasinal surfaces that are distinguished in shelf settings by the presence of erosional truncation, subaerial exposure, and a basinward shift in facies. Incised drainage lines formed during lowstands of sea level produce erosional truncation. The erosional surface associated with incised valleys passes laterally into

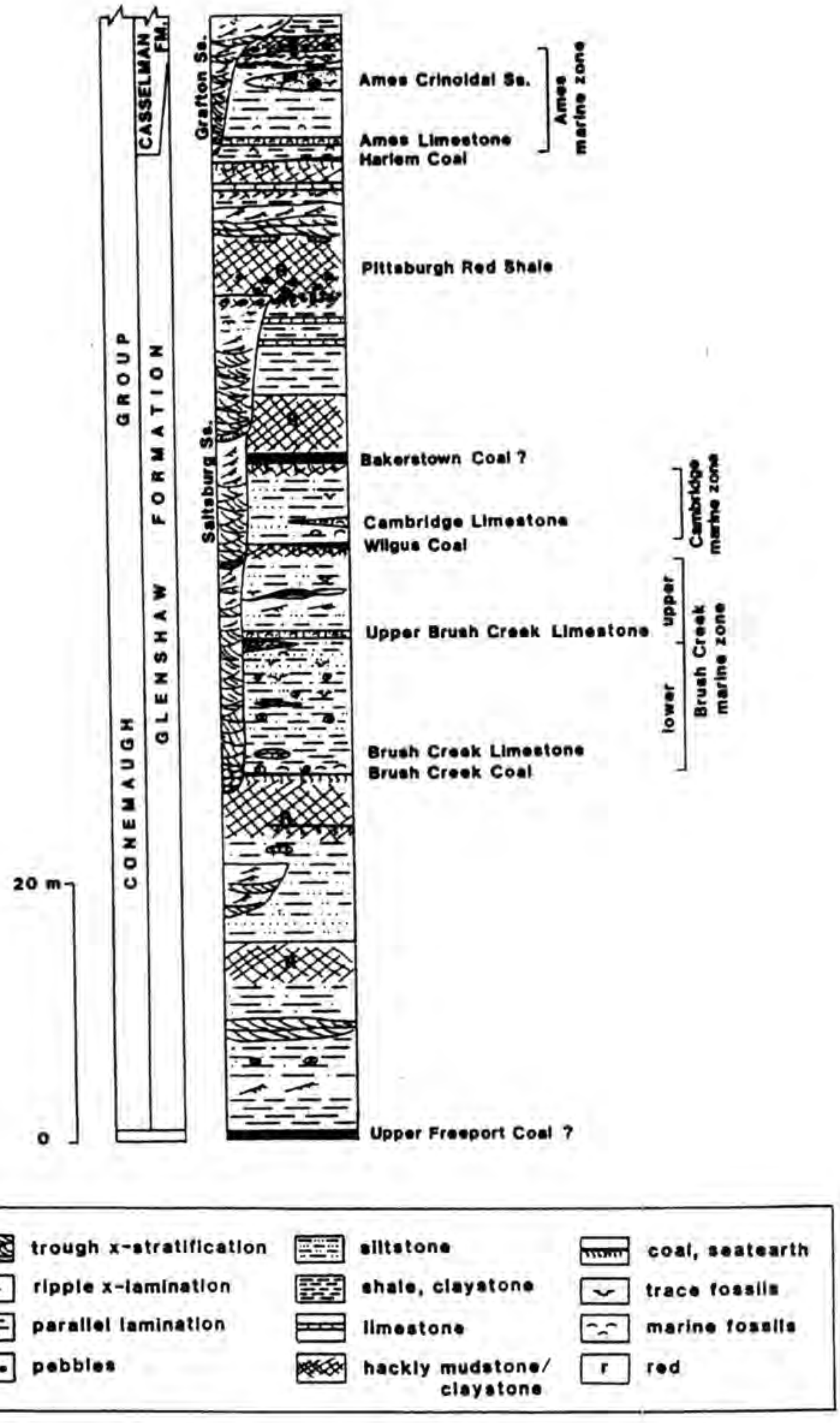


Figure 5. Composite stratigraphic section for the Glenshaw Formation in the vicinity of Huntington, W.Va. (Martino, 1992; Martino and others, 1996).

Table 1. Summary of Glenshaw facies attributes.

Facies	*Lithology*	*Sedimentary Structures*	*Geometry*	*Fossils*
Fluvial/ Deltaic Channel	vf-v.cs sandstone, rarely conglomeratic;	x-strat: trough + tabular sets; compound (epsilon) x-beds	channelform ribbon; 6–10 m thick	rare burrows; plants
	shale/mudstone plugs	laminated/hackly		
Estuarine Channel	md-vf sandstone	x-strat w/ clay-draped foresets; parallel lamination w/ thick-thin bundles	6–10 m	rare burrows
Flood Basin (a) Crevasse splay/levee	f-vf sandstone-shale	scour-fill trough sets, ripple x-lamination; parallel lamination	tabular-wedge shaped; channels 1–4 m thick	plant fragments
(b) Lakes	shale, siltstone, micritic limestone	laminated to massive	pods, sheets	*Lockeia sinusites*
(c) Mires	coal, carbonaceous shale	laminated	pods, sheets	ostracodes, *Spirorbis*, *Conchastracus*, plants, coprolites, stromatolites, vertebrate fragments
Offshore marine	shale, limestone, siltstone	thin-bedded, graded bedding	sheets	brachiopods, bivalves, gastropods, echinoderms, bryozoans, cephalopods, conodonts, fusilinids
Shoreface	shale, siltstone, vf ss,	thin-bedded, ripple bedding, parallel lamination, HCS	elongate/lobate	*Wilkingea*, *Paleophycus*, *Aulichnites*, *Teichichnus*, *Rhizocorallium*
Mouth bar	shale, siltstone, vf ss siderite nodules	thin-bedded, parallel lamination, graded bedding, parting lineations, HCS	lobate	*Curvolithus*, plant fossils
Sand bar/ shoal	vf sandstone	highly bioturbated; rare trough x-strat	elongate	crinoids, brachiopods, gastropods+

Table 2. Stages of paleosol development (from Retallack, 1990).

Stage	*Features*
Very weakly developed	Little evidence of soil development apart from root traces; abundant sedimentary, metamorphic, or igneous textures remaining from parent material
Weakly developed	With a surface rooted zone (A horizon) as well as incipient subsurface clayey, calcareous, sesquioxidic or humic, or surface organic horizons, but not developed to the extent that they would qualify as USDA argillic, spodic, or calcic horizons or histic epipedon
Moderately developed	With surface rooted zone and obvious subsurface clayey, sesquioxidic, humic, or calcareous or surface organic horizons: qualifying as USDA argillic, spodic, or calcic horizons or histic epipedon and developed to an extent at least equivalent to stage II of calcic horizons
Strongly developed	With especially thick, red, clayey, or humic subsurface (B) horizons or surface organic horizons (coals or lignites) or especially well-developed soil structure or calcic horizons at stages III to V
Very strongly developed	Unusually thick subsurface (B) horizons or surface organic horizons (coals or lignites) or calcic horizons of stage VI: such a degree of development is mostly found at major geological unconformities

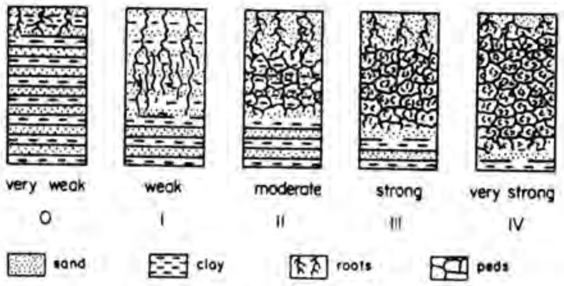


Figure 6. Stages in the formation of clayey subsurface soil horizons (Bt) in mixed clayey and sandy alluvium (from Retallack, 1990).

a correlative paleosol formed during subaerial exposure (Van Wagoner and others, 1990). These paleosols represent condensed sections formed in terrestrial settings due to low rate of deposition or nondeposition. Rejuvenation and incision of rivers would sharply reduce or eliminate sediment to interfluvial uplands and would be expected to accompany falling relative sea level or tectonic uplift.

A critical feature of Glenshaw paleosols that mark sequence boundaries is that they characteristically exhibit evidence for well-drained conditions and apparently were subsequently drowned. This is illustrated by a common vertical facies sequence observed in the area of this study, which is (1) vertisol or aridosol, (2) coal/histosol, (3a) marine shale, or (3b) lacustrine shale and/or limestone. In some cases (2) is missing, and lacustrine or marine facies directly overlie the paleosol. This indicates initially low water tables that subsequently rose to inundate the topography. Busch (1984) reached a similar conclusion for Glenshaw paleosols representing allocycle boundaries in the northern Dunkard Basin. Rising sea level may have led to a wetter climate, which also helped to raise the water table in the coastal plain (climate change surfaces of Busch, 1984; Busch and West, 1987), a viewpoint that was subsequently supported by Heckel (1995).

Valley fills are elongate cut-and-fill bodies that are larger than a single channel. In valley fills formed by relative sea-level change, the valley wall and floor represent type I sequence boundaries and the fills typically include some evidence for marine influence. Simple valley fills are produced by a single relative sea-level cycle. In compound valley fills, more than one sea-level cycle may take place during valley filling. This can produce a complex mixture of fluvial facies of varying styles, estuarine facies, and possibly shallow-marine facies within the valley fill.

Channel fills may also develop during regression as coastal-plain drainage systems override shoreline and shallow-marine deposits. In these cases, channel

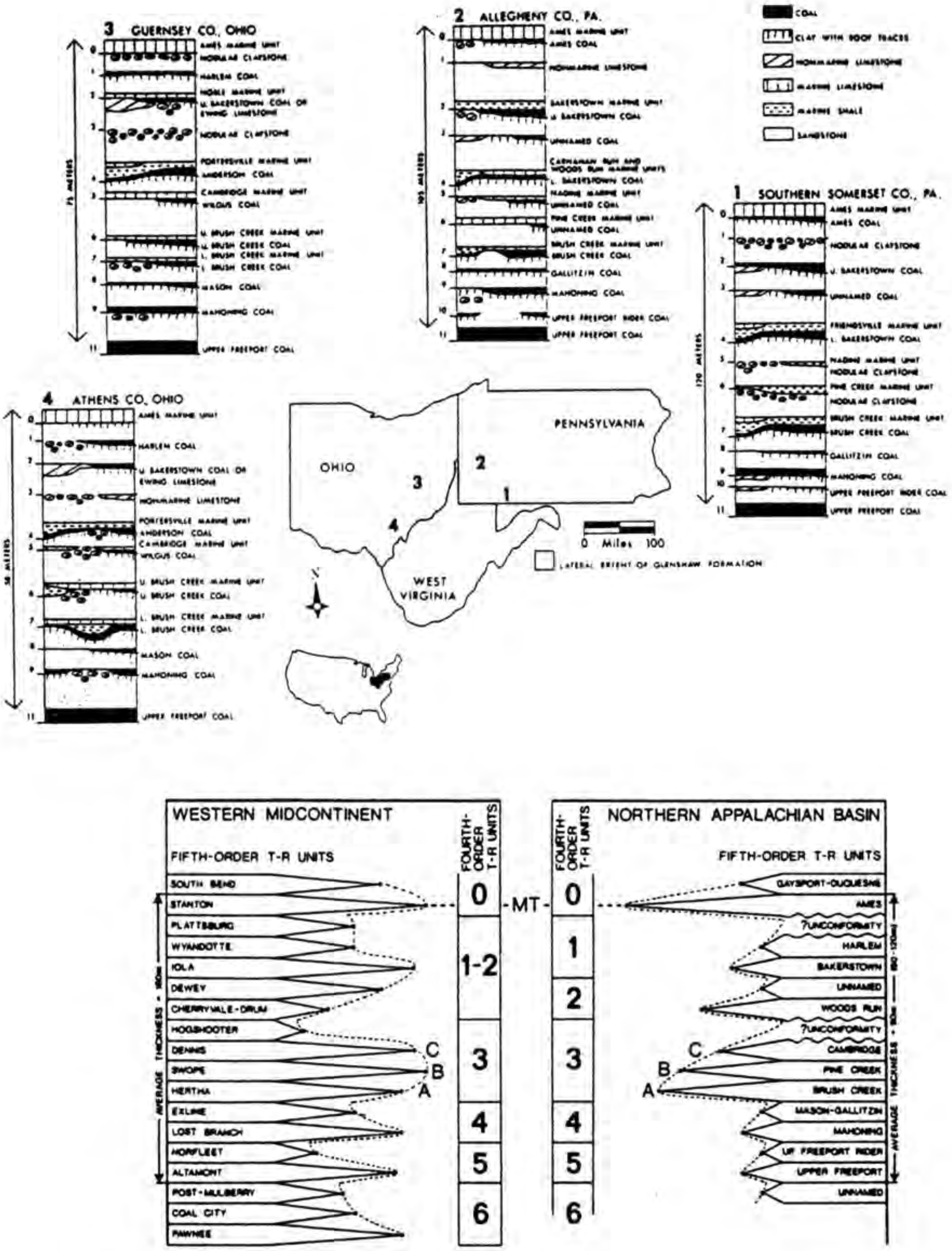


Figure 7. Eleven fifth-order T-R allocycles of Busch and West (1987) recognized in the Glenshaw Formation of Pennsylvania and Ohio.

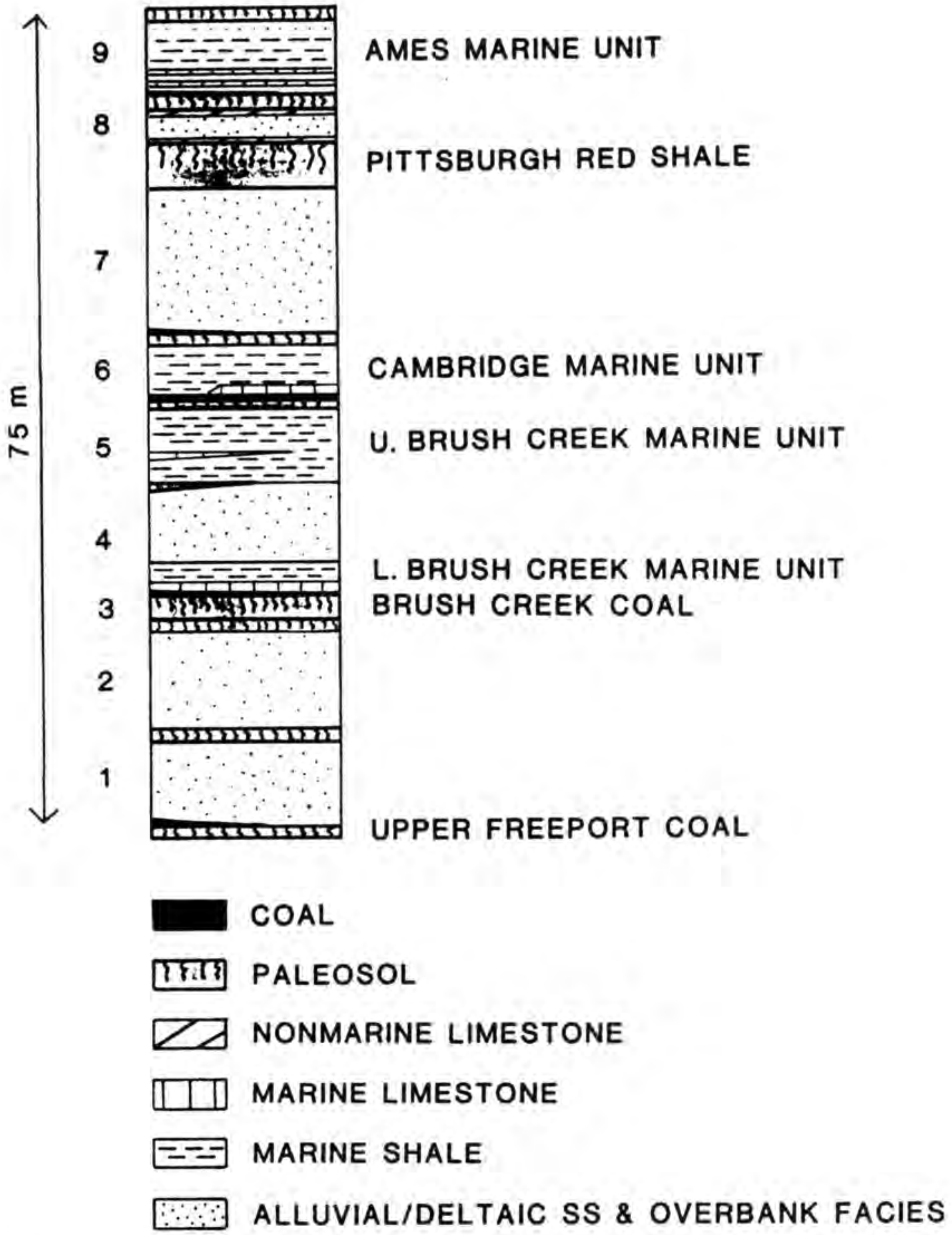


Figure 8. Composite section of the Glenshaw Formation in the Huntington, W.Va., area showing nine paleosol-bounded allocycles (Martino, 1998). Channel- and valley-fills are omitted for simplicity. Section is 75 m thick.

sands will represent coarse members within coarsening-upward sequences deposited during sea-level highstands. This pattern of sedimentation is usually terminated by a fall in base level and fluvial incision (Miall, 1997). Glenshaw strata can be interpreted using the following model (Fig. 9):

(1) During lowered base level associated with sea-level lowstands, coastal-plain rivers downcut, leading to valley incision; sediment bypassing of interfluves leads to pedogenesis; a lowered water table (following falling river and sea level) leads to well-drained conditions for soil development. A type 1 sequence boundary forms, marked by erosional disconformity along the paleovalley and the top of the well-drained paleosol on interfluve.

(2) Rising sea level and base level initiates aggradation of the fluvial system within the paleovalley (LST); and pedogenesis continues on interfluves.

(3) Continued rise in sea level/base level leads to a rising water table; standing shallow water results in peat accumulation where clastic influx remains low; later stages of valley filling associated with high-sinuosity streams commonly show evidence of tidal influence (TST). Completion of valley filling allows the alluvium to begin spreading out over interfluves that had been sediment starved up to this point. Lakes develop in the coastal plain where water depth becomes too great to support standing vegetation, whereas marginal- to shallow-marine environments onlap downdip (TST).

(4) During sea-level highstand, rapid aggradation of the coastal plain occurs in association with high accommodation space. This produces isolated, high-sinuosity fluvial channel deposits encased in overbank fines (Shanley and McCabe, 1993; Fig. 10). Regression occurs within marine units during highstand once estuarine sediment sinks are filled. Deltaic channels and mouth bars may form locally during late highstand.

(5) Incision of fluvial drainage lines into the HST coastal plain and sea-fill deposits occurs in response to falling sea level/base level. Between rivers, withdrawal of the sea leads to exposure and pedogenesis of shallow-marine or flood-basin facies, producing the next sequence boundary.

The distinction between HST coastal-plain channel systems and LST/TST valley fills may be possible by the presence or absence of thick, mature paleosols above the channel fills. If present, they suggest channels formed during sea-level highstand as the coastal plain aggraded and prograded. If mature, well-drained paleosols are absent above a stacked channel deposit, it suggests valley incision and filling took place with coeval pedogenesis on adjacent interfluves. Rising base level may have allowed for infilling of valleys and peat accumulation. In this way, coal seams would develop across the region, but the same seam would overlie well-drained paleosols on former interfluves and hydromorphic paleosols above the valley fills (Fig. 9).

A generalized illustration of Glenshaw stratigraphy is shown in Figure 11. Nine fifth-order stratigraphic sequences are identified. The tops of well-drained paleosols are used as sequence boundaries and correspond to allocycles previously reported (Martino, 1998; Fig. 8). Sequence boundaries and systems tracts are numbered in vertical succession (SB1, LST1, TST1, HST1; SB2, LST2, etc.).

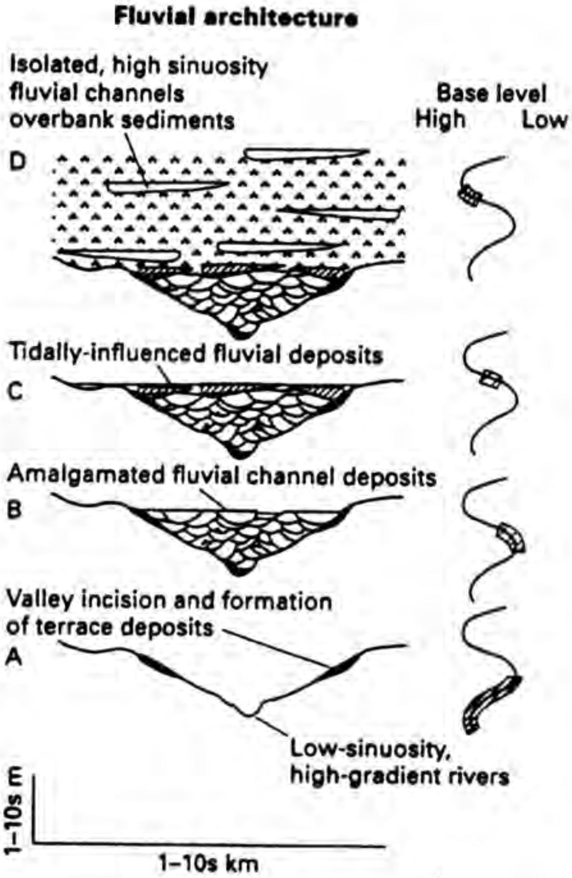


Figure 10. Model for development of an incised valley fill (Shanley and McCabe, 1993). Tidal influence occurs as estuaries succeed fluvial systems within the valley. Once aggradation expands onto interfluves, a much lower channel/overbank ratio occurs.

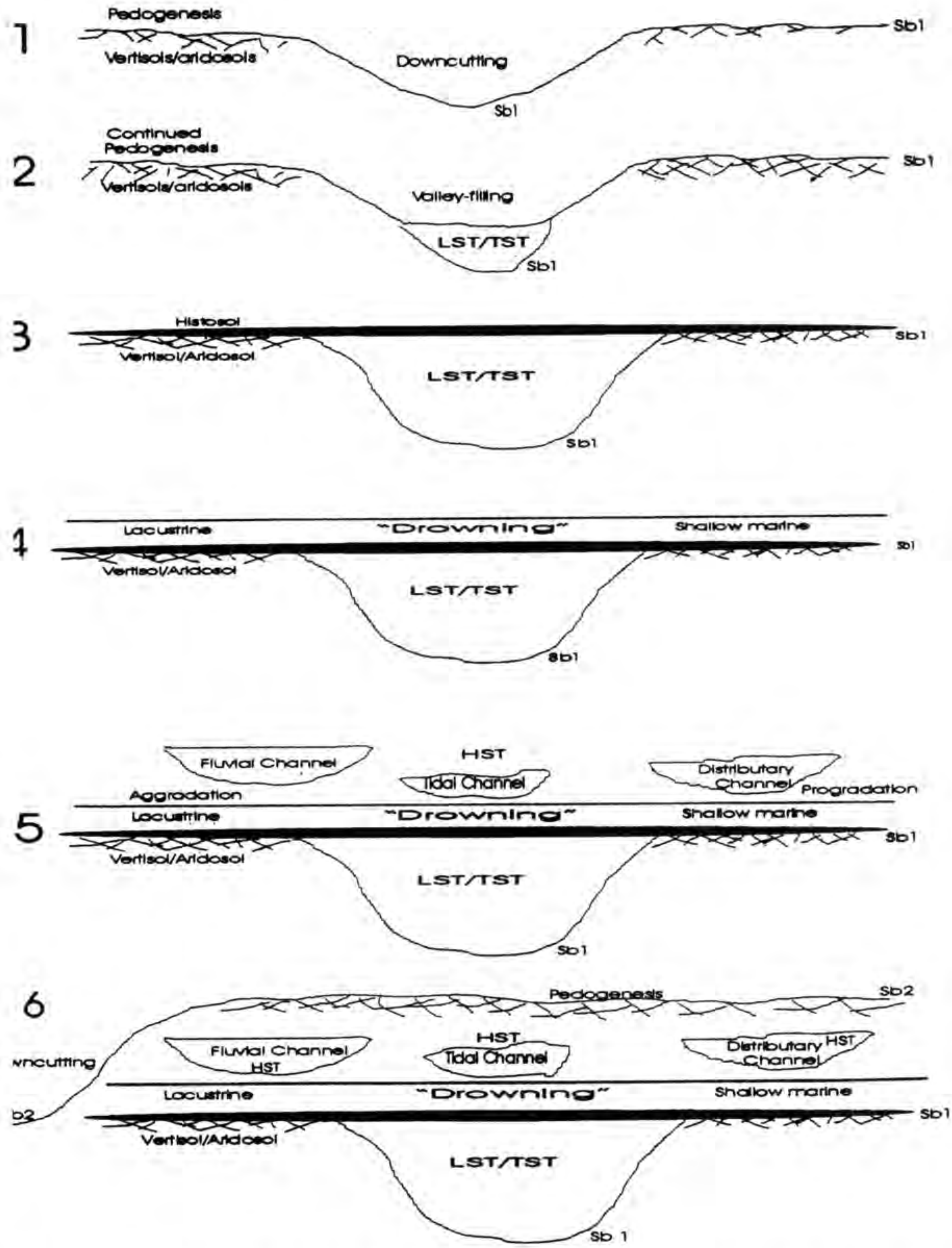


Figure 9. Sequence-stratigraphic model for Glenshaw Formation. Sequence boundaries (Sb) develop at the top of well-drained paleosols formed on interfluves during lowstands, and pass laterally into erosional disconfomities of incised valleys. LST, TST, and HST include lowstand, transgressive, and highstand systems tracts.

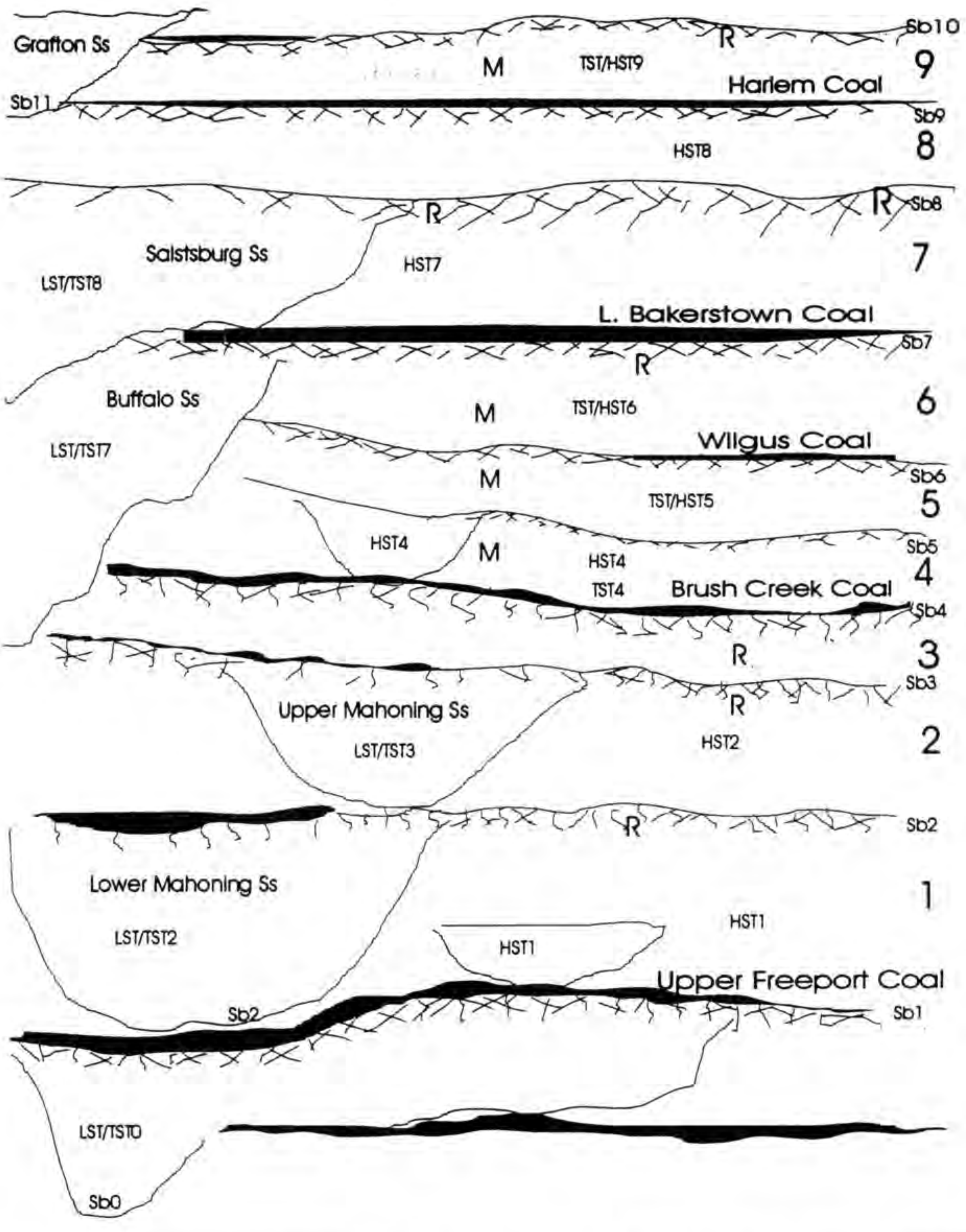


Figure 11. Sequence-stratigraphic model for the Glenshaw Formation and Upper Allegheny Formation at the south-western end of the Dunkard Basin. Numbers 1 to 9 at right identify Glenshaw Formation sequences and correspond to paleosol-bounded allocycles in Figure G.

Palynology of Coal Beds in Northeastern Kentucky

Coal palynology has long been of value in helping to identify and correlate Pennsylvanian coal-bearing strata. This technique primarily relies on the identification of stratigraphically constrained spores and pollen, although some beds can be identified and separated from adjacent beds based on the relative abundance of otherwise common, long-ranging forms. Coal palynology is also a very useful tool in reconstructing the ancient floras that inhabited late Carboniferous mires. As we travel east from Lexington on Interstate 64, we will transect Pennsylvanian-age coal-bearing strata between mile markers 149 and 191. The following is a discussion of the palynology of the coals we will see and examine on this field trip. Please refer to the included roadguide for Interstate 64 by Chesnut (1992b) for geologic and geographic reference.

The stratigraphically oldest Pennsylvanian-age coals along I-64 occur just above the Olive Hill Flint Clay, a refractory-grade clay that marks the Mississippian-Pennsylvanian systemic boundary in northeastern Kentucky. Palynologically, these coals are variable in composition (Fig. 12). An unnamed coal bed at mile marker 152.3 contains abundant *Densosporites* (47 percent), a type of spore that was produced by a small lycopod tree called *Omphalophloios* (Fig. 13). In contrast, another unnamed coal at mile marker 166 is dominated by *Lycospora*, especially *Lycospora pellucida*, which was produced by *Lepidophloios harcourtii* (Fig. 14). Other palynomorphs present in these coals that are helpful biostratigraphically are *Laevigatosporites minor* and *Punctatisporites minutus*, both of which suggest a late Langsettian (late Morrowan) or Early Duckmantian (early Atokan) age assignment (Fig. 12). This indicates that a substantial unconformity exists between the Mississippian and Pennsylvanian in northeastern Kentucky. Over 500 m of Lower Pennsylvanian rocks assigned to the Pocahontas and New River Formations in the proposed Pennsylvanian stratotype area of southern West Virginia (Englund and others, 1979) are missing in northeastern Kentucky (Fig. 3B), as are a great deal of Mississippian strata. For example, at mile marker 152 along Interstate 64, the Olive Hill Clay rests directly on the Nada Formation, which directly underlies the Newman Limestone (=Greenbrier Limestone). As such, nearly 1,400 m of Upper Mississippian strata (Bluestone Formation, Princeton Sandstone, Hinton Formation, Bluefield Formation and Greenbrier Limestone) that are present in the stratotype area are also missing in much of northeastern Kentucky.

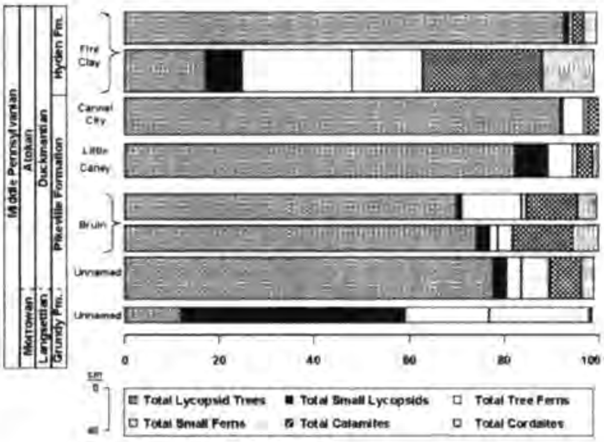


Figure 12. Miospore composition, grouped together according to botanical affinity, of two unnamed coals, the Bruin, Little Caney, Cannel City, and Fire Clay coal beds exposed along Interstate 64 in northeastern Kentucky.

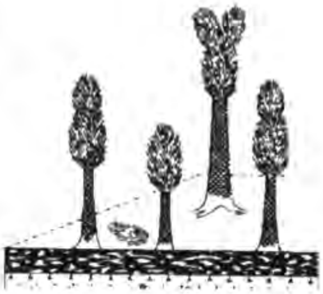


Figure 13. Reconstruction of *Omphalophloios*, a subarborescent lycopod that produced *Densosporites* (Wagner, 1989).

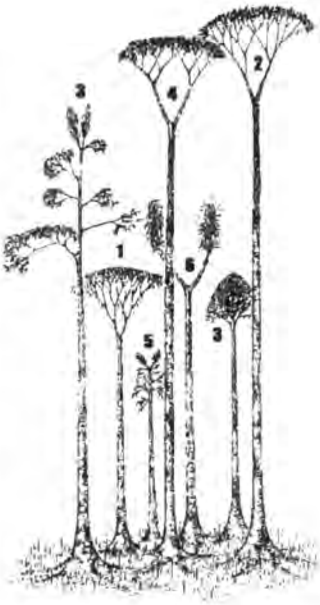


Figure 14. Examples of Pennsylvanian arborescent lycopods (Bateman and others, 1992). Genera names are as follows: *Lepidophloios* (1), *Lepidodendron* (2), *Diaphorodendron* (3), *Synchysidendron* (4), *Paralycopodites* (5), and *Sigillaria* (6).

The next coals in stratigraphic sequence, the Bruin, Little Caney, and Cannel City (Fig. 12), are all dominated by *Lycospora*, but differ in species composition. The Bruin (sampled at mile marker 166), which is double-benched, contains roughly equal percentages of *Lycospora pellucida*, *L. pusilla*, and *L. granulata* , whereas the Little Caney (sampled at mile marker 163.3) is dominated by *Lycospora micropapillata* and *L. pusilla*. The Cannel City coal (sampled at mile marker 163.8) is dominated by *Lycospora pellucida* and *L. pusilla*. *Lycospora micropapillata* and *L. orbicula* are the dispersed spores of *Paralycopodites*, which is believed to have been an aborescent lycopod that assumed a colonizing role in Pennsylvanian mires. In contrast, *Lycospora pellucida* and *L. granulata* are the dispersed spores of *Lepidophloios*, and *Lycospora pusilla* was produced by *Lepidodendron*. Both *Lepidophloios* and *Lepidodendron* are considered to be elements of a more mature, mire-centered paleoflora (DiMichele and Phillips, 1985, 1994) (Fig. 14).

Lycopod trees were the largest plants in the Pennsylvanian, with some exceeding 30 m in height. With one exception *(Sigillaria)*, they appear to have inhabited wet areas, possessing anatomical and reproductive features that allowed them to proliferate in areas with long periods of substrate submergence. For example, the *Stigmaria* root system that anchored the plant had abundant aerenchymatous (air-chambered) tissues to help facilitate gas exchange, a very useful adaptation in flooded environments. Both *Lepidophloios* and *Lepidodendron* also produced a boat-shaped megasporangium, specifically designed for dispersal in water. In addition, lycopsid bark tissue, which occupied the majority of the trunk cylinder, was impregnated with a resin-like substance that may have helped to "waterproof" the plant (DiMichele and Phillips, 1985, 1994).

Biostratigraphically, the Bruin, Little Caney, and Cannel City coal beds all contain spore assemblages that are lower to middle Duckmantian (lower to middle Atokan) in age (Fig. 12). This agrees with proposed lithostratigraphic correlation of these coal beds (Rice and Hiett, 1994).

The Fire Clay coal in northeastern Kentucky is typically thin and discontinuous, which contrasts greatly with the thick, extensive Fire Clay coal that is heavily mined to the southeast. The Fire Clay coal along Interstate 64 (sampled at mile marker 164.5) is double-benched and impure, with ash yields exceeding 30 percent in both benches. Palynologically, the bottom bench is strongly dominated by *Lycospora orbicula (Paralycopodites)*, whereas the top bench contains abundant calamite spores *(Laevigatosporites* spp. and *Calamospora)* and cordaite pollen *(Florinites)* (Fig. 12).

Calamites were woody trees (Fig. 15), though considerably smaller than the lycopsids. They are commonly ascribed to riparian floras, and areas of mire disturbance (e.g., clastic influx, fire splay) (DiMichele and Phillips, 1994), as appears to be the case here, given the high ash yields, though spore data suggest that at least some calamites probably were more mire-centered.

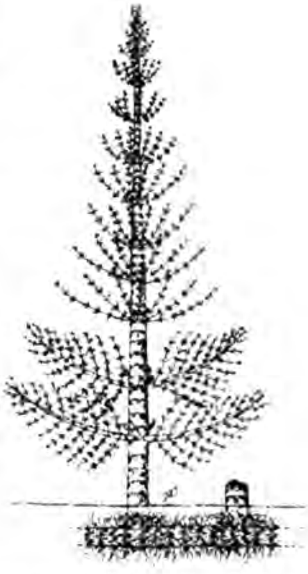


Figure 15. Reconstruction of *Calamites* (Gillespie and others, 1978).

Cordaites were also small, woody trees (Fig. 16), on the order of 2 to 3 m high, with a stilt-like root system not unlike that found in modern mangroves. Unlike many other Pennsylvanian mire plants, their trunks were comprised of true wood (secondary xylem), which strongly resembles the wood of modern conifers. Cordaites were a diverse group that cumulatively encompassed a broad ecological spectrum, ranging from dry mineral to wet peat substrates. Some cordaites may have even been halophytes to a certain degree. Cordaites were probably most common in mire margin areas, expanding into the more central parts of mires during periods of stress (e.g., drought) or disturbance (e.g., clastic influx, fire splay) (DiMichele and Phillips, 1994).

Biostratigraphically, the Fire Clay coal, which occurs near the middle of the Hyden Formation (Fig. 12), marks the first appearance of *Triquitrites sculptilis* and *Vestispora*. Overall, the palynoflora is indicative of a middle to late Duckmantian (middle Atokan) age. The Fire Clay coal is also rather unusual in that it typically contains a flint-clay parting of volcanic origin (e.g., a tonstein), which has been age-dated at 311 million years. See Greb and others (1999) for references.

The Princess No. 3 (sampled at mile markers 174.5 and 176.5) and Princess No. 4 (sampled

Figure 16. Reconstruction of *Cordaites* (Gillespie and others, 1978).

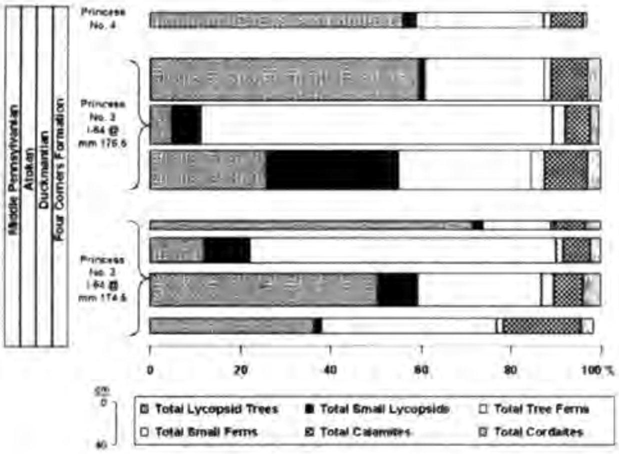


Figure 17. Miospore composition, grouped together according to botanical affinity, of the Princess No. 3 and No. 4 coal beds exposed along Interstate 64 in northeastern Kentucky.

at mile marker 177) coal beds overlie the Fire Clay coal in northeastern Kentucky (Fig. 17). Tree fern spores (*Punctatisporites minutus*, *Punctatosporites minutus*, and *P. rotundus*), which are present in minor amounts in older coals, become much more abundant in these coals, and new tree fern spores appear as well (e.g., *Laevigatosporites globosus* and *Punctatosporites granifer* in the P3, *Torispora securis* in the P4). The Princess No. 3 also marks the range zone base of *Radiizonates difformis*, a distinctive small lycopod spore with a highly dissected flange.

Ferns were a diverse group of plants in the Pennsylvanian. Ecologically, they fall into two groups: columnar trees and small ground cover (some vines?) habits. All were herbaceous and homosporous (produced spores of one size). Small ferns account for most of the diversity we see among Pennsylvanian-age ferns, but their biomass contribution was minimal. Examples of small ferns include *Anachoropteris*, *Botryopteris*, and *Zygopteris*. Collectively, they are indicators of exposed peat substrates, a requirement of their free-sporing method of reproduction. Small ferns produced spores that were sphaerotriangular and trilete. Examples include *Granulatisporites*, *Lophotriletes*, and *Acanthotriletes*.

Psaronius, a tree fern, was the most important biomass producer among the ferns (Fig. 18). The tree habit was largely achieved by root-mantle support of the stem, most of which was comprised of aerenchymatous (air-chambered) tissues. In effect, they were very "cheaply constructed," a distinct advantage in nutrient-poor environments like mires. Westphalian tree ferns apparently reached heights of 3 to 4 m, with stem diameters on the order of 10 to 11 cm; root mantles were relatively small. Late Pennsylvanian (Stephanian) forms are reported to have been larger (DiMichele and Phillips, 1994). Tree ferns had a very cosmopolitan distribution during the Pennsylvanian, occupying areas with both peat and clastic substrates.

Figure 18. Reconstruction of *Psaronius* (Gillespie and others, 1978).

Tree fern spores are rare to absent in Early Pennsylvanian coals, and then expand progressively in a stratigraphically younger direction, with the greatest diversity of tree fern spores occurring in late Middle Pennsylvanian (Westphalian D) coals. Late Pennsylvanian coals are dominated by tree fern spores, but have less species diversity. Biostratigraphically, the Princess No. 3 and No. 4 coals, which correlate with the Peach Orchard and Broas coals of the Four Corners Formation in southeastern Kentucky, are early to middle Bolsovian (late Atokan) in age (Fig. 17).

Although similar to the Princess No. 3 and No. 4 coals in overall palynomorph composition, the Princess No. 5 coal (sampled at mile marker 184.5; Fig. 19) is an important coal biostratigraphically in that it marks the last appearance of a number of spore taxa, including *Radiizonates difformis*, *Densosporites annulatus*, *Vestispora magna*, *Savitrisporites nux*, and *Dictyotriletes bireticulatus*. The Princess No. 5 coal also marks the first appearance of *Triquitrites minutus*, *Murospora kosankei*, *Mooreisporites inusitatus*, and (sporadic) *Cadiospora magna*. The Bolsovian–Westphalian D (Atokan–Desmoinesian) stage boundary is placed at the top of the Princess No. 5 coal bed.

The Princess No. 5 is overlain by two thin coals,

Figure 19. Miospore composition, grouped together according to botanical affinity, of the Princess No. 5, No. 5a, No. 5b, No. 6, No. 7, and No. 8 coal beds exposed along Interstate 64 in northeastern Kentucky.

the Princess No. 5a and No. 5b (sampled at mile marker 184.5; Fig. 19). In places, these two coals are bounded by the Kilgore Flint Member (Rice and others, 1994), which underlies the Princess No. 5a coal, and a marine limestone over the Princess No. 5b coal that is believed to be equivalent with the Vanport Limestone of south-central Ohio (Ferm, 1963). The No. 5a coal represents the first occurrences of *Thymospora pseudothiessenii*, *T. obscura*, and *Schopfites carbondalensis*, three stratigraphically important taxa. A thick, well-developed paleosol separates the Princess No. 5b from the Princess No. 6. This paleosol, known locally as the Hitchens clay bed, is one of the most laterally extensive claystones in the area and is an economically important refractory-grade clay. Biostratigraphically, the Princess Nos. 5a and 5b coals are basal Westphalian D (Desmoinesian) in age (Fig. 19).

Palynologically, the Princess No. 6 coal (sampled at mile marker 184.5; Fig. 19) marks the first occurrence of *Schopfites dimorphus*. *Schopfites dimorphus* has a very limited range in northeastern Kentucky, occurring in only the Princess No. 6 and Princess No. 7 coal beds (Kosanke, 1973). As such, it is an extremely useful palynomorph for bed identification and correlation. The Princess No. 7 coal (sampled at mile marker 184.5) contains a very diverse palynoflora codominated by *Lycospora* and tree fern spores, and marks the last sporadic occurrence of *Densosporites* in northeastern Kentucky. Biostratigraphically, the Princess No. 6 and No. 7 coals are middle Westphalian D (middle Desmoinesian) in age (Fig. 19).

The Princess No. 8 (sampled at mile marker 190.5 and the Ky. 67/I-64 interchange) and No. 9 (sampled at the Ky. 67/I-64 interchange) coal beds are palynologically similar, being codominated by *Lycospora* and tree fern spores (Figs. 19 and 20). The Princess No. 9 (Fig. 20) marks the range zone tops for several miospore taxa including *Lycospora*, *Granasporites medius*, *Cirratriradites*, *Thymospora pseudothiessenii*, *Torispora securis*, *Vestispora*, and *Triquitrites sculptilis*. Biostratigraphically, the Westphalian–Stephanian (Desmoinesian–Missourian) is placed at the top of the Princess No. 9 coal bed (Fig. 20).

Historically, the base of the Conemaugh Formation in the Appalachian Basin has been placed at the top of the Upper Freeport coal, mainly because of its widespread nature. Although the name "Upper Freeport" isn't used in northeastern Kentucky, the palynofloras of the Princess No. 8 and No. 9 coals are very similar to the Lower Freeport, Upper Freeport, and Mahoning coals from northern West Virginia (Eble, 1996) and northeastern Ohio (DiMichele and others, 1996). As such, it is uncertain which bed, the Princess No. 8 or No. 9, is correlative with the Upper Freeport coal.

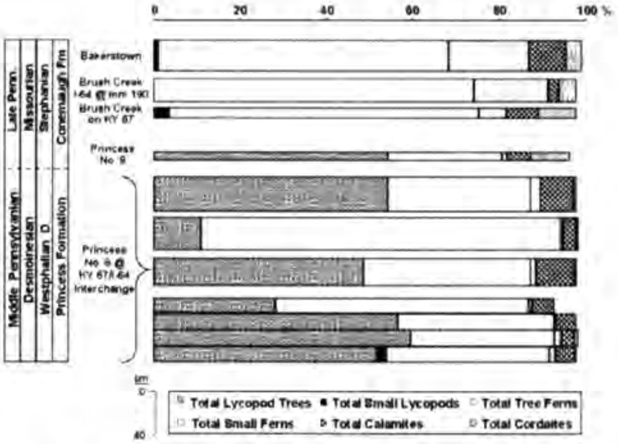


Figure 20. Miospore composition, grouped together according to botanical affinity, of the Princess No. 8 and No. 9, Brush Creek, and Bakerstown coal beds exposed along Interstate 64 and Ky. 67 (Industrial Parkway) in northeastern Kentucky.

Late Pennsylvanian coals in northeastern Kentucky include the Brush Creek (sampled at mile marker 190.5 and on Ky. 67) and Bakerstown (sampled at mile marker 188) coals (Fig. 20). Both are dominated by fern spores, with a conspicuous lack of *Lycospora*, the genus that is so prominent in older coals in the section. The loss of every major lycopod tree genera, except for *Sigillaria*, has been attributed to a major change in climate from wet to dry. This appears to have caused the demise of the lycopods, which had adapted to growth and reproduction in wet areas (Phillips and others, 1974; DiMichele and Phillips, 1994). An important distinction between these two Lower Conemaugh Group coals is that the Brush Creek contains *Laevigatosporites globosus*, whereas this taxon does not occur in the Bakerstown coal.

Correlation within the Appalachian Basin

Wanless (1939) correlated the Princess Nos. 6 through 9 coals of northeastern Kentucky with the Lower and Middle Kittanning coals, and Lower and Upper Freeport coals of eastern Ohio and western Pennsylvania:

Northeastern Kentucky	Ohio and Pennsylvania
Princess No. 9	Upper Freeport coal
Princess No. 8	Lower Freeport coal
Princess No. 7	Middle Kittanning coal
Princess No. 6	Lower Kittanning coal

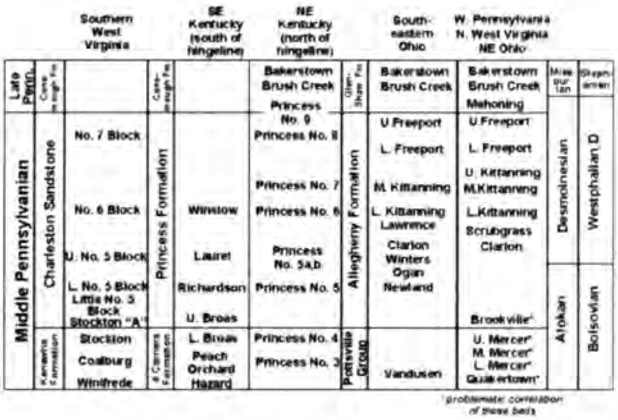


Figure 21. Correlation chart of mid- and late-Middle Pennsylvanian strata in the Appalachian Basin.

Although largely based on lithostratigraphy, these correlations seem fairly reasonable when the palynological data for these coals are considered (Fig. 21). The Princess No. 6 and Lower Kittanning coals mark the introduction of *Schopfites dimorphus*. Gray (1967) observed a similar relationship in north-central Ohio, with *Schopfites dimorphus* being present in the Lower Kittanning coal, but not in the underlying Lawrence coal bed. In southeastern Ohio, the first occurrence of *Schopfites dimorphus* is also in the Lower Kittanning coal bed, which is locally called the No. 5 coal (Rice and others, 1994). The Princess No. 7 coal represents the last occurrence of *Densosporites* in northeastern Kentucky, whereas the last occurrence of *Densosporites* in Ohio is reported to be in the Middle Kittanning coal (Denton, 1957; Gray, 1967).

The proposed lithostratigraphic correlation of the Princess No. 8 and No. 9 coals with the Lower and Upper Freeport coals may be correct, although a correlation of the Princess No. 8 and No. 9 with the Upper Freeport and Mahoning coals is just as plausible (Fig. 21). The Brush Creek coal (Princess No. 10) in Kentucky appears palynologically identical to the Brush Creek coal of northern West Virginia, Pennsylvania, and Ohio (Eble, unpublished data).

Other palynological correlations are also warranted. The ranges of taxa previously mentioned, notably *Radiizonates* and *Thymospora*, suggest that the Princess No. 5, No. 5a, and No. 5b (sometimes referred to as the Princess 5 coal zone; Ferm, 1963) are probable correlatives of the No. 5 Block coal of southern West Virginia and Richardson coal of southeastern Kentucky. In southeastern Ohio, the Newland (No. 4) coal correlates with the Princess No. 5, whereas the overlying Winters and Clarion probably correlate with the Princess No. 5a and No. 5b, respectively (Fig. 21).

The Princess No. 4 coal (Torchlight or Broas coal zone in southeastern Kentucky; Ferm, 1963) contains the first occurrence of *Torispora securis* in the Interstate 64 section, and therefore is a probable correlative with either the Stockton or Stockton "A" coal of the Birch River section in southern West Virginia. It follows that the Princess No. 3 (Peach Orchard coal zone in southeastern Kentucky; Ferm, 1963) is correlative with the Coalburg coal in southern West Virginia.

Stops 1 and 2: Exit 179—Industrial Parkway (Ky. 67)

Stops 1 and 2 will be along the newly constructed Industrial Parkway (Ky. 67). Figure 22 is a cross section along the road from Interstate 64, north. The Princess No. 5 coal is exposed as a coal "bloom" at road level along Interstate 64 just west of the westbound

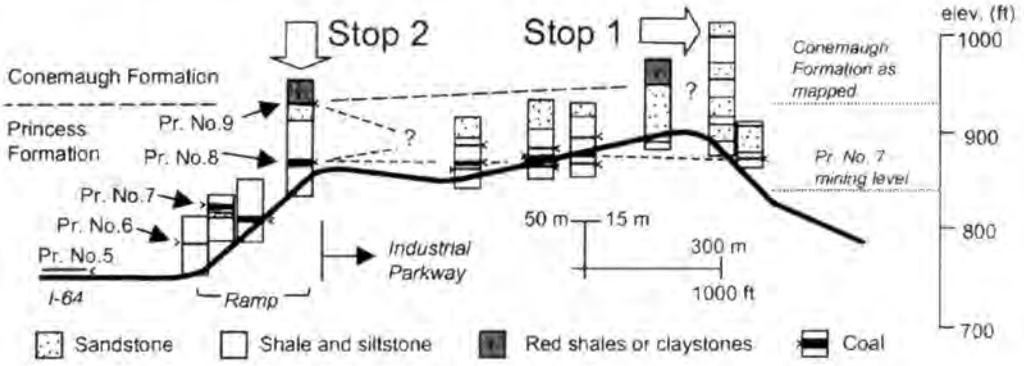


Figure 22. Cross section from the westbound ramp of Interstate 64 and the Industrial Parkway, north on the Industrial Parkway between stops 1 and 2. Based on test borings made during road planning (data from the Kentucky Department of Transportation).

entrance ramp from the Industrial Park. The Princess No. 6 coal lies 10 m (30 ft) above the No. 5 coal. The Princess No. 7 coal occurs 6 to 11 m (19 to 35 ft) above the No. 6 coal and is exposed toward the base of outcrops at stop 2. The Princess No. 8 coal occurs 10 to 12 m (31 to 38 ft) higher, and is exposed toward the top of the ramp; it will be the focus of stops 1 and 2. The Princess No. 9 coal is sporadically distributed, generally 7 to 12 m (22 to 39 ft) above the No. 8 coal bed. At stop 2, the coal occurs in a scour that lies directly above the Princess No. 8 coal bed. Variability in coal thickness, continuity, and bench architecture along the road will be demonstrated at the first two stops.

Stratigraphic Correlations

Shepperd and Ferm (1962) mapped the strata in this quadrangle (Argillite 7.5-minute) prior to construction of I-64 and Ky. 67 (Industrial Parkway), and before extensive drilling and coal mining of the 1970's. Conemaugh strata were found to occur only on hilltops in the southeastern part of the quadrangle, and no Conemaugh marine units were reported. The Brush Creek coal and overlying marine shale and limestone were recently discovered at this location. The stratigraphic interval between the coal mapped as the Princess No. 8 and the Brush Creek Coal is 88 ft (27 m) (Fig. 23). The lowest red-bed paleosol occurs only 28 ft (8.5 m) above this coal. In Ohio, the lowest red beds occur between the Upper Freeport and the Brush Creek Coals, and the UF-BC interval is 92 ft (28 m) (Sturgeon and Hoare, 1968). These considerations suggest the possibility that the coal at the base of this section (mapped as the Princess No. 8) is the equivalent of the Upper Freeport. Unfortunately, the Upper Freeport and Lower Freeport are not distinguishable palynologically. An alternative explanation could be that the Upper Freeport coal is not present in this area due to limited accommodation along the hinge of the basin. The number of coal beds between the Obryan and Brush Creek Limestones generally increases southward toward Louisa, Ky., based on published geologic quadrangle maps.

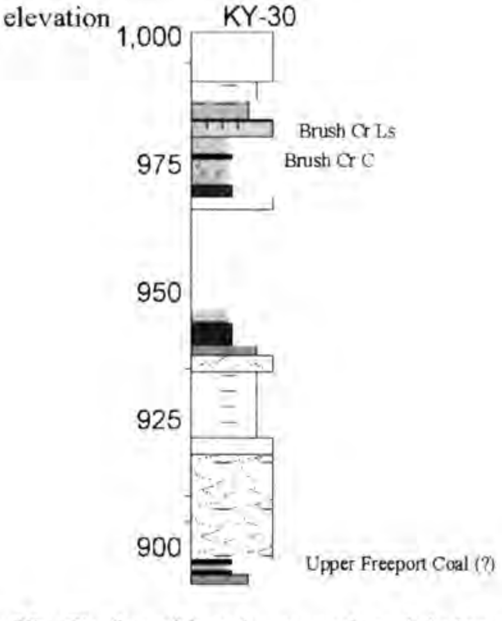


Figure 23. Stratigraphic column produced during geologic mapping from for the Argillite Quadrangle by Sheppard and Ferm (1962).

Stop 1: Princess No. 8 Coal Thickness Variation

Two miles north of exit 179, on the new Industrial Parkway, is an outcrop that exposes strata between the Princess No. 8 coal bed and the lower part of the Conemaugh Formation. The Princess No. 8 coal occurs at road level. The Princess No. 9 coal is absent. The Brush Creek marine zone of the Conemaugh Formation is situated midway up the roadcut, but is poorly exposed here. The Princess No. 8 coal at this stop occurs above two shallow scours (Fig. 24). The coal thins on the margins of the scours and thickens into the scours. Thin leader coals occur at the base of each scour and pinch out onto the margins of the scours. A rooted paleosol beneath the coals (marking the scour) drapes the margin between scours, even where the leader coals are absent. Red coloration within the scours is considered typical of the overlying Conemaugh Formation, but here occurs within the upper Breathitt Group, associated with paleosols. A similar scour, above which the Princess No. 8 thickens downdip and pinches out updip, is exposed between stop 1 and stop 2.

Samples of the Princess No. 8 lower bench and top bench zone were examined palynologically and geochemically from several sample points along each scour (Figs. 25–26). All of the samples are dominated by *Lycospora* and tree fern spores, which is typical of Princess Formation coals in general. Most of the samples are also high in ash and sulfur.

Interpretation

Coal beds can be examined in terms of their architecture. Beds can be divided into benches based on the occurrence of clastic partings or persistent changes in coal lithotypes (Staub, 1991; Greb and others, 2002), and then interpreted based on compositional groups within the benches (Eble and Grady, 1990, 1993; Greb and others, 1999, 2002). Compositional groups utilize

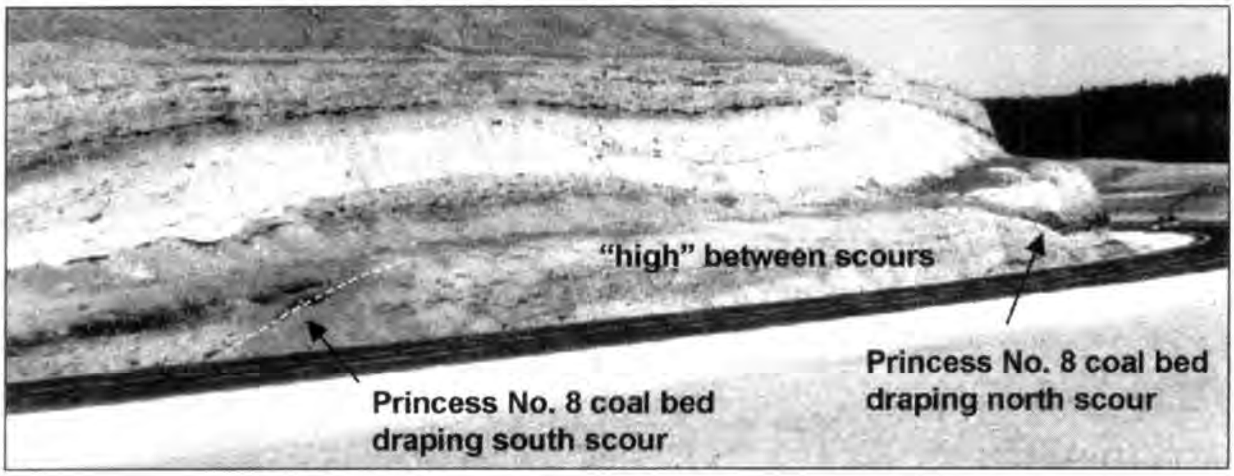


Figure 24. Princess No. 8 coal bed above two scour fills at stop 1.

palynology, petrography, sulfur content, and ash yield to infer original mire environments.

At this location, multiple coal benches occur above each scour and thicken into the scours. Because the number and thickness of coal benches increases into the scours, both can be seen to be a function of local paleotopographic accommodation at the time of peat accumulation. Channel-filling coals have also been noted in younger coal beds (Early and early Middle Pennsylvanian) on the western margin of the basin—another low-accommodation setting (Greb and Chesnut, 1992; Eble and Greb, 1997).

The coal at this location clearly reflects peat accumulation in small mires that were subject to frequent clastic influx, as is shown from the ephemeral nature of the coal and high ash yields. The palynoflora is fairly heterogeneous; no one plant type dominates. It should also be noted that *Lycospora micropapillata* and *L. orbicula* occur in relatively high percentages in many of the samples. Both of these species were produced by *Paralycopodites*, which was a colonizing lycopod tree. Collectively, this probably is the result of rapidy changing edaphic conditions within the mire, related to infilling of the paleotopographic depression..

Stop 2: Accommodation Influences in the Princess Nos. 7 through 9 Coal Interval

Stop 2 is located at the top of the northwest ramp onto Interstate 64. Don't park on the ramp, as we will be heading eastbound after this stop. There are three outcrops at the interchange (Fig. 1). Outcrop A occurs on the eastern side of the Industrial Parkway. Outcrop B occurs on the western side of the Parkway and north

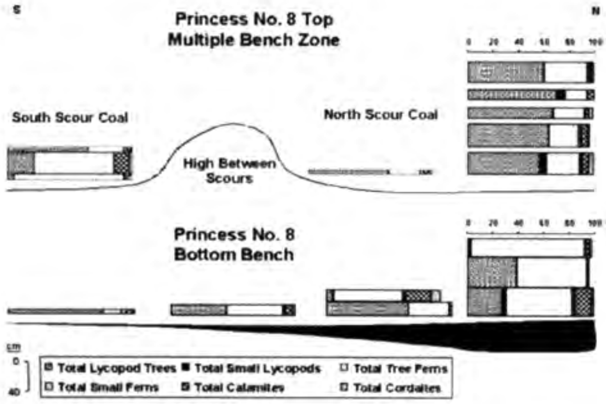


Figure 25. Palynological composition of coals at stop 1.

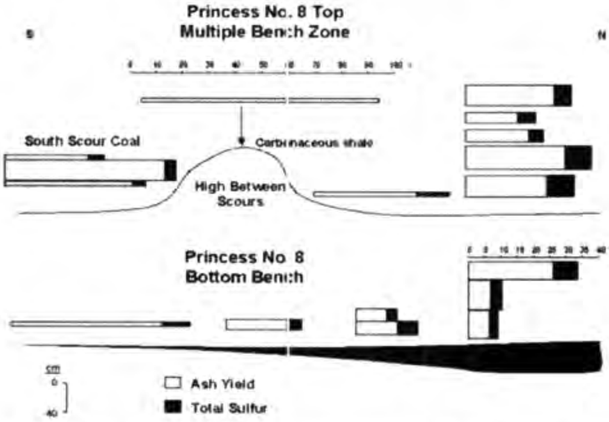


Figure 26. Geochemical composition of coals at Stop 1.

side of the northwest ramp to I-64. Outcrop C occurs on the south side of the ramp (Fig. 1).

Outcrop A. Fault and Heterolithic Paleochannel

The Princess No. 8 coal bed is exposed near the base of the outcrop. On the southern end of the outcrop there is a sharp offset in the coal, and the coal abruptly thickens on the downthrown side of the fault (Fig. 27A). The coal is only thick for a short distance, and then continues northward with little thickness variation. This is the coal that was surface-mined on both sides of the road, which results in the local flat topography. On the north side of this outcrop, a paleochannel cuts down toward the top of the coal (Fig. 27B). The paleochannel consists of laterally accreting and slumped sandstone and shale, which cuts the top of the Princess No. 8 coal bed.

Interpretation. The offset in the Princess No. 8 coal bed (Fig. 27A) is interpreted as a small listric fault. The lower part of the fault is covered, and it is uncertain how much strata was affected by movement along the structure. The local thickening of the coal has the appearance of a small-scale graben (deci-centimeters in width), indicating tensional stress during formation. Thickening of coals along faults has been noted throughout the coal field (Greb and Weisenfluh, 1996; Greb and others, 1999), and is related to the generation of local accommodation space during peat accumulation. A similar type of offset in the Princess No. 5 coal bed was noted by Ferm and others (1971) near Ashland, such that these types of offsets may be common in the Princess District.

Channeling at the north end of the roadcut (Fig. 27B) represents post-peat incision and fill by a small, mixed-load meandering channel. Slumping repeatedly followed lateral accretion, possibly as a result of rapid stage change within the channel. Mixed-load, relatively

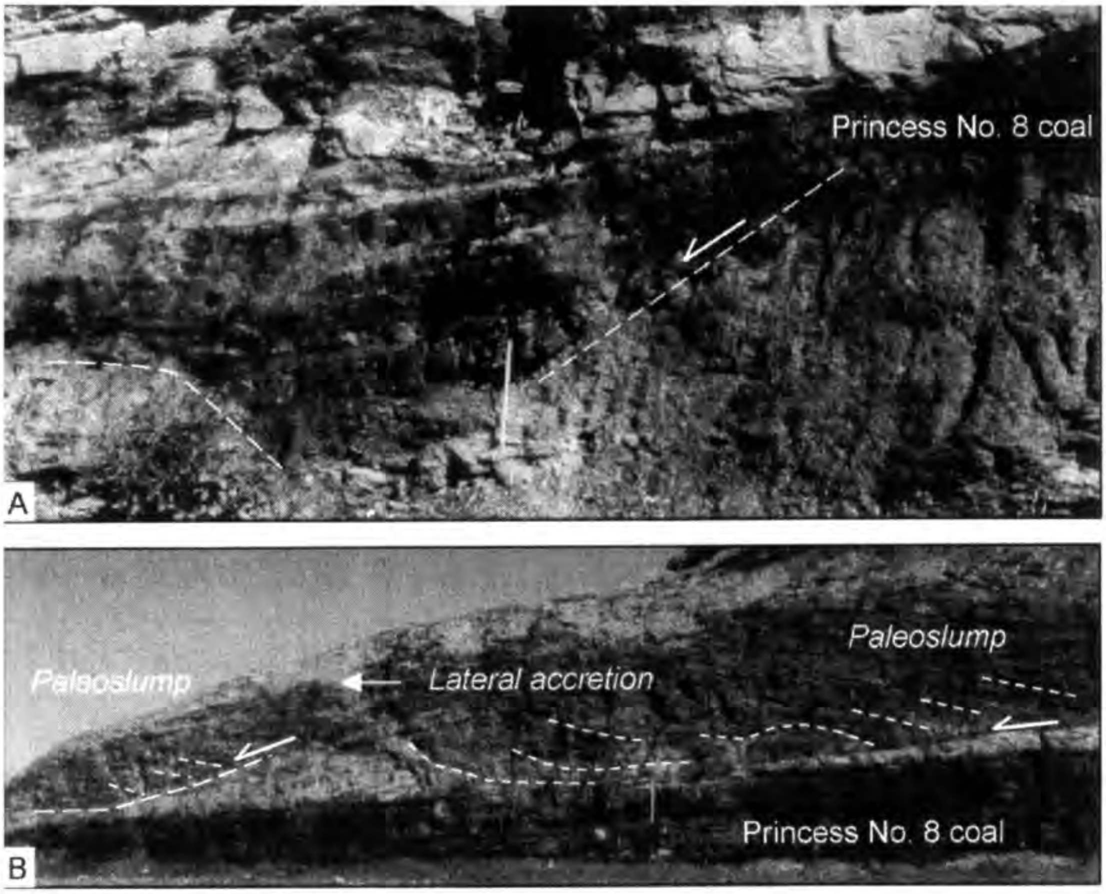


Figure 27. Outcrop A, Stop 2. A. Thick coal on down-dropped side of a small fault toward the southern end of the outcrop. Yard stick for scale (1 yd=0.9 m). B. Heterolithic paleochannel on the northern end of the outcrop exhibiting slumps between lateral accretion surfaces. Yard stick for scale (1 yd=0.9 m).

narrow paleochannels are common at this stratigraphic level.

Outcrop B. Merging Rather Than Splitting Coals

Across the road from outcrop A, there appears to be a southwestward split near the base of the Princess No. 8 coal bed (Fig. 28A). Upon closer inspection, it can be seen that the underclay of the Princess No. 8 coal bed actually cuts across the lower coal "split" (Fig. 28B). The truncation appears gradational because of paleosol development above the scour, but siderite nodules within the underclay of the upper coal can be traced laterally beneath the main coal bench, where the leader coal bench is missing. Also, examination of lithotypes in the leader coal bench are different than those in the base of the main coal benches north of the apparent split, such that they do not appear to split from the same bench.

The Princess No. 8 coal is actually composed of at least three smaller benches, each separated by rash (coaly shale) or gray silty shale. Tracing benches of the coal updip along the ramp of the apparent split shows that each bench thins, but the lower benches thin most. Palynologically, the Princess No. 8 coal at stop 2 is quite similar to the Princess No. 8 at stop 1, being dominated by *Lycospora* and tree fern spores (Fig. 29). The bottom part of the main bench is low in ash and sulfur, as is the

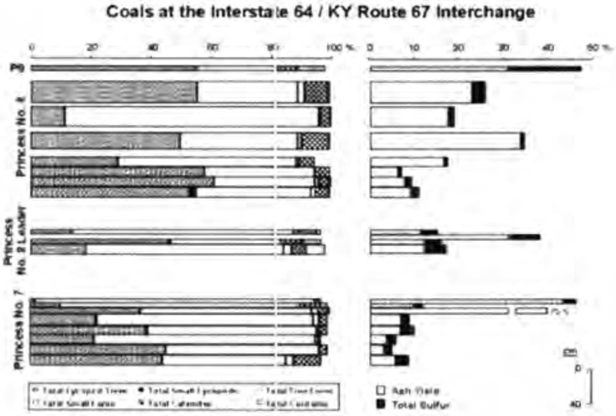


Figure 29. Palynology and geochemistry of coals at stop 2.

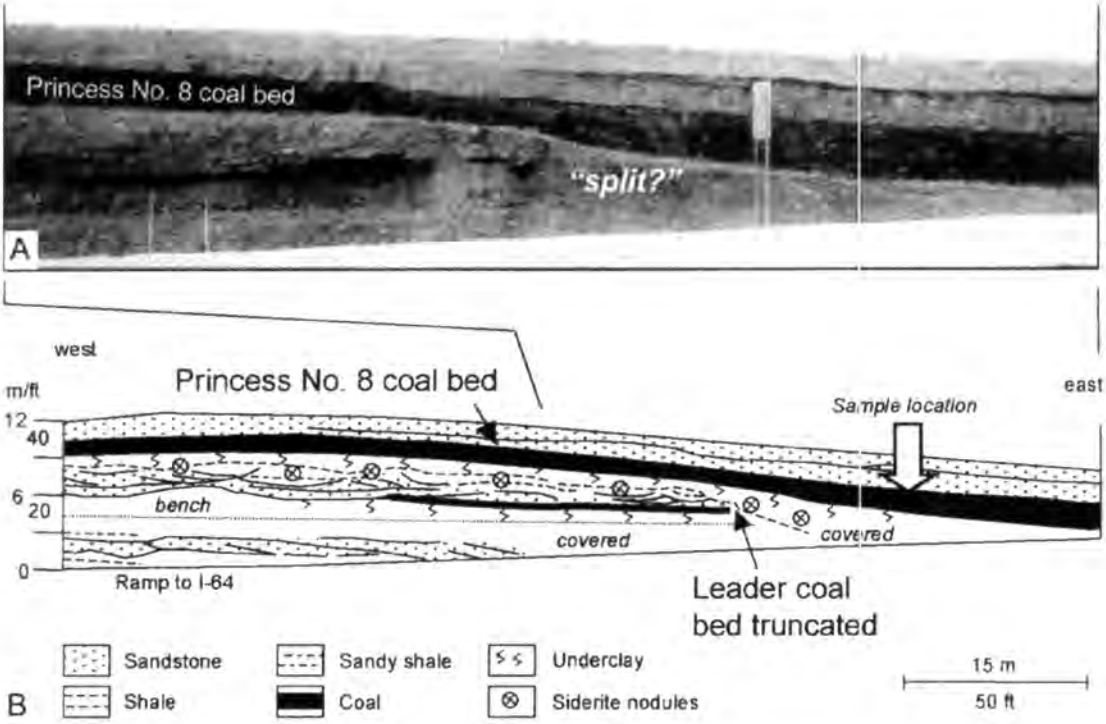


Figure 28. Outcrop B, stop 2. (A) Princess No. 8 coal apparently split along the westbound ramp to Interstate 64. (B) Diagram showing that the apparent split is actually truncation of the Princess No. 8 coal into an underlying coal along a scour beneath the No. 8 coal bed.

underlying leader coal, while the three top benches are high in ash.

Interpretation. Rather than a split in the coal caused by syndepositional clastic influx, this stop highlights an example of truncation and "merge." An exposure surface at the base of the Princess No. 8 coal bed truncated the underlying peat/coal (probably only a local unit) and the Princess No. 8 peat accumulated above the scour. The Princess No. 8 coal thickens down the wedge-ramp clastic interval between the two coals, into a presumed paleotopographic depression, similar to what was seen at stop 1, but here truncating an underlying coal because of locally low accommodation.

The Princess No. 8 paleomire at stop 2 that resulted in the Leader coal was spatially limited and short-lived. Most likely, peat began filling a local depression, prior to being terminated by sediment cover. The subsequent paleomire of the overlying main bench was better developed, and formed fairly thick, low-ash, low-sulfur coal. This bench was no doubt the principal target when this area was being mined. The top three benches of the No. 8 are much higher in ash, which reflects a change from little to no clastic influx during accumulation of the main peat bench to frequent sediment incursion during accumulation of the upperentering benches.

The truncation and merging of coals also shows one possible reason for correlation problems in the Princess Formation in northeastern Kentucky, as well as for coals in other low accommodation areas. In a borehole, this type of truncation and merge would most likely be attributed to splitting of a coal bed. Both coals are underlain by underclays of similar consistency, although more siderite nodules (root-related) occur in underclay beneath the overlying coal. The upper claystone thickens above the scour just as the coal does, and as seen at stop 1. In the Princess Reserve District, the thickest mined coal was often assumed to be the Princess No. 7 coal bed, which has a locally thick underclay. At this location, the Princess No. 8 coal is thick above a well-developed underclay because of local paleotopographic accommodation.

Outcrop C. Scour Fill and Princess No. 9 Coal

At outcrop C, the Princess Nos. 7 through 9 coals are exposed (Fig. 30A). The Princess No. 7 coal bed is exposed toward the base of the outcrop on the ramp to Interstate 64. The Princess No. 8 coal bed is overlain by a lenticular deposit of sandstone and shale, which thins westward. A scour filled with coal and carbonaceous shale occurs on the west-dipping slope of the lenticular deposit, cutting down near the top of the Princess No. 8 coal (Figs. 30A–B). The base of the scour is a nodular, siderite-cemented sandstone (Fig. 30B). The scour is filled with iron-stained (yellow and red) claystones, thin coals, and carbonaceous shales. Coals and coaly shales thicken into the center of the scour (Fig. 30B). The scour fill is capped by at least two horizons of claystones with large elongate siderite nodules and concretions. The claystone is overlain by green- and red-mottled clayey shales, which are truncated by another lenticular sandstone and shale, which thickens westward (Fig. 30A). Because the coals in the scour fill occur at the transition from gray shales and sandstones above the Princess No. 8 coal bed and variegated claystones typical of the Conemaugh Formation at the top of the outcrop, the coals are correlated to the Princess No. 9 coal bed. These coals are restricted to the scour fill at this location.

Palynologically, the Princess No. 9 coal is identical to the underlying No. 8 coal, though higher percentages of *Florinites*, which is cordaite pollen, are seen in the Princess No. 9 (Fig. 29). Geochemically, the Princess No. 9 coal bed is high in ash and sulfur, which isn't all that surprising given the ephemeral nature of the coal and the apparent infilling of a topographic depression at this location. As was mentioned previously, the Princess No. 9 is the last coal in stratigraphic sequence that contains *Lycospora*. The overlying Brush Creek coal is devoid of this genus, and instead is dominated by tree fern spores, as are most Late Pennsylvanian coals. This represents a major change in paleoflora composition that appears to be related to a change in climate from mainly wet to much drier (DiMichele and Phillips, 1994).

The upper lenticular sandstone has a sharp scour base. A thick lag of sideritic nodules occurs on the limb of the deposit. Where the scour cuts into the underlying green silty shale, the lag is apparently truncated by crossbedded, medium-grained sandstones. Sideritic granules and nodules are common along foresets and set boundaries within the crossbedded sandstone. Toward the top of the sandstone, sideritic rootlets and large ironstone masses occur above two crossbed set boundaries.

Interpretation. The two larger lenticular deposits above the Princess Nos. 8 and 9 coals (Fig. 30A) in outcrop C represent meandering paleochannels. The paleochannels are offset, indicating compactional controls on their position. Note also that the paleochannels are relatively narrow. Possible continuations of these paleochannels, or different channels, can be seen across the Interstate to the southeast. Narrow, incised paleochannels are common at several stratigraphic horizons along the Industrial Parkway, possibly reflecting low

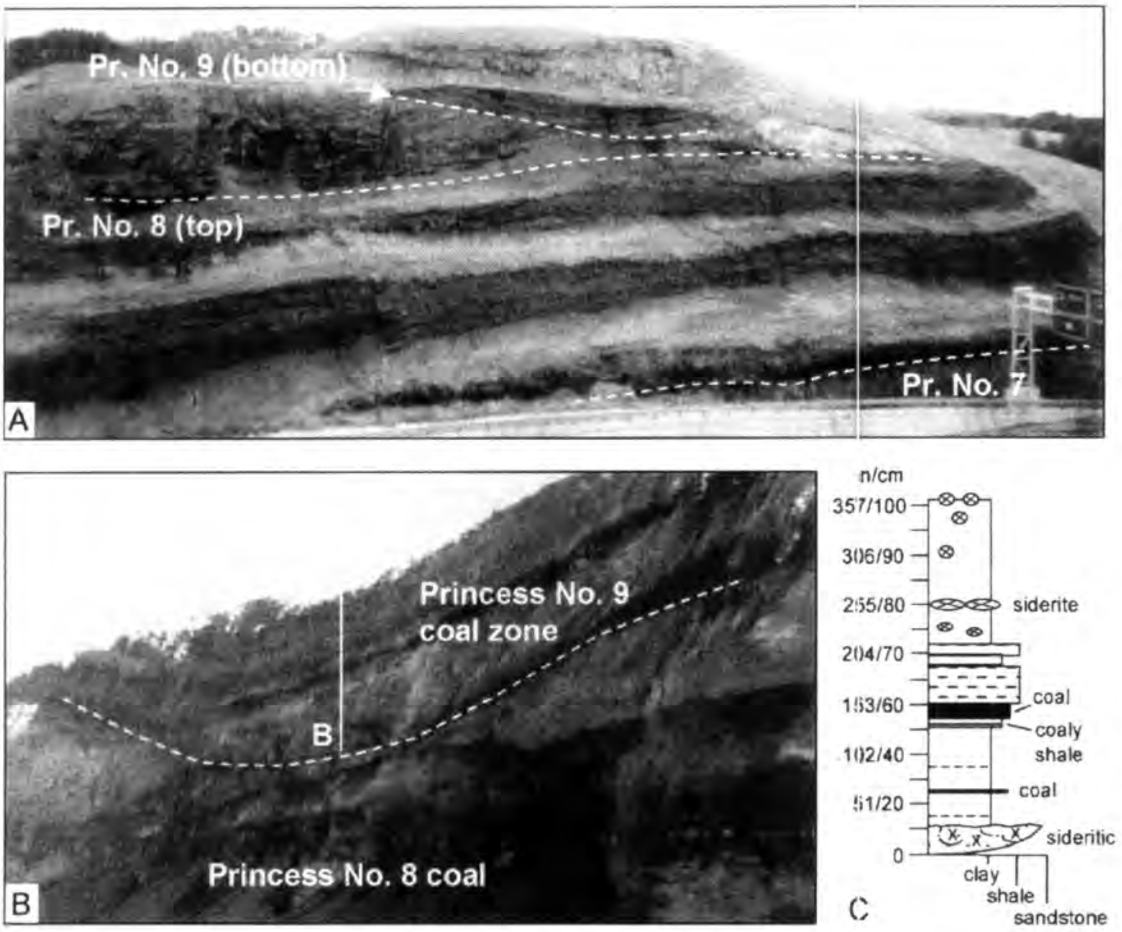


Figure 30. Outcrop C, stop 2. (A) Stratigraphic relationships of the Princess No. 7 (Pr. No. 7), Princess No. 8 (Pr. No. 8), and Princess No. 9 (Pr. No. 9) coals. Lenticular paleochannels above the Princess Nos. 8 and 9 coals are offset relative to each other. (B) Scour cutting toward the top of the Princess No. 8 coal is overlain by thin coals and carbonaceous shales of the Princess No. 9 coal zone. (C) Measured section through the axis of the scour fill (location shown in B).

accommodation and changing paleoclimate influences in this area. An interesting affect of the offset stacking pattern is that the red claystones of the Conemaugh come down closer to the top of the Princess No. 8 coal bed on the dipping slope of the lower paleochannel than was seen at stop 1. On the western margin of the outcrop, those shales are truncated by the upper paleochannel, such that no variegated shales are preserved and the lower boundary of the Conemaugh Formation would be difficult to delineate (without the lateral exposure).

The upper paleochannel (in the Conemaugh Formation) contains abundant sideritic nodules, probably from reworked paleosols beneath. In situ rooting may be represented by the larger concretions toward the top of the sandstone. The occurrence of apparently in situ siderite rootlets at set boundaries toward the top of the sandstone may document seasonal stage fluctuation within the paleochannel, with bar tops being vegetated between lateral dune migrations.

Whereas the merging coal benches in the Princess No. 8 coal at outcrop B were caused by truncation along a gently sloping ramp surface, the coal-filled scour in the upper part of outcrop C fills a narrow depression, similar to what occurs at stop 1, but here completely confined within the scour. As at outcrop B, truncation following Princess No. 8 peat burial causes another coal to come near the top of the underlying coal bed. It is easy to see that with only a little more incision the two coal horizons would have merged. It is certainly possible in this district, or in other areas of low accommodation, that overlying coals might completely replace underlying coal beds along such truncation surfaces, resulting in correlation problems. Downhole, this type

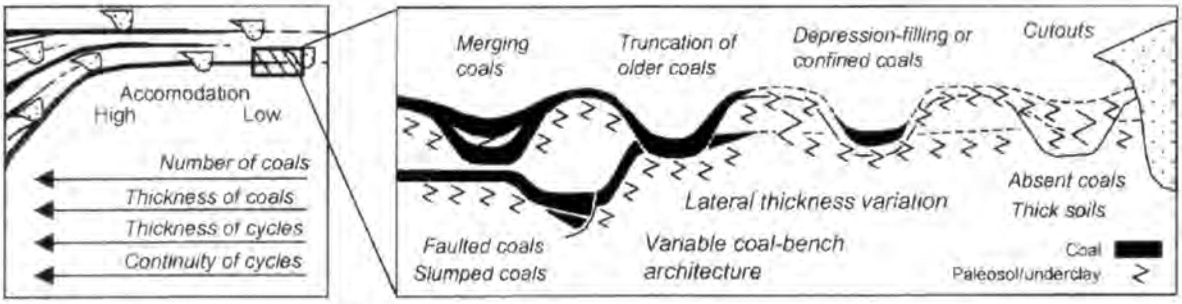


Figure 31. Summary diagram showing coal characteristics in low-accommodation settings.

of truncation would most likely be attributed to thickening of the Princess No. 8 coal, rather than to two separate coals.

At this one stop (outcrops A, B, and C), variability in coal attitude (changing dip and ramps), coal thickness, bench architecture, underclay thickness, coal-clastic cycle (allocycle) thickness, and continuity, can all be seen (Fig. 31). In low-accommodation settings, this type of variation may be common and can be attributed to strong paleotopographic influences on peat accumulation and clastic sedimentation.

Stop 3: Flying J Truckstop—Ky. 180, 0.25 Mile South of the I-64 Cannonsburg Exit (185)

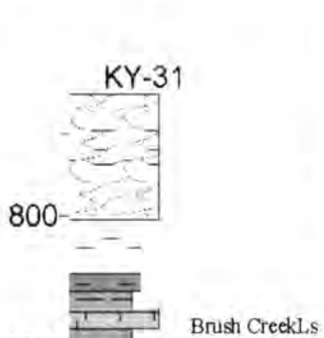


Figure 32. Stratigraphic column for stop 3.

Stratigraphic Correlations

The Brush Creek coal and overlying marine shale are exposed at the north end of this cut, but they are truncated in the middle of the cut by stacked channel sandstones interpreted as part of an incised valley fill (Figs. 5, 32). A coal mapped as the Princess No. 7 was mined in this area at an elevation of about 640 to 650 ft (195 to 198 m) (Boltsfork quadrangle; Spencer, 1964). The Brush Creek coal occurs at an elevation of 772 ft (235 m). This corresponds closely with the unnamed coal 110 to120 ft (33.5 to 36.6 m) above the Princess No. 7 that was used by Spencer as the top of the Breathitt Formation in his general stratigraphic column for the quadrangle. The coal at the base of the section correlates with what was mapped as the Princess 8 coal bed in the Boltsfork quadrangle. It should be noted that this coal comprises the upper portion of a paleosol with variegation (red/purple/green/gray) in the lower part. The position of this coal 55 ft (16.8 m) below the Brush Creek coal, along with the red-bed paleosols that occur in close proximity to it, suggest that it may be equivalent to the Mahoning Coal rather than the Lower Freeport (Rice and Hiett, 1994).

The beginning of the Stephanian was marked by a long-term climate change toward increased aridity in the Appalachian Basin, attributable to orogenesis and associated rain-shadow effects. These changes brought about widespread extinction of floras and the appearance of red-bed paleosols; both have been reported to occur between the Mahoning and Brush Creek Coals in Ohio and West Virginia.

Abundant marine fossils of the Lower Brush Creek limestone and shale occur in a 3.6 ft (1.1 m) interval that begins 5.6 ft (1.7 m) above the top of the Brush Creek coal. The fauna includes chonetid and productid brachiopods, bivalves, gastropods (especially *Pharkodontus*), cephalopods, and crinoids.

Sequence Stratigraphy

The paleosol beneath the Princess No. 8 coal is interpreted as an interfluvial sequence boundary (Sb2 in Figure 11), and only rarely is capped by coal. Fluvioestuarine channel sandstones occupy the interval between this horizon and the Princess No. 7 coal bed along the Interstate 64 westbound Cannonsburg exit ramp. The 23-ft (7-m) shale-dominated interval overlying the coal contains well-preserved plants at the base and coarsens upward, and is interpreted as a lacustrine facies. Base-level cycles in the coastal plain would be capable of producing such a sequence. Coals are known to onlap interfluvial sequence boundaries as water table and base level rise. In this regard, the coal is part of the TST, with the maximum flooding surface represented by maximum lake level (=depth). Lake-filling occurred during HST.

The interval from 33.5 to 63 ft (10.3 to19.2 m) contains individual and stacked paleosols split by what appear to be splay deposits. This is a complex interval that is interpreted as two overlapping interfluvial sequence boundaries. At nearby locations, the tops of individual paleosols in this complex are marked by carbonaceous shale or mudstone.

The Brush Creek Coal accumulated as the coastal-plain water table rose with transgression of the Brush Creek sea. The lower Brush Creek cyclothem and overlying strata are better illustrated at stop 5A . The lower Brush Creek marine unit is TST4 and HST4. It is truncated here by LST7 and TST7, associated with the Buffalo Creek Sandstone (Fig. 11).

Stop 4A: Interstate 64 East, Mile Marker 190.25, 0.5 Mile West of Catlettsburg Exit (191)

Stratigraphic Correlations

The coal at the base of the Interstate 64 roadcut at this stop occurs at an elevation of 567 ft (173 m) and corresponds to the Princess No. 7 coal bed, as mapped by Dobrovolny and others (1963). The section measured here continues up over the top of the I-64 roadcut and up through a second roadcut that existed along Ky. 3. The stratigraphic interval between the Princess No. 7 and the Brush Creek coal is 92 ft (28 m). At stop 1 the coal mapped as the Princess No. 8 was 88 ft (26.8 m) below the Brush Creek coal, so in all likelihood, these are the same coal beds. Palynologic analysis of both beds suggests that they are no older than the Princess No. 8; and the interval below the Brush Creek may be the Princess No. 9 coal bed. Dobrovolny and others (1963) used what is now recognized at the Brush Creek coal as the base of the Conemaugh Group (Fig. 33). The Princess No. 7 (probable No. 8) coal at this location correlates with the Upper Freeport Coal of Wayne County, W.Va., less than 1 mi to the east, as described and mapped by Krebs and Teets (1913) (Martino and others, 1996).

Sequence Stratigraphy

Strata from the Princess No. 7 (=Upper Freeport) to the red-bed paleosol are interpreted as TST1 and HST1 swamps and lakes formed as accommodation space was increased and maximized. Thin, cross-laminated sands are probably fluviolacustrine splays. Rhythmically laminated, shale draped siltstones with thick-thin bundles along with cross-stratified channel sandstones; southeast-directed paleocurrents suggest that estuarine facies are also present (Martino, in review) in nearby outcrops in West Virginia.

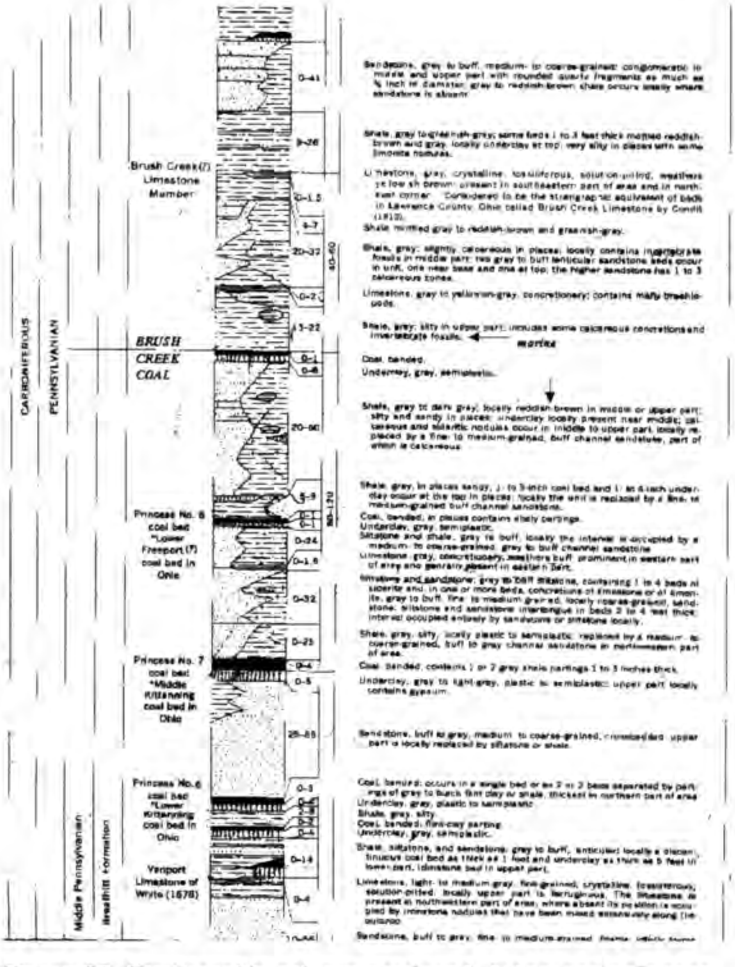


Figure 33. Stratigraphic column produced during geologic mapping of the Ashland quadrangle (Dobrovolny and others, 1963).

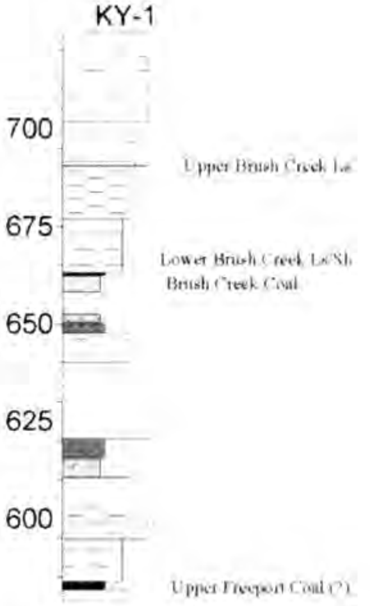


Figure 34. Stratigraphic column for outcrops at stop 4 (see also Figure 5).

Stop 4B: Ky. 23 South Roadcut—Southwest Side of Ky. 23/Ky. 3 Intersection

The paleosol marking SB2 in Figure 11 is accessible in the ditch along Ky. 23 just south of the intersection with Ky. 3. This paleosol occurs at the level of the Mahoning coal and represents a noncalcic vertisol and is capped by flood-basin sands and muds. A second exposure about 1,120 ft (341 m) west along Ky. 3 shows the thick compound paleosol interval below the Brush Creek coal. Paleosols within the lower part of this interval include red-variegated calcic vertisols. The Brush Creek coal in the Ky. 3 roadcut west of this is 7 in. (18 cm) thick. The coal is truncated here by a spectacular conglomerate containing a wide range of locally derived lithologies, including cobbles from the Upper Brush Creek and possibly the Cambridge limestones. This marks the base of the Saltsburg/Buffalo Sandstone IVF (LST/TST7-8; Fig. 5), which is at least 148 ft (45 m) thick at this location. Before the outcrop west of this cut was reclaimed, the unconformity as the base of this unit was observed to ascend at least 40 ft (12 m) into overlying strata. Strata overlying the conglomerate consist of stacked, mudstone-filled channels (Fig. 34). We will see these channel fills at stop 5B.

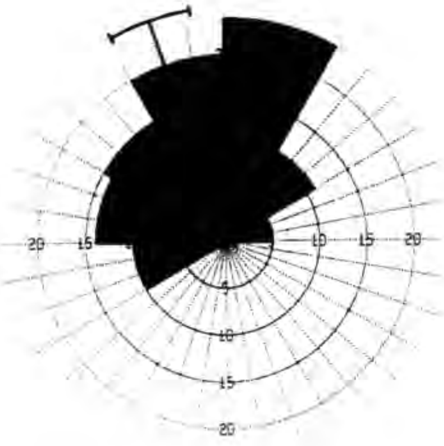
Stop 5A: Ky. 23 South—Mike Marker 9.3, 450 Feet South of Campbells Run Road

The Brush Creek coal exposed at the base of the cut is 15 in. (37 cm) thick and includes bright coal and carbonaceous shale. It is offset by a small fault at the north end of the cut. It overlies a thick paleosol complex and apparently represents drowning of a well-drained landscape in response to rising sea level. The coal is overlain by interlaminated, very fine sandstone and carbonaceous shale with plant fragments and rare pectinid bivalves. A narrow black shale band with intermittent limestone nodules represents the peak of the transgression (mfs) and caps the TST4. Fossils within the shale and limestone are similar to those observed at stop 3, but mollusks predominate, and chonetids and crinoids are rare at this location. The sequence coarsens upward from the black shale band through prodelta and mouth-bar facies, which comprise the HST4. The bench at the top of this cut marks the base of the Upper Brush Creek transgression. This interval is best exposed along Ky. 23 north of Campbells Run Road.

Stop 5B: Ky. 23 South, About 246 Feet North of Campbells Run Road

The Upper Brush Creek limestone is up to 16 in. (40 cm) thick and consists of a discontinuous graded bed of burrowed limestone with abundant very fine quartz sand and silt, and sparse crinoid plates. It occurs 35 ft (10.7 m) above the Brush Creek coal. The Upper Brush Creek marine zone (TST/HST 5) is about 26 ft (8 m) thick and coarsens up into sandstones with HCS, trough cross-stratification, and parallel lamination. Burrows including *Teichichnus* are common. The marine zone is capped by a hackly mudstone with micritic limestone nodules that may represent a paleosol, but is poorly exposed here.

Three stacked fluvioestuarine channel fills of the Buffalo-Saltsburg IVF systems make up the upper 23 ft (7 m) of the section here (LST/TST 7 and 8, Fig. 11). Incision removed important stratigraphic markers, including the Wilgus coal, Cambridge limestone, and Lower Bakerstown coal. The channel fills contain lateral accretion surfaces and abandoned channel mud plugs. Cross-stratification indicates paleoflow was toward the north-northwest (Fig. 35). Most of the sedimentologic features of the channel fills are consistent with meandering river systems. The local occurrence of clay-draped foresets, burrowing sand layers that



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Population 101
Maximum Percentage ... 23.8 Percent
Mean Percentage ...... 11.1 Percent
Standard Deviation ... 7.92 Percent
Vector Mean .... 341.12 Degrees
Confidence Interval .. 10.3 Degrees
R-mag 0.66

Figure 35. Paleocurrent data for the Saltsburg and Buffalo Creek Sandstones in the Huntington-Ashland area. These sandstones are interpreted as incised valley fills.

show thickening and thinning cycles are suggestive of tidal influence in an upper estuarine setting. IVF's cut during lowstands and filled during rising sea level typically contain fluvial facies that grade upward and downdip into estuarine facies (Fig. 10).

Stop 6: On Ramp to Ohio 52 at the North End of the West Huntington Bridge Over the Ohio River

This roadcut exposes the Cambridge marine unit (TST/HST6) at the base, which is capped by a thick paleosol (Sb7, Fig. 11). The Cambridge marine zone is more extensive in Wayne County than previously thought (Martino and others, 1996). Its underlying calcic vertisol is locally capped by the Wilgus coal and its equivalent. The single-story channel fill that overlies the Cambridge is 33 ft (10 m) thick and represents the Saltsburg Sandstone (LST/TST8). It contains large-scale northwest-dipping lateral accretion surfaces. Internal trough and planar cross-strata indicate flow toward the east-northeast. Clay-draped foresets and rhythmically laminated mudstone plugs suggest this is a fluvio-estuarine channel fill. The base of the Ames marine unit occurs about 82 ft (25 m) above the Cambridge. The Ames marine unit and bounding paleosols will be seen at stop 7.

Stop 7: Ohio 52 West, Mile Marker 0.3

The Pittsburgh Reds, a calcic vertisol sequence that is up to 16 ft (5 m) thick, is exposed at the east end of the cut. It is interpreted as an interfluvial sequence boundary (Sb8). Little relief occurs in association with the overlying splay sandstone, a 13-ft-thick (4-m-thick), very fine sandstone that contains plant fossils and burrows. It is separated from the Ames Shale by a compound paleosol (Sb9). Pedogenic carbonate (Bk, K horizons) at shallow levels are characteristic features of aridosols and indicate well-drained, semiarid conditions. The upper part of the soil is gleyed with a thin carbonaceous shale at the top. These characteristics are best explained by a rising water table that preceded transgression of the Ames sea. Marine fossils are abundant in the lower 12 in. (30 cm) of the Ames marine zone (mainly the brachiopod *Neochonetes grannulifer*, which readily weather out of the shale). A thin biomicrite about 12 in. (30 cm) above the base may represent the transgressive peak (mfs). It contains *Neochonetes*, *Derbya*, crinoid plates, and bryozoans. The rest of the marine zone is silty and/or sideritic, suggesting more rapid deposition, dilution, and perhaps high turbidity. Within the upper 20 in. (50 cm), wave ripples and HCS occur. The Ames marine zone is 23 ft (7 m) thick and is capped by an 8-ft-thick (2.5-m-thick) calcic vertisol (Sb10).

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The Impact of Geology on the Culture and History of Central Kentucky

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Introduction

The geology of Kentucky has profoundly influenced the history of settlement, migration, industry, and transportation in the state. A thick accumulation of thin-bedded, phosphatic limestone is the key geologic element that has helped central Kentucky's Bluegrass area develop distinctive industries of world renown. This field trip will examine a few selected examples of geology's impact on the history of this area. This one-day trip will, however, be only scratching the surface of the region's rich natural and cultural heritage.

Physiographic Setting

Most of central Kentucky is within the Bluegrass Section of the Interior Low Plateaus Province (Fenneman, 1938). The Bluegrass Section is underlain by Ordovician limestone and shale, and is bordered on the east and south by the rugged Knobs Region (Fig. 1). Depending on the proportion of limestone versus shale, the Bluegrass landscape varies from a gently rolling upland plain to an intensely dissected plateau with steep hills and narrow ridges. The origin of the name comes from a grass *(Poa pratensis)* imported by the earliest European explorers, which sometimes appears bluish-green when lit by the sun.

The Inner Bluegrass consists of gently rolling hills underlain by the Middle to Upper Ordovician Lexington Limestone (Fenneman, 1938; McFarlan, 1943; Andrews, in press). Karst development is locally extensive, especially in areas with minimal shale in the underlying bedrock. The gently rolling landscape of the Inner Bluegrass drew the attention of early explorers and settlers because of its legendary beauty and high soil fertility. This region is home to several of Kentucky's more famous industries: burley tobacco production, bourbon whiskey distilleries, and thoroughbred horse farms. The horse farms of Kentucky's famous thoroughbred industry are almost exclusively found on the gentle hills around Lexington, and the state's renowned bourbon whiskey industry had its beginnings utilizing karst springs in the Inner Bluegrass. The Kentucky River has

Figure 1. Subdivisions of the Bluegrass Section in Kentucky (modified from Andrews, in press).

carved a steep gorge known as the Palisades across the Inner Bluegrass. The Kentucky River Palisades stood as a barrier to north–south communication and transportation for early settlers, while the river itself provided a seasonal trade route for moving timber, coal, and other products from otherwise isolated eastern Kentucky communities to downstream commercial markets. This field trip will focus on selected sites within the Inner Bluegrass Region.

Between the Inner and Outer Bluegrass is the Bluegrass Hills Region, formerly known as the Eden Shale Belt. The area is underlain dominantly by shale and limestone of the Clays Ferry and Kope formations (Upper Ordovician). Some valley bottoms on the inner margins are eroded into the Lexington Limestone (Middle to Upper Ordovician). The topography is relatively steep in comparison with the gently rolling hills of the Inner and Outer Bluegrass. The Outer Bluegrass consists of gently rolling to moderately steep hills underlain by Upper Ordovician to Middle Devonian shale, limestone, and dolostone, contrasting sharply with the taller, steeper hills of the adjacent Knobs Region. Karst development is locally significant, but much less than in the Inner Bluegrass, inhibited by the significant quantities of shale in the Upper Ordovician bedrock. The Knobs Region forms a horseshoe-shaped belt beyond the outer edge of the Bluegrass Section. The Knobs are erosional remnants and outliers of the Mississippian Plateaus of the Highland Rim Section, and are typically conical hills or narrow ridges of Devonian black shale and Lower Mississippian shale and siltstone, which in some places are capped by resistant Middle and Upper Mississippian limestones.

Bedrock Geology

High Bridge Group

The High Bridge Group of Middle Ordovician age is a thick (430 to 570 ft), widespread body of limestone and dolomite (Dever, 1980). The High Bridge Group comprises, in ascending order, the Camp Nelson Limestone, Oregon Formation, and Tyrone Limestone (Fig. 2). High Bridge rocks crop out in the cliffs along the Kentucky River and in lower parts of its tributaries in the southern part of the Inner Bluegrass (Cressman and Noger, 1976). The limestones of the High Bridge Group are generally more massive than those of the Lexington Limestone. The contact between the micrograined limestone of the High Bridge and the bioclastic limestone of the basal Lexington Limestone is distinct (Dever, 1980). The limestones and dolomites of the High Bridge are interpreted to be tidal-flat carbonates and intervening shallow-marine lagoonal deposits, analogous to environments of the modern Bahamas (Kuhnhenn and others, 1981).

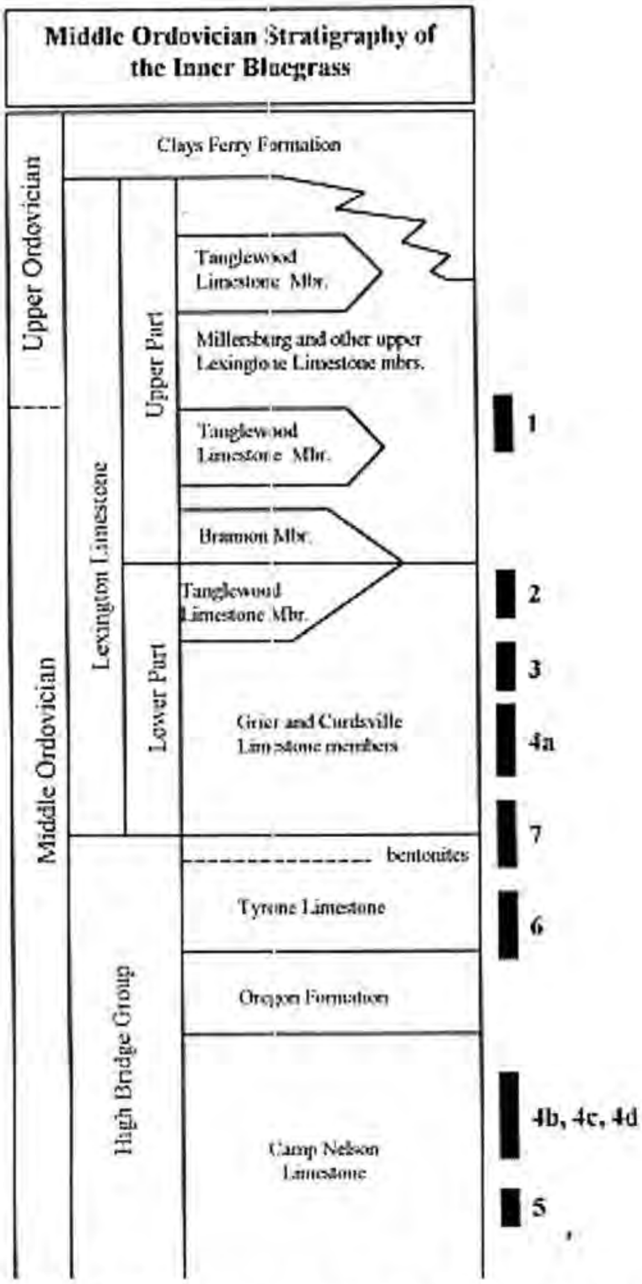


Figure 2. Stratigraphic column of Middle–Upper Ordovician stratigraphy of the Inner Bluegrass, showing stratigraphic range of field trip stops.

The Camp Nelson Limestone is massive and consists of fine- to micrograined limestone, which is partly mottled with small irregular pods and interlaced burrows of finely crystalline dolomite (Dever, 1980). The dolomite seems to replace the calcite in irregular vugs in the limestone. A distinctive shale unit, 5 to 12 ft thick, occurs in the upper Camp Nelson and is widespread across the region (Dever and Greb, 1997). Near the town of Camp Nelson, 320 ft of rock is exposed above drainage (Cressman and Noger, 1976). Fossils found include brachiopods, gastropods, tabulate corals, bryozoans, ostracods, and algal mats.

The Oregon Formation, ranging from 6 to 65 ft thick, consists of a light-brown to light-yellow, very finely crystalline dolostone, partly interbedded with micrograined limestone. The Oregon has a sucrosic (sugar-like), crystalline texture. Relict fabrics in the Oregon Formation show laminae and burrowing similar to that of the Tyrone and Camp Nelson Limestones (Dever and Greb, 1997).

The Tyrone Limestone, 55 to 155 ft thick, is a gray to light gray, microcrystalline, relatively structureless limestone. Specks and small tubes of clear calcite, commonly called bird's-eye structures, are present throughout the formation. The Tyrone exhibits, in some places, rhythmic laminae, which are produced by the rise and fall of tides in the tidal-flat environment. The Tyrone commonly contains mud-cracked horizons, algal laminae, and marine corals. The top of the Tyrone is generally placed at the Mud Cave bentonite, a regionally extensive, potassium-rich claystone (Greb and Dever, 1997a). Several thin bentonites that serve as useful markers for local and regional correlation are present in the High Bridge (Dever, 1980). During the Ordovician, island arc volcanos—formed as a result of subduction during the Taconic Orogeny—produced an ash fall that covered parts of two plates, which can be correlated over much of eastern North America as bentonite layers.

Continuing growth in commercial, residential, and highway construction creates a demand for construction aggregate in central Kentucky (Dever, 1997). The High Bridge rocks are massive, dense, micrograined limestone and dolomite, which are excellent for industrial use. The High Bridge Group is mined for construction stone, concrete aggregate, agricultural lime, and production of lime for flue-gas desulfurization. The rocks of the High Bridge Group are of a high chemical purity, a designation for high-carbonate and low-silica (SiO_2 less than 4 percent) rocks. The thick deposits of the High Bridge Group across a wide region represent large reserves of stone for industrial use.

Lexington Limestone

Much of Kentucky's Inner Bluegrass Region is underlain by the Lexington Limestone of Middle to Late Ordovician age. A heterogeneous sequence of fossiliferous and bioclastic limestones, the Lexington Limestone is divided into 11 members that are complexly intertongued (Cressman, 1973). The Lexington Limestone is overlain by interbedded limestone and shale of the Clays Ferry Formation and rests disconformably on the Tyrone Limestone of the High Bridge Group (Fig. 2). The complex facies changes and abundance of fossils in these rocks are a result of shallow-marine deposition. Isolated platforms of marine shelf environments during Ordovician time, much like the present-day Bahamas, provided favorable conditions for the growth of fauna. This field trip will examine exposures of the Curdsville, Grier, and Tanglewood Members of the Lexington Limestone.

Curdsville Member. The Curdsville is the basal unit of the Lexington Limestone (Cressman, 1973). Near the Kentucky River, south of Lexington, the Curdsville typically rests directly on the Mud Cave bentonite (volcanic ash bed) of the Tyrone Limestone (High Bridge Group). The upper contact of the Curdsville varies due to the complex intertonguing of members. The Curdsville consists of finely to coarsely crystalline, irregularly bedded limestone, interbedded with shale. It is described as a bioclastic calcarenite and calcirudite interbedded with an argillaceous calcisiltite and shale (Cressman, 1973). Fossils commonly found in the Curdsville include pelecypods, brachiopods, crinoids, bryozoans, and mollusk-shell coquina. Microcrystalline apatite is present as fillings in openings and pores of bryozoans and crinoid fragments. The Curdsville was deposited in a relatively shallow-water environment, above fair-weather wave base where wave reworking led to accumulation of coarse sediment and shell debris (Greb and Dever, 1997b).

Ball-and-pillow structures are common in the calcisiltite layers of the Curdsville. Ball-and-pillow structures can be created by a variety of mechanisms: (1) vertical loading on a coherent substrate, (2) slumping, (3) changes in shear strength at the sediment-water interface, or (4) violent shaking caused by earthquakes (Ettensohn and Rast, 1997). Soft-sediment deformation or ball-and-pillow structures that are interpreted to be products of seismicity have been termed seismites (Rast and Ettensohn, 1995). Ball-and-pillow structures have been noted throughout the region, generally increasing in abundance toward faults, which suggests that they may be evidence for the reactivation of faults during Ordovician tectonism (Rast and Ettensohn, 1995).

Grier Member. The Grier Limestone Member overlies the Curdsville at stop 4. The Grier Member generally consists of thin, nodular, fossiliferous calcisiltite to calcarenite. The most common bedding assemblage is 0.5-ft thick, nodular, fossiliferous calcisiltite with minor shale partings. Each bed consists of a scour base overlain by irregularly to wavy bedded calcarenite, overlain by wavy, often bioturbated, calcisiltite. In many places the nodular bedding has weathered to become a rubbly limestone in a matrix of dolomitic calcisiltite

(Cressman, 1973). Fossils found include brachiopods, bryozoans, and gastropods. The Grier in part intertongues with the lower tongue of the Tanglewood Limestone Member. The Grier was deposited in relatively shallow water, just below fair-weather wave base, and was susceptible to periodic storms (Greb and Dever, 1997b).

Tanglewood Limestone Member. The Tanglewood Limestone Member is an extensive, irregular unit of bioclastic calcarenite that makes up much of the upper part of the Lexington Limestone (Cressman, 1973). The Tanglewood ranges between 60 and 100 ft thick, extending eastward from Frankfort, and thinning northward, westward, and southward (Cressman, 1973). Because of the complex intertonguing of the Tanglewood with other units, the contact relations are difficult to describe in detail. Generally, it is overlain by nodular fossiliferous limestone and shale of the Millersburg Member as a gradational contact, but where the Tanglewood is overlain by the Clays Ferry Formation, the contact is sharp and planar (Cressman, 1973). Other tongues of the Tanglewood rest on the nodular and fossiliferous Grier Member, or on calcisiltite and shale of the Brannon Member.

The Tanglewood Member typically consists of medium to light gray, medium-grained, well-sorted bioclastic calcarenite (Cressman, 1973) (Fig. 3). As with other members, there is considerable variation in color, grain size, and fossil content. Beds in the Tanglewood range from 0.2 to 1 ft thick and are generally planar to irregularly surfaced, commonly containing low-angle, small- to medium-scale crossbedding. Many beds contain alternating phosphatic laminae from less than 0.3 to 2 in. thick (Cressman, 1973). Fossils found include crinoid columnals, bryozoans, and brachiopods. Stromatoporoids are common in the upper tongues of the Tanglewood Member.

Structural Geology and Tectonic History

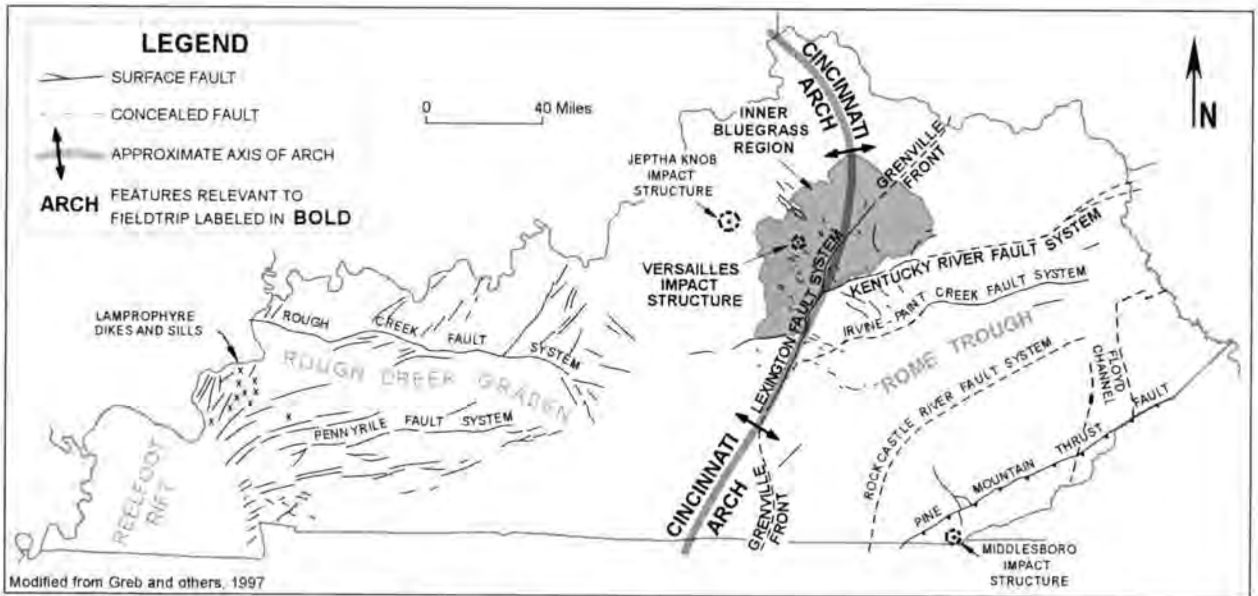
The structures and landforms of the Inner Bluegrass are dominated by six major, interrelated regional elements: the Cincinnati Arch and Jessamine Dome, the Grenville Front, the Lexington and Kentucky River Fault Systems, and the Rome Trough.

Around 990 million years ago, the Grenville Orogeny occurred along what is now the eastern margin of North America (Drahovzal and others, 1992). This collision thrust the Grenville metamorphic terrain up onto the existing Granite-Rhyolite Province, which comprises much of what is now the Midcontinent of the United States. Today, these two provinces are several thousand feet below the surface and make up the crystalline "basement" of Kentucky and the surrounding states. The western edge of this ancient thrust belt is also called the Grenville Front. While the Grenville basement material itself has little to do with the land surface of Kentucky, later movements of its boundary faults do. The faults in the Grenville Front caused a predisposed zone of weakness that extensional forces, hundreds of millions of years later, reactivated into a down-to-the-southeast normal fault zone. This formed the faults of the Lexington Fault System (Fig. 4).

Studies of the Lexington faults, as well as those of the Kentucky River Fault System, indicate several periods of movement beginning in Early to Middle Cambrian time (Harris and Drahovzal, 1996). These two fault systems form the northwestern boundary of the Rome Trough in Kentucky (Fig. 4). The Rome Trough is a deep, failed rift basin formed during the continental breakup and formation of the Iapetan Ocean. This Lower to Middle Cambrian graben complex extends from the subsurface of central Kentucky, northeast through West Virginia, and into Pennsylvania. Like the Grenville described above, the Rome Trough is not evident at the surface, but it influenced the deposition of later strata. The offsets along these normal fault systems total as much as 600 ft at the surface.

The Cincinnati Arch is a broad regional feature that strikes roughly north to south through Kentucky and western Ohio; it separates the Illinois Basin to the west from the Appalachian Basin to the east. The Jessamine Dome is a second-order structure along the axis of this arch, centered near the intersection of the Kentucky River and Lexington Fault Systems in central Kentucky. The uplift of this dome has caused the oldest strata at the surface in Kentucky (Middle Ordovician High Bridge

Figure 3. Outcrop of the Tanglewood Limestone Member of the Lexington Limestone, central Kentucky.



Modified from Greb and others, 1997

Figure 4. Major structural features in central Kentucky.

Group and Lexington Limestone) to be exposed in this area (Fig. 4). The existence of soft-sediment deformation in the form of flow rolls or ball-and-pillow structures has led some researchers to believe that the dome formation was synsedimentary, and that these structures are in fact seismites related to local fault movement (Ettensohn, 1992a). The uplift and doming of this structure also caused numerous smaller normal faults throughout the area, most of which trend northwest (Black and Haney, 1975). Although the vertical displacements on these faults are small (most are less than 20 ft), they locally influence drainage and karst development.

Bedrock Geology and Phosphatic Soils

It has been suggested that during Ordovician time Kentucky had fairly direct access to waters of the open ocean. This provided central Kentucky with abundant phosphate, presumably more than was needed to support Ordovician flora and fauna (Cressman, 1973). The average limestone contains only 0.04 percent PO_4, whereas the Tanglewood Limestone Member averages 2.4 percent PO_4. The phosphate content in the Tanglewood occurs as apatite fillings and phosphorite nodules, both of which vary in abundance from bed to bed. Phosphorite nodules in the Tanglewood occur as dark gray, poorly sorted, abraded bodies that have been reworked. Apatite is present as fillings of bryozoans, crinoid plates, and gastropod steinkerns (Cressman, 1973). The exact depositional or diagenetic origin of the phosphate in the Lexington Limestone is poorly understood.

Weathering of Lexington Limestone bedrock produces a very phosphate-rich soil. The rich soil, via nutrients in grasses, is the basis of a healthy life for horses and other animals in the region. The unusually high concentration of phosphate allows this region to be the top producer of thoroughbreds in the country. There is such an abundance of phosphate in the soils of the central Bluegrass that it must be balanced with added calcium. Calcium is added by liming the horse pastures, in order to obtain a proper Ca-to-PO_4 ratio. This process allows the soils to maintain a satisfactory pH level of 6.5 to 6.8, to allow maximum nutrient uptake by grasses and plants (Allman, oral communication, 2001). A proper Ca-to-PO_4 ratio will produce both good quantity and a good quality of bone for the thoroughbred horses.

Other factors such as topography and a temperate climate provide thick soils for the major thoroughbred farms (Fig. 5). The gently rolling karst landscape not only provides rich soil, but an adequate water supply due to abundance of springs. Karst topography also allows the land to be very well drained; this is especially important for animals in the rainy or winter season. In dealing with a karst terrain, sinkholes and local areas of high relief are common. Horse farms are strategically placed where the land is less steep and away from sinkholes as much as possible. It is important for horses to grow in an environment that is not physically demanding or dangerous.

Hydrology

The field trip area is within the Inner Bluegrass karst region, as defined by Thrailkill and others (1982). The bedrock of this region is highly susceptible to dissolution, with some members of the Lexington Limestone containing less than 5 percent insoluble material (Fisher, 1968). Isolated karst groundwater basins with well-organized dendritic conduit systems have developed to feed major base-level springs. These groundwater basins typically exhibit prominent surficial karst features (Fig. 6). These include dolines, swallets, blind valleys, and karst windows. Beyond the margins of the groundwater basins are "interbasin" areas, where groundwater flow is relatively shallow and discharges at high-level springs. Many of the high-level springs are perched above bedrock strata with higher insoluble-residue contents. Surficial karst features may be more subdued in the shallow-flow interbasin areas. The interbasin areas commonly contribute to the surface catchment area of the groundwater basins.

Although lithology is—in the broadest sense—critical to the formation of karst landforms, only the smaller karst conduits appear to be stratigraphically controlled. Even the "shales" of the Lexington Limestone contain over 50 percent calcite, and are thus somewhat soluble. The larger karst conduits are capable of enough flow to sweep away any residual insoluble material, and thus effectively disregard the shalier layers. Structure also appears to only locally control karst development. Dolines and conduit passages commonly align with fractures, but extensive karst development parallel to mapped faults has only been documented in a relatively few locations, and in some instances flows perpendicular to mapped faults or bedrock anticlines (Thrailkill and others, 1982). Hydraulic paleogradient appears to be the primary influence on the development of karst landforms and trends.

Across most of the Bluegrass upland, the karst conduits are primarily horizontal, or nearly so, flowing to springs feeding base-level streams. Much of the karst development in even the largest groundwater basins in the Bluegrass is limited to 75 ft or less below the land surface, due to the subdued relief between the highest parts of the upland and adjacent base-level streams (Hopper, 1992). However, near the Kentucky River Palisades, where fluvial erosion has removed the impermeable bentonites in the upper parts of the Tyrone Limestone, numerous vertical karst pits and shafts up to 200 ft deep have developed.

The freshwater aquifer in the area is fairly shallow, and apparently confined primarily to the conduit system and associated epikarst flow. Saline and sulfur-rich brines are encountered at relatively shallow depths below the conduit system. The shallow saline waters were the source for the numerous salt springs and salt licks the earliest settlers and explorers found in the area.

Figure 5. Kentucky horse farm, Lexington, Ky. Photo taken by James Archambeault, courtesy of Lexington Convention and Visitors Bureau.

History and Culture

Early Settlement, Industries, and Transportation (from Harrison and Klotter, 1997)

Kentucky's human inhabitation began at least 10,500 years ago, as Paleo-Indian tribes migrated into the area following the retreat of Ice Age glaciers. Native peoples lived in Kentucky until as late as 1750, when disease, intertribal conflicts, and growing pressures from European settlers and explorers led to the abandonment of the last native villages within the area of modern Kentucky.

The first Europeans to view Kentucky were probably Spanish and French explorers and traders travelling along the Mississippi and Ohio Rivers during the late 17th century. The first documented travels through the interior of the state were in 1673, when a young English colonist, Gabriel Arthur, accompanied a native war party across the state. Intensive exploration of the state began in the 1750's with Dr. Thomas Walker's and Christopher Gist's expeditions through the state, at the request of speculative land companies. They found abundant coal deposits in eastern Kentucky, as well as salt springs, salt licks, and fertile savannahs and cane breaks in the central Bluegrass. Long hunters were trekking through the area during this time, and the tales they took back east with them encouraged the first settlers to take a chance in this transmontane wilderness. The first permanent settlements were established in

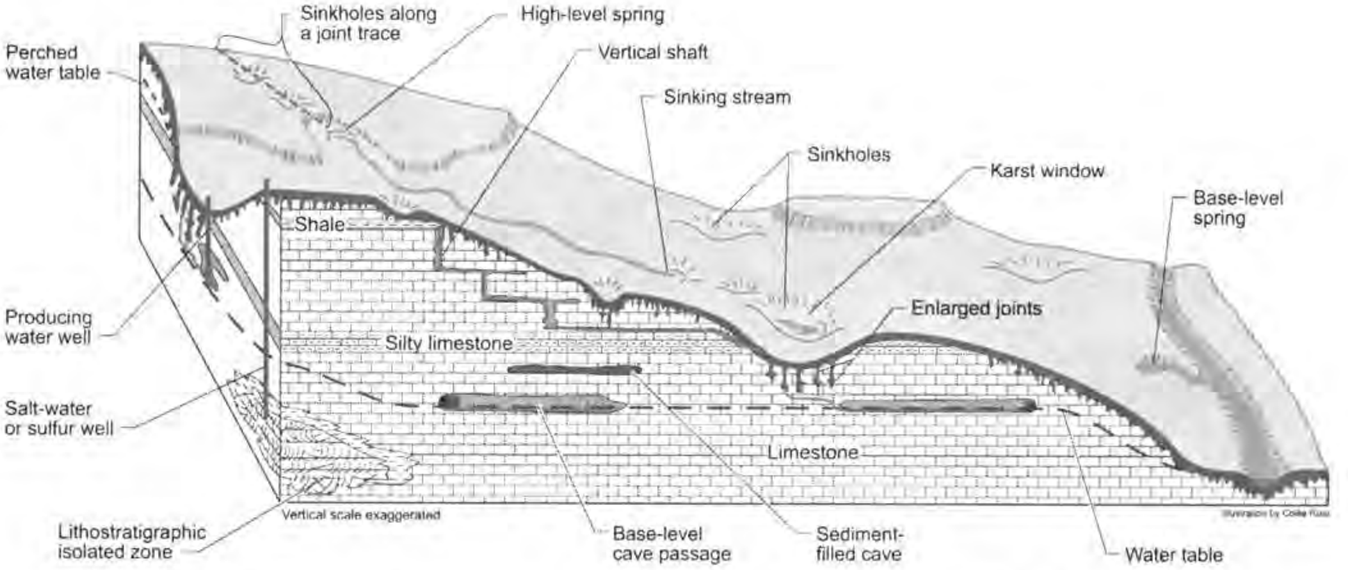


Figure 6. Common features in the Inner Bluegrass Karst Region, from Currens (2001).

1775, but the outbreak of the American Revolution (1776–1783) slowed the early flow of settlers. During the Revolution, British agents supported and encouraged attacks against the Kentucky settlements by the Shawnee and other tribes. As the war came to a close, many who had suffered through the partisan strife in the east moved west to find a quieter life, and the flow of settlers into Kentucky dramatically increased.

The rapidly increasing population, the great distance across the mountains from the state capital in Richmond, and continued problems with hostile natives led to an effort to gain independence from Virginia. Some Kentuckians favored a complete split from the fledgling United States, seeking instead an alliance with France or Spain to secure a trade route down the Mississippi River. However, after 10 (yes, 10!) constitutional conventions held in Danville, Kentucky was admitted to the Union as the 15th state in 1792. Kentucky had grown from an uninhabited native hunting ground to a thriving Commonwealth in 17 short years.

Through the early 19th century, Kentucky rose to prominence as an agricultural, commercial, political, and educational center for the expanding American "West," due in large part to the state's rich soils and convenient location along major rivers. The rivers were key transportation corridors for early Kentucky commerce. Kentucky's livestock, crops, and bourbon whiskey were sold primarily down the Mississippi River through New Orleans, and rapidly gained a reputation for high quality. Early Kentuckians began to exploit the Commonwealth's varied mineral reserves; coal, iron, salt, saltpeter from cave deposits, and timber were exports through much of the early 19th century. Kentucky also played a major role in the political life of the young nation during this time, with Henry Clay and others serving in key roles in Washington, D.C. The earliest schools west of the Appalachian Mountains were established here, and several, including Transylvania University, Berea College, and Centre College, continue to carry a very high reputation for their quality of education.

Civil War

The coming of the mid-19th century, however, saw a rise in sectional tensions, and Kentucky found herself a border state between the seceded southern slave states and the Unionist northern free states. The leaders of the two sides of the Civil War, Abraham Lincoln and Jefferson Davis, were both born in Kentucky, and Kentuckians brokered many compromises that delayed the onset of war. Kentucky occupied a precarious position, with strong industrial and manufacturing ties to the North, but equally strong agricultural and trade ties to the South. Kentucky chose a stance of neutrality through the early months of the conflict, but eventually sided predominantly with the Union. Over 100,000 Kentuckians served in the Union armies, while over 35,000 Confederate soldiers called Kentucky home.

Richard Robinson, a staunch Garrard County Unionist, offered his farm for use as a Federal training camp and recruiting center, and Camp Dick Robinson was established in August 1861. Several Federal regiments from central and eastern Kentucky, as well as eastern Tennessee, were organized there. Confederates viewed the camp as a hostile violation of Kentucky's declared neutrality, which led to the Confederate occupation of far-western Kentucky in September 1861, and the subsequent establishment of a Confederate defensive line through southern Kentucky. Through late 1861 and early 1862, several small skirmishes and small battles were fought across Kentucky. The Federal army used Camp Dick Robinson as a supply depot for the Camp Wildcat (October 1861), Mill Springs (January 1862), and Cumberland Gap (May–June 1862) campaigns (Hughes, 1992).

The late summer of 1862 brought a large-scale Confederate invasion of Kentucky, which was part of a larger effort to move the war into northern territory and out of the South to enable southern farmers time to gather their harvests for the war effort. The battles of Antietam (Maryland), Corinth (Mississippi), and Perryville (Kentucky) ended this offensive. The Battle of Perryville was the largest Civil War battle fought on Kentucky soil, and effectively ended Confederate hopes of occupying the state. On October 8, 1862, approximately 16,000 Confederate soldiers attacked portions of a 60,000-man Union army on the outer margin of the Inner Bluegrass near Perryville, driving parts of the Union army back nearly a mile. Troops on both sides suffered tremendously from thirst before and during the battle due to a severe drought in the region. Confederate troops initially camped at Perryville to secure a water supply from the springs in the area, and attempted to refuse access of the Union troops to the precious pools. The contested springs and sinkholes are associated with the Lexington Limestone. The fighting here was some of the fiercest of the Civil War for the numbers engaged, with over 7,600 men killed, wounded or captured in a half-day battle. At day's end, however, the Confederates realized they were greatly outnumbered and retreated from the field, and ultimately from the state (Noe, 2001).

Because of the poor defensibility of the camp on the gentle Inner Bluegrass hills, Confederate forces easily captured the supplies at Camp Dick Robinson during the Perryville campaign. Upon regaining control of central Kentucky after the Battle of Perryville, Union forces moved the depot a few miles to a more defensible location on the north side of the Kentucky River. The new depot, named Camp Nelson, occupied a naturally fortified position atop the Palisades of the Kentucky River between deeply entrenched tributaries. Steep limestone cliffs prevented attack of the depot from three sides, and only a narrow neck of land on the north side of the facility required fortification against overland approach. The warehouses for the depot were constructed in a blind karst valley nestled within the central part of the facility, which hid the warehouses from outside viewers and potential artillery attacks. Despite numerous forays into the state by General John Hunt Morgan and his Confederate raiders, the depot was never attacked, due in large part to the natural strength of the position (Sears, 1992).

From early 1863 until the close of the war, Camp Nelson served as a major supply depot and waypoint for the Union war effort in central Kentucky. Over 20,000 former slaves and free blacks were recruited and trained as United States Colored Troops here. Many of these recruits brought their families with them to the camp to protect them from Confederate or racist reprisals. At one point, many of these nonmilitary refugees were driven out of the camp by the military authorities. After many of them died of exposure, disease, and starvation, the civilians were allowed to return. The refugee community that was subsequently established remains today as the nearby community of Hall. In 1867, many Union dead buried throughout central Kentucky were moved to Camp Nelson with the establishment of the Camp Nelson National Cemetery (Sears, 1992).

The remainder of the war saw mostly cavalry raids and guerrilla attacks across the Commonwealth. Harsh treatment from occupying northern armies against slave-holding Kentuckians led to a gradual erosion of Unionist support from the state, until the end of the war, when sympathies for the defeated Confederates became more prevalent. Many famous feuds, especially in eastern Kentucky, had their roots in animosities developed during the Civil War.

Postwar Years

Following the Civil War, Kentucky did not regain her prominent position as a national economic and political leader. The unsettled years of conflict and discord had discouraged additional development of industry to the state, and the geographic isolation of the state became more acute as railroads took precedence over steamboats as the primary mode of transportation. Completion of railroads in the late 19th and early 20th centuries allowed extensive development of Kentucky's eastern coal field, while construction of the Federal Interstate Highway System in the mid-20th century facilitated industrial development across much of the state by providing inexpensive and reliable transportation corridors. Many of Kentucky's communities are now experiencing an unprecedented period of growth and expansion, which has led to numerous problems related to construction on the karst terranes common across the state.

Bourbon Whiskey Production

Differing and conflicting versions of the history of Kentucky bourbon production exist. What is well accepted is that the production of whiskey in the Bluegrass Region began in the late 1700's. Many of the first settlers in this area were of Scots-Irish descent, and brought their whiskey-making knowledge with them to America. Because of the fertile soil, harvests of their crops of corn and other grains quickly outgrew what one family could reasonably consume. The sale of this surplus grain was problematic due to difficulties in transporting it to markets in more populated areas because of its bulky and perishable character. Fermenting and distilling these grains into whiskey solved both of these problems. A wagon or barge full of whiskey barrels could easily survive the trip to larger markets, as well as bring a much higher price than the original corn or other grains once it got there. By the mid-1800's, the sale of this whiskey became so popular that farming in central Kentucky became secondary to whiskey production.

This "corn whiskey" would later evolve by accident into what is known as bourbon today. One of the first pioneers in whiskey production, the Rev. Elijah Craig of Georgetown, Ky., used one batch of white oak barrels even though they had been partially burned in a cooperage fire. By the time these barrels had made it all the way down the Ohio and Mississippi Rivers to New Orleans, the raw corn whiskey had aged in the charred oak, giving it a mellower, caramel taste and amber color. The customers loved this "new" product, and its popularity caused the distillers to purposely toast or char the interiors of their barrels before adding the whiskey. Much of the whiskey that was shipped out of central Kentucky went through Bourbon County, which was stamped on the barrel. Thus, regional recognition of the whiskey from Bourbon County, or "Bourbon whiskey," was started. Today, Bourbon whiskey is legally defined as being made from at least 51 percent corn, being aged for at least 2 years in new white oak barrels charred on the inside, and bottled at a minimum of 80 proof (40 percent alcohol by volume).

The geology and environment of the Bluegrass support the production of bourbon in several ways. These include the groundwater, the fertile soil for grain production, the local native white oaks for the barrels, and the climatic temperature swings needed to properly age the bourbon. The most important of these is undeniably the water. All of the distilleries in this area obtain their water from limestone springs or limestone aquifers. The Ordovician limestones act as a natural filter, yielding clean, iron-free water for brewing (Thornton, personal commun., 2001). The lack of these impurities prevents undesired flavors from forming in the final product.

Thoroughbred Horse Industry

Early pioneer settlers arriving after Daniel Boone in the late 1700's came by horseback or on foot through Cumberland Gap, in the southeastern part of Kentucky. The horse remained the predominant means of transportation at that time, and their population increased as the central and southern Bluegrass Region was settled. Boonesborough was the first town to adopt a law to preserve and improve horse breeds (Kentucky Horse Park, written communication, 2001).

Many social and cultural changes took place in Kentucky after the Revolutionary War as new settlers arrived in the Bluegrass area. The first Kentucky racetrack was established in between Boonesborough and Harrodsburg. Racing became so popular that the downtown streets of Lexington were used as racetracks (Kentucky Horse Park, written communication, 2001). Many of these settlers came from Virginia, where the "English" way of life was still prevalent. This included love of land, love of the horse, love of horse racing, and fine breeding (Kentucky Horse Park, written communication, 2001). Virginians encouraged the breeding of thoroughbreds, as the first one, Bull Rock, was imported to Virginia in 1730 from England.

The first thoroughbred made its way to Kentucky in 1779. The growing popularity of racing, in addition to the arrival of English thoroughbreds, boosted Kentucky's young breeding industry to a national level. The early settlers referred to horses with English thoroughbred lineage as "thoroughbred-bred blooded horses" or "high bred" horses (Kentucky Horse Park, written communication, 2001). By the 1800's, Kentucky was a leader in thoroughbred breeding and had a national demand for its horses. With Kentucky in the national breeding spotlight, the best of American thoroughbred bloodlines were brought into Kentucky's horse farms, solidifying the thoroughbred industry.

During the Civil War, thoroughbred racing was disrupted and almost eliminated in the South. Many Kentucky horse farms suffered when guerrillas stole horses to use in the war. A breed of horse known as the Kentucky Saddler was the favorite cavalry mount of the Confederates (Kentucky Horse Park, written communication, 2001). The Confederacy's initial success was due, in part, to the quality of the Saddler as a cavalry horse. Racing ceased in Louisville, but Lexington missed only one racing season during the war, when Union soldiers were camped at the racetrack. With southern racetracks destroyed, the North took control of racing after the Civil War. Kentucky still remained the capital of the horse industry, as wealthy folk bought Kentucky horse farms to raise and breed horses and found new markets in the Northeast, Midwest, and West.

The horse industry has played a major role in Kentucky's history, and will continue to do so in the future. Kentucky's horse farms flourish due to the fertility of soils that help build strong bones, and abundant water supply fed by Lexington Limestone springs. Kentuckians benefit from the horse industry in a recreational fashion by participating in many types of equine sporting events. One such event is the famous Kentucky Derby, where Kentucky thoroughbred farms produce a large percentage of the winners. Kentucky's affection for the horse allows various horse industries to bring economic growth, knowledge, and tradition to the Bluegrass State.

Acknowledgments

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Field Trip Roadlog

The field trip begins in downtown Lexington. Lexington was originally named for the Revolutionary War battle by a party of hunters camped at nearby McConnell Springs. Figure 7 shows the field trip route. For each field trip stop, we note selected previous field trips that have utilized the same roadcuts, in case readers wish to further explore the geology of those sites.

Depart downtown Lexington and drive north on North Broadway (U.S. 27/68). Outside of Lexington, North Broadway becomes known as Paris Pike. Turn left (west) onto Iron Works Pike (Ky. 1973). This road traverses the Inner Bluegrass in a roughly east–west direction and was originally used to transport iron products from early iron works in Bath County to boat landings near Frankfort, the head of Kentucky River navigation at that time.

Stone Fences

One of the most honored symbols of the Kentucky Bluegrass landscape is the stone fence (Fig. 8). These low walls once lined almost every turnpike and horse farm in central Kentucky (Murray-Wooley and Raitz, 1992). This field trip will pass numerous examples throughout the day. In the 18th and 19th centuries, large groups of immigrants from Ireland, Scotland, and northern England settled in this area of Kentucky. These immigrants encountered rocks and landscapes that were similar to what they had left in Great Britain, due to the Middle to Upper Ordovician strata exposed here in the Bluegrass. The thinly bedded limestones of the Lexington Limestone lent themselves especially well to "dry" fence (mortarless) construction used by these immigrant masons. Due to the alternating layers of clay or shale with layers of limestone less than 6 inches thick, blocks of appropriate size were easy to quarry with simple hand tools. Many of the original fences have been lost due to neglect, development, or agricultural efficiency efforts that encouraged use of wire or plank fencing.

Continue westbound along Iron Works Pike, crossing Russell Cave Road (Ky. 353) and Newtown Pike (Ky. 922).

Spindletop Farm

In 1925, Miles Frank Yount struck oil at the Spindletop Field in Beaumont, Tex. Within 5 years, this field had produced more that 50 million barrels of oil, spurring the Texas oil boom. When Miles Frank died 8 years later, his widow, Mildred (Pansy) Yount, decided to relocate to the Bluegrass Region of Kentucky to start anew and breed American Saddlebred horses. At great expense, Spindletop Farm was created on 800 acres (later expanded to 1,066) just north of Lexington, and a 45,000-square-foot mansion was built on site in 1935. This mansion, which took 2 years to complete, was intended by Mrs. Yount to be a "showplace of Kentucky, a modern mansion of classical architecture" (University of Kentucky, 2001).

Unfortunately, her family was considered "new money" by the Kentucky bluebloods, and was never accepted into Bluegrass high society. Mrs. Yount left the Spindletop Farm in 1955, and it was sold to the University of Kentucky in 1959. Today, the mansion and 52 acres of surrounding land are used as a private club restricted to UK faculty, staff, and alumni. Ironically, much of the remaining land is used by State facilities that support the petroleum and mining industries that gave the Yount family the wealth to build the farm in 1935. These facilities include the Kentucky Geological Survey's Well Sample and Core Library, the Asphalt Research Institute, and the UK Center for Applied Energy Research.

Kentucky Horse Park

Located in Lexington, in the heart of the Bluegrass, the Kentucky Horse Park is a working farm with 1,032

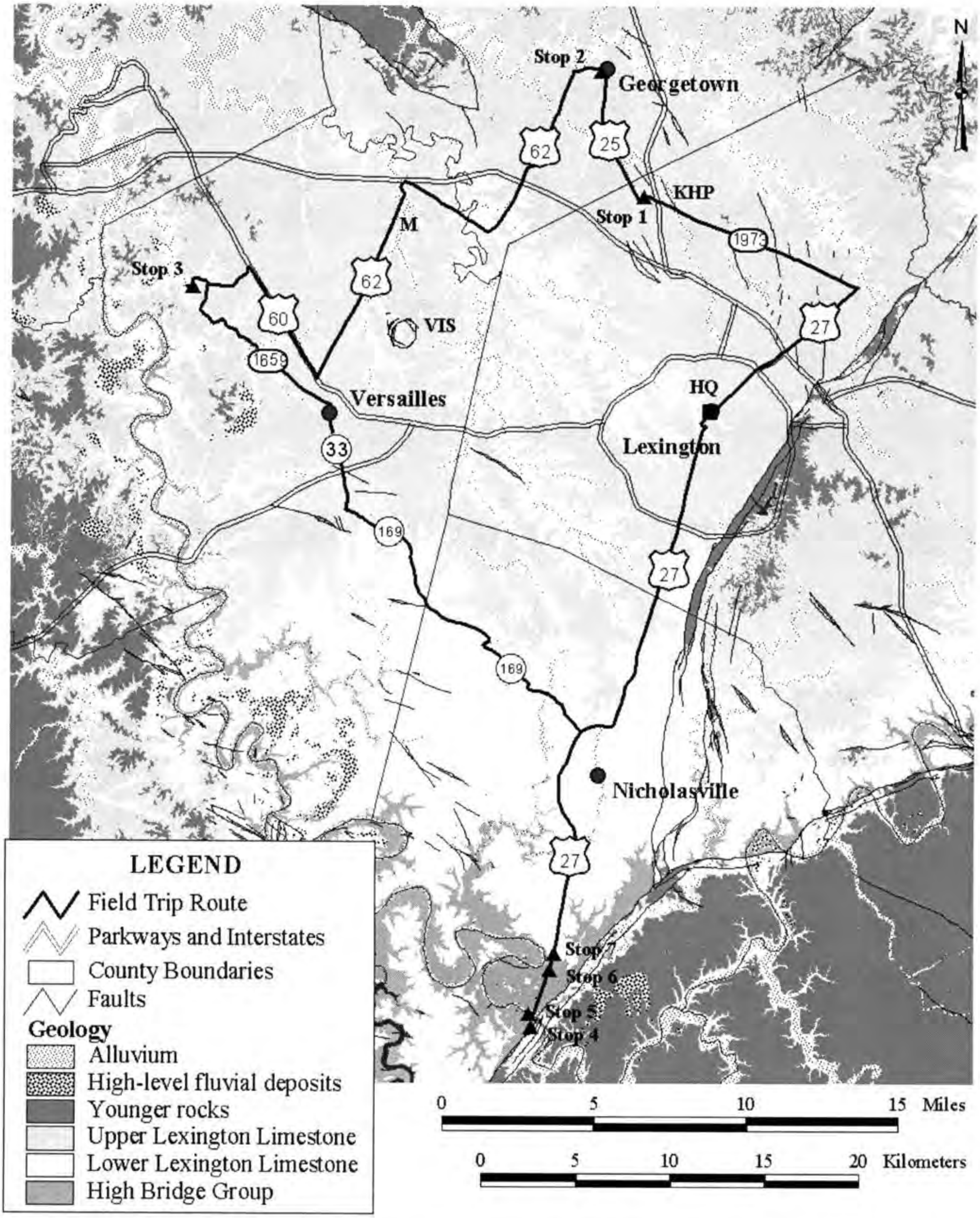

Figure 7. Map of the field trip area, showing generalized bedrock geology, structures, and field trip route. HQ: field trip headquarters; KHP: Kentucky Horse Park; M: Midway; VIS: Versailles Impact Structure.

Figure 8. (a) A dry stone fence on a horse farm along Newtown Pike, Fayette County. (b) Detail of the same fence.

acres and 32 mi of white plank fencing. Like many other horse farms, the Kentucky Horse Park has taken advantage of the gently rolling topography and fertile soil for its horses. The 40 different breeds of horses that reside there make the park unlike any other. Museums, shows, walking tours, and educational programs are just a few of the many things the park has to offer.

Continue on Iron Works Pike past the interchange with Interstate 75, and pull off the road just west of the railroad underpass.

Stop 1. Roadcut, Iron Works Pike, Tanglewood Member of the Lexington Limestone (Stop 4 of Thrailkill, 1984)

The purpose of this stop is to examine an outcrop of the Tanglewood Member of the Lexington Limestone. Stratigraphy, lithology, paleontology, structure, and hydrology will be discussed, along with how the geology is related to horse farms and stone fences of the Inner Bluegrass. Note the thin, planar to irregularly surfaced limestone beds, some of which exhibit crossbedding. The limestone is interbedded with shales, which are thin and discontinuous. These "shales" consist of more than 50 percent calcite and most likely do not inhibit the development of karst features (Thrailkill, 1984). Shallow karst solution features can be seen on all parts of the outcrop. Two small conduits are present on the south side of the road. Phosphate nodules are present as dark gray, abraded grains or masses. Many large stromotoporoid fossils are present throughout the roadcut.

Stop 1 is located in an interbasin area adjacent to the Royal Springs groundwater basin (Fig. 9). Flow in nearby Cane Run is captured into underground conduits and ultimately emerges in or near Royal Springs in Georgetown. Flow in the interbasin area is primarily in epikarst systems and in shallow joint-controlled flow paths that emerge at high-level springs. Dolines, solution-enlarged joints ("cutters"), and small, shallow phreatic conduits are well-exposed at this stop. The current groundwater flow is inferred to be only a few feet below road level (Thrailkill, 1984).

Two regional joint sets can easily be seen within the Tanglewood limestones at this stop. The primary set trends northwest and is parallel to the numerous minor normal faults of the Georgetown-Gratz Fault System. The second, conjugate set of joints trends to the northeast. Although none of the Georgetown-Gratz faults are exposed in this roadcut, two have been mapped in the vicinity to the north and northeast (Cressman, 1967). These joint sets can be observed not only from the actual fracture surface plane, but also from karst features that are often associated with them. This tendency for joints to act as groundwater conduits has probably led to the rectangular drainage pattern of Cane Run. The primary flow direction of Cane Run is parallel to the primary joint set (northwest), and the majority of its tributary drainage is parallel to the secondary joint set (northeast).

Continue west on Iron Works Pike to the intersection with U.S. 25, and turn right (north). Follow U.S. 25 into Georgetown. Turn left onto Main Street (U.S. 62/460), and then left again to Royal Springs Park.

Stop 2. Royal Springs (Stop 5 of Thrailkill, 1984; Stop 7 of Spangler, 1992)

Royal Springs is the largest spring in the Inner Bluegrass karst region, and has served as the primary municipal water supply for Georgetown for over 200 years. The spring, originally known as "Big Spring," is fed from a large groundwater basin that extends southeastward to the northern parts of Lexington (Fig. 9) (Currens and others, 2002). Intense industrial development in northern Lexington and two Interstate highways (64 and 75) create a significant risk of major contaminant

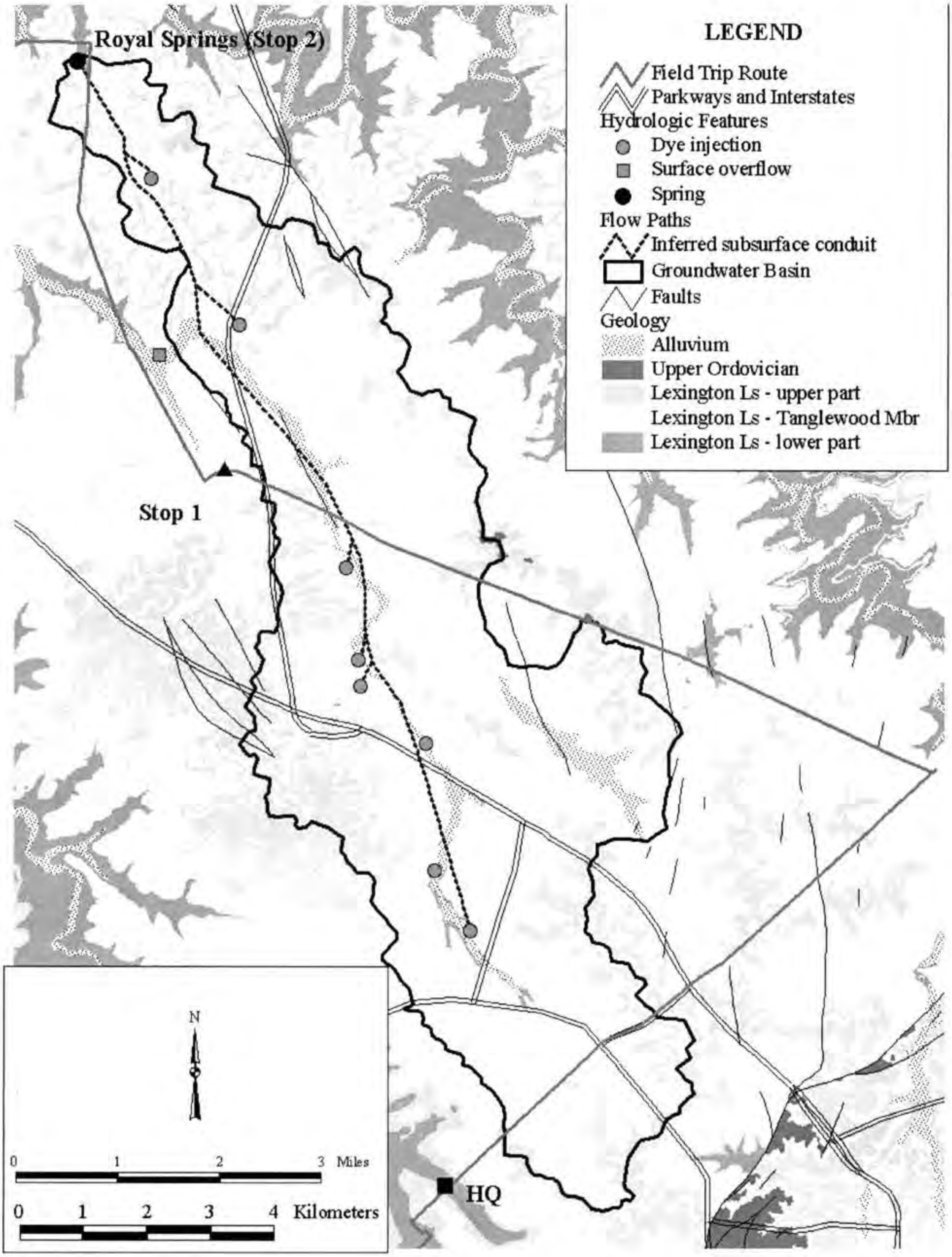

Figure 9. Map of the Royal Springs groundwater basin.

spills into the Royal Springs system. Much of the flow in the karst conduit feeding Royal Springs is captured from surface flow in the middle portion of Cane Run by a series of swallets. Stratigraphy plays a role in the capture of the surface flow of Cane Run, as most of the sinks enter the subsurface only where the Brannon Member is absent or where the Cane Run Bed has been truncated by surface erosion (Fig. 10). Flow in the groundwater basin closely parallels mapped surface faults, suggesting very strong structural or fracture control on development of the conduit system. Based on dye-dilution studies, only about half of the flow in the subsurface conduit emerges at the spring, with the rest entering surface stream below the spring along bedding planes and fractures. No other major spring has been identified to carry this flow.

John McClelland and other pioneers constructed a fort near the Big Spring in 1776. After an attack by Mingo Indians in late 1776, the settlers abandoned the fort and spring. In 1786 Elijah Craig, a Baptist minister from Virginia, led a new party of settlers to the site to found the town of Lebanon, later renamed Georgetown. In the early days, the spring was the site of a ropewalk, fulling mill, and paper mill. According to legend, Craig produced the first "Bourbon" whiskey at the spring in 1789. Throughout the 19th century, the spring was the popular site for fishing, swimming, and almost all of the local baptisms. Townspeople filled buckets with water from the spring to meet their daily needs. In 1890, the Georgetown Ice Company sold mineral-rich ice from the spring. Georgetown established its first municipal water works here in 1899. The spring continues to serve as the primary water supply for Georgetown, but is now supplemented by water from the North Elkhorn Creek and the Kentucky River via a pipeline. The area has served as commons for the town for much of its history, with the park being expanded and improved in the 1970's and 1990's.

Follow U.S. 62/460 west out of Georgetown, then turn south on U.S. 62. Follow U.S. 62 through the town of Midway.

Meteorite Impacts in Kentucky

To date, fragments from at least 27 meteorites have been found within Kentucky (Ehmann, 2000). In addition, there are three known meteorite impact structures in Kentucky: two in the Bluegrass Region and one in the Pine Mountain Overthrust Belt in the extreme southeastern corner of the state (Fig. 4). This field trip will pass close to the Versailles meteor impact structure, which is east of U.S. 62 and 3 mi northeast of Versailles, Ky. (Fig. 7). This highly eroded remnant of an impact (ring faults and associated curvilinear streams and karst features) is on private land, and inaccessible to the public. The exact age of this structure is not known, but is estimated as post-Middle Ordovician.

At the intersection of U.S. 62 and U.S. 60, turn right (north) onto U.S. 60. After 4.2 mi, turn left onto Ky. 1685. Bear right onto Ky. 2331, and bear right again to reach the distillery, which will be on your left.

Stop 3. Labrot & Graham Distillery, Versailles, Ky.

This historic distillery was first built in 1812 in Versailles, Ky. (6 mi to the southeast), and moved to its present location along Glenns Creek in 1832. Both the distillery building and the aging house are built of Tyrone Limestone from local quarries. The water used for brewing and distilling is collected from both a limestone spring, and a shallow limestone aquifer. Further details about the distillery and the specific bourbon production process used by it will be given on the distillery tour.

Return to U.S. 60, and turn right (south). On the outskirts of Versailles, bear right and follow U.S. 62 (Business) into the downtown area. Continue straight through downtown, now following Ky. 33 south out of town. Beyond the interchange with the Blue Grass Parkway, turn left onto Ky. 169. Follow Ky. 169 across the Bluegrass countryside, crossing several other highways, eventually reaching U.S. 27. Turn right (south) on U.S. 27. On the hill past the Kentucky River bridge, turn around and return on northbound U.S. 27. Pull to the side of the road just before (south of) the Kentucky River bridge.

Stop 4. U.S. 27 Roadcuts, Camp Nelson, Ky. (Stops 8–9 of Black and Haney, 1975; Stop 5 of Kuhnhenn and Haney, 1986; Stop 2C of Ettensohn, 1992b; Stop 4 of Greb and others, 1997)

A portion of the Kentucky River Fault Zone is exposed along U.S. 27, south of Camp Nelson, Ky. The fault zone crosses the highway at a fairly low angle, and proceeds northeast, forming the steep-walled valley that Little Hickman Creek follows to the Kentucky River (Fig. 11). The structures observed here are fairly complex due to three different factors. First, there has been more than one period of movement along this fault zone (some of which may have been reverse in nature during the Appalachian orogenies). Second, the full width of the fault zone involves numerous individual faults that may or may not have moved simultaneously. And third, the net fault motion is oblique, with both left-lateral and normal, down-to-the-southeast motion. The east side of the

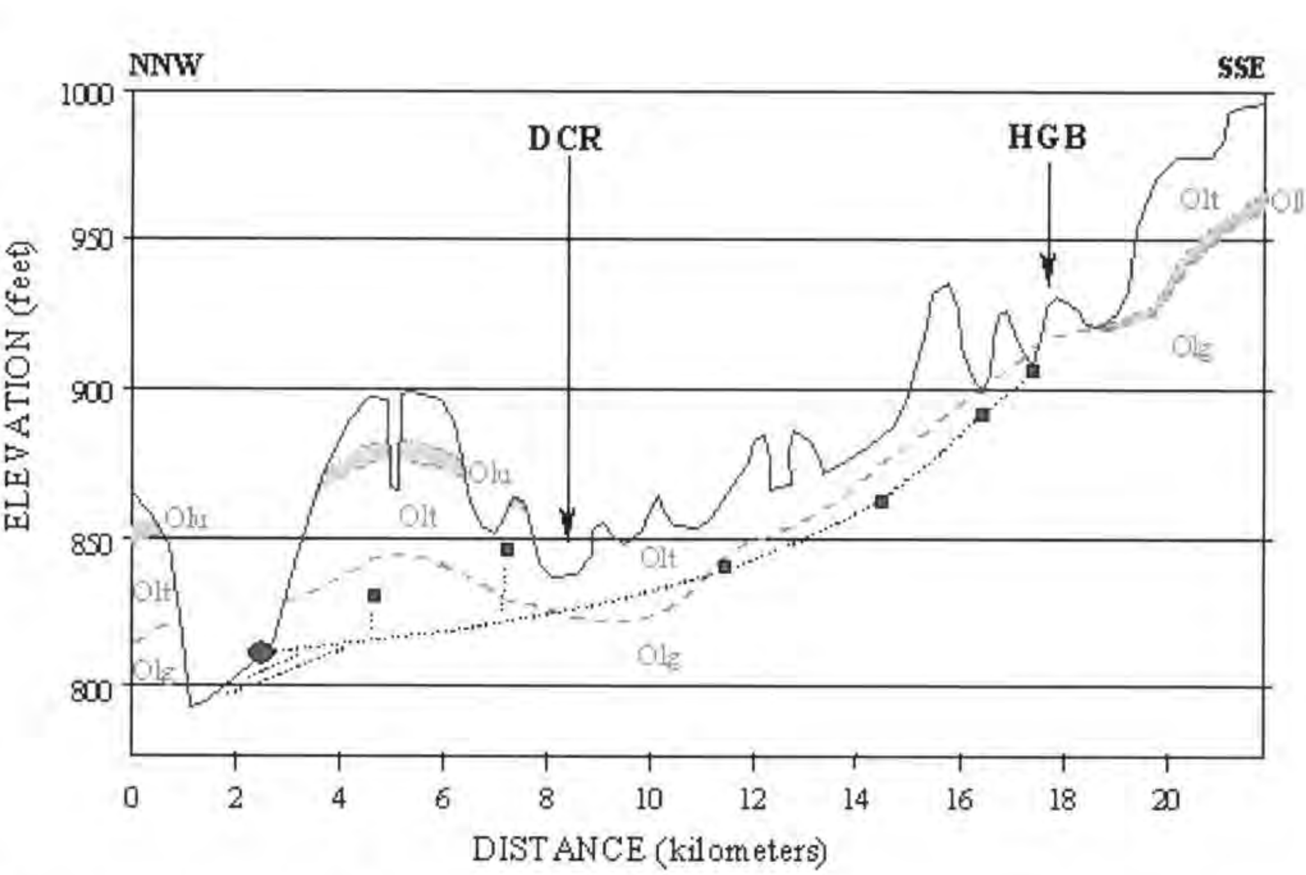

Figure 10. Generalized profile of the Royal Springs groundwater basin. Modified from Cressman (1967) and Thrailkill and others (1982). Dashed line is the approximate contact between the Grier and Tanglewood Members; dotted line is the inferred conduit profile; squares mark the base of swallets; circle represents Royal Spring. DCR: downstream end of Cane Run swallets; HGB: head of groundwater basin; IB: interbasin area; Olg: Grier Member of Lexington Limestone; Olb: Brannon Member of Lexington Limestone; Olt: Tanglewood Member of Lexington Limestone; Olu: unnamed shaly limestone in Tanglewood Member.

roadcut is downdropped approximately 300 ft so that the older Camp Nelson Limestone and the younger Lexington Limestone both occur at road level (Wolcott, 1969). Figure 12 is a detailed sketch of the features along the outcrop on the eastern side of U.S. 27 (modified from Gilreath and others, 1989).

Stop 4a. Lower Lexington Limestone

The lithology, stratigraphy, paleontology, and structure of the Curdsville and Grier Members of the lower Lexington Limestone are discussed here. Note the ball-and-pillow bed (seismite?) in the lower part of the roadcut. Some of these "fractures" in this roadcut are actually tiny faults with minor displacements that were probably due to compaction or other readjustment of the strata, but do not account for any substantial movement along the Kentucky River Fault Zone.

Stop 4b. Kentucky River Fault Zone

This section contains the exposure of the primary fault and some tilted beds (Fig. 13) in the footwall. The tilted beds are a kink fold, probably due to local rotation from left-lateral motion in the fault zone. This may be evidence for local transpression within a restraining bend of the fault zone. The exact axis of the kink fold is weathered and covered at this location. This makes it appear to be a fault, but the same fold is exposed on the other side of the highway with individual, unfaulted beds visible across the entire fold.

Stop 4c. High Bridge Group

The Camp Nelson Limestone of the High Bridge Group is exposed on the east and west sides of the road. The lithology, stratigraphy, paleontology, and structure of the High Bridge Group will be discussed here. Note the more massive bedding of the High Bridge rocks compared to the thin-bedded Lexington Limestone. Several

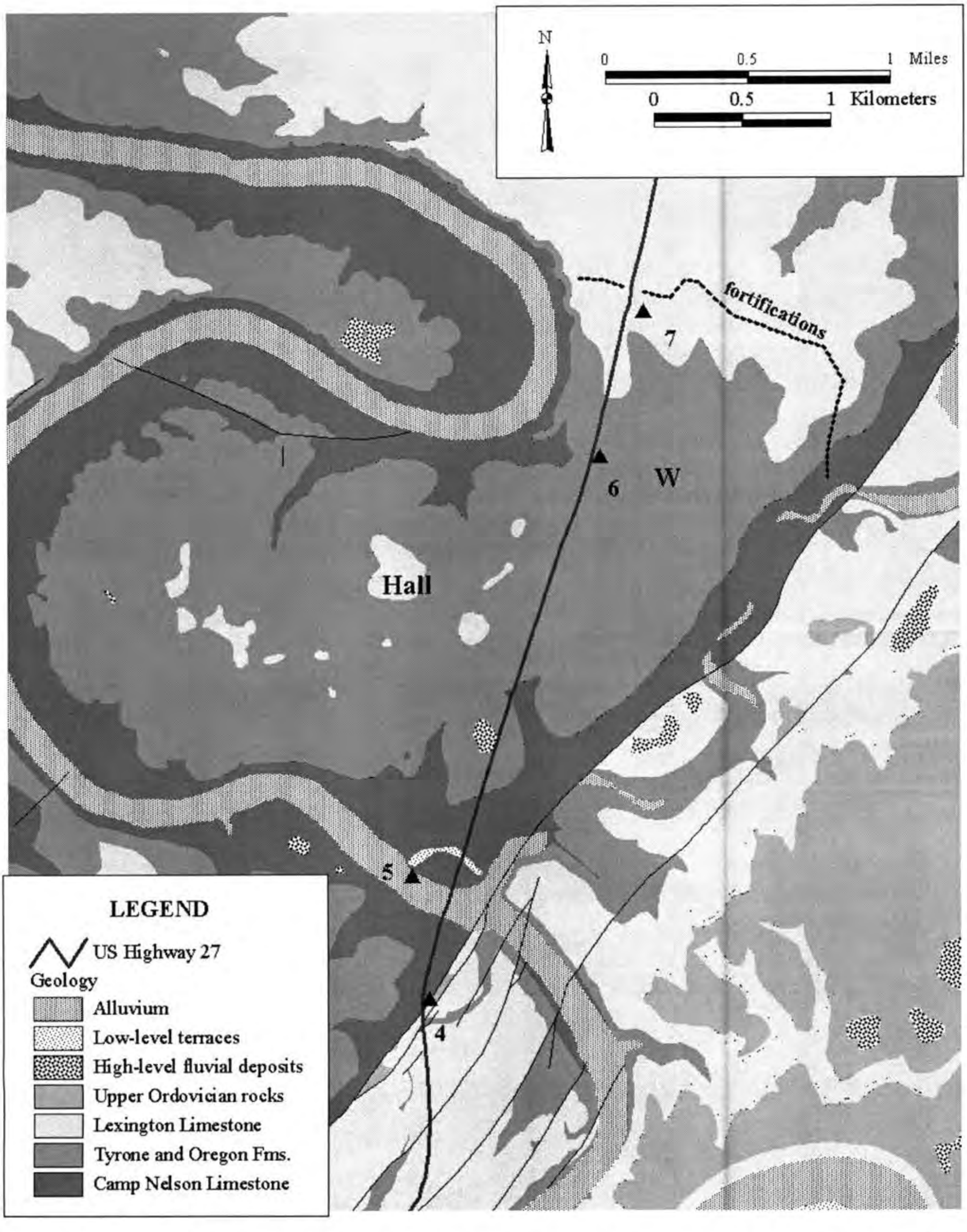

Figure 11. Map of the Camp Nelson area, showing bedrock geology, structures, Civil War fortifications, and field trip stops.

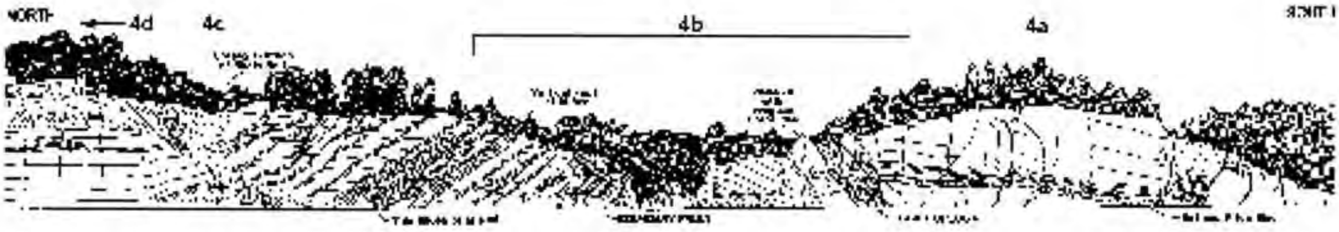

Figure 12. Profile of Kentucky River Fault Zone and associated deformation exposed in a roadcut along northbound U.S. 27. Modified from Gilreath and others (1989).

prominent fractures can be seen in the roadcuts along both sides of the highway (Fig. 14). Many of the fractures have been solutionally widened and/or mineralized, by fault-related fluids when the faults were active and also by the more recent weathering and solution processes.

Stop 4d. Kentucky River Geomorphology

The northern end of the exposure affords a view of the Kentucky River Palisades and associated landscape features. Three generations of stream valley are identifiable in this portion of the Palisades: a high-level upland remnant of the Old Kentucky River, a low-level terrace system, and the recent floodplain. Impoundment of the Kentucky River with a series of locks and dams has altered the fluvial system. Of historical importance is the deep incision of the Kentucky River and its tributaries. The linear incision of Little Hickman Creek was controlled by a graben in the Kentucky River Fault Zone. A Bluegrass Hills landscape has developed on downdropped Upper Ordovician strata to the southeast, while Inner Bluegrass topography has developed adjacent to the Palisades to the north and northwest.

Continue north on U.S. 27 over the bridge and up the long hill, and turn right onto Old U.S. 27. Follow the road down to the abandoned iron highway bridge.

Stop 5. Old U.S. 27 Bridge (Stop 3 of Andrews, 2001)

From the now-abandoned Old U.S. 27 bridge over the Kentucky River, we have a clear view of the depth and beauty of the Palisades. The bedrock in the nearby roadcut was described as stop 4 in Kuhnhenn and Haney (1986) and stop 1 in Kuhnhenn and others (1981). The Palisades resulted from incision of the meandering Old Kentucky River over 300 ft into the limestone plateau of the Inner Bluegrass within the last 1.5 million years, based on radiometric dating elsewhere by Granger and Smith (2000) and Granger and others (2001). The steep-walled gorge served as a barrier to transportation between the northern and southern parts of the Bluegrass, and most crossings were at fords passable only in good weather. Ironically, the Kentucky River served as the main transportation corridor for moving timber and coal out of eastern Kentucky's Cumberland Plateau coal fields, although the river was only suitable for this dur-

Figure 13. Tilted beds in the kink fold associated with the Kentucky River Fault Zone.

Figure 14. Large fractures and massive bedding in the Camp Nelson Limestone. Note the kink fold and faulted zone in the left part of the picture.

ing periods of high flow when the shallow fords and riffles could be safely navigated by rafts and flatboats. In the early 20th century, the Palisades were a frequent subject of renowned Kentucky Impressionist Paul Sawyier. Modern residential and commercial development of the Palisades versus environmental and ecological preservation is a growing debate in the region.

Return up Old U.S. 27 to the modern U.S. 27, and turn right (north). Just beyond the entrance to Camp Nelson National Cemetery, turn right (south) onto the frontage road (Ky. 3026). Park in the driveway of the first barn on the left.

Stop 6. Camp Nelson Karst Valley (Stop 2 of Andrews, 2001)

Here we will visit the blind karst valley in which the warehouses for Camp Nelson's depot were constructed, and be able to view some of the remaining foundation stones used for the warehouses. Field trip participants will be given a brief taste of Civil War infantry drill and tactical training. We will have the opportunity to view some of the karst features while in the warehouse valley. The stream in the blind valley is fed by several high-level springs perched above bentonites in the Tyrone Limestone. The surface flow sinks in the western end of the valley and emerges as a spring in the nearby incised valley of the Kentucky River.

Travel north on the frontage road, and turn right into the driveway of the Camp Nelson Heritage Park.

Stop 7. Camp Nelson Perry House

The Perry House served as the headquarters for the Commissary and Quartermaster departments at Camp Nelson. The camp headquarters was originally located in the area of the modern highway to the southeast. From this area, visitors can view remnant and reconstructed earthworks from the original fortifications, the locations of other original buildings and structures on the post, as well as one of the high-level springs feeding the surface flow in the blind karst valley to the south.

Return to U.S. 27, and turn right (north) and continue back to the meeting headquarters in downtown Lexington.

End of Trip

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Field Trip 8: The Geology of Pound Gap on the Pine Mountain Thrust Sheet: Eastern Kentucky and Virginia, by Stephen F. Greb.

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Middle and Late Ordovician Seismites from Central Kentucky

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Introduction

Historic and prehistoric seismites, or seismically deformed sediments (Seilacher, 1969, 1984; Cita and Lucchi, 1984), abound in recent sediments of the Midcontinental New Madrid and Wabash Valley areas within and near western and west-central Kentucky (e.g., Obermeier and others, 1993, 1996; Wesnousky and Leffler, 1994), and yet there is only scant mention of similar features from the older, Midcontinental sedimentary record. If the abundance of seismites in the recent sedimentary record is any indication of expected frequency, then what has happened to indications of older Phanerozoic seismicity that should be present in the sedimentary record? We believe that such seismites are present and locally abundant, but that they have been systematically overlooked and misinterpreted. In fact, the Middle and Upper Ordovician rocks of central Kentucky are replete with horizons of soft-sediment deformation (Fig. 1), commonly called pseudonodules, ball-and-pillow structures, contortion, or dikes, and regularly ascribed to submarine slope failure or simple loading. In 1990, Rast and Moshier first suggested that most of these horizons are seismites, and subsequent work (Pope and Read, 1992; Rast and Ettensohn, 1995; Pope and others, 1997; Rast and others, 1999; Ettensohn and others, 2002a, b) continues to affirm those interpretations. These interpretations are important because most currently recognized seismites have been recorded from terrestrial to marginal-marine, Tertiary or Quaternary clastic sequences on active margins. The possibility of seismic influence in older, intracratonic marine sequences, especially epicontinental carbonates, has been seldom seriously considered. Yet the Paleozoic rocks of central Kentucky provide ideal situations in which to examine paleoseismicity, for deposition occurred in an area that sits astride two ancient rift systems that were periodically reactivated. Moreover, there is growing evidence in the area for reactivation of rift structures by coeval,

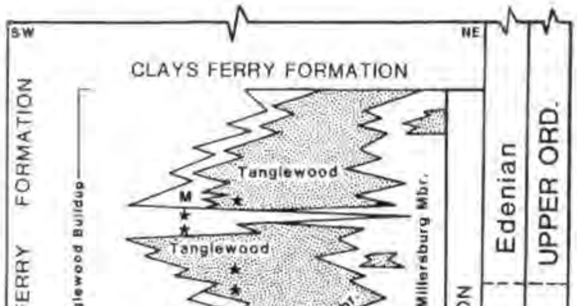

Figure 1. Generalized stratigraphic column for the Lexington Limestone of central Kentucky, showing the relative positions of likely seismites (stars). Lower parts of the Lexington through the Brannon reflect regional transgression; upper parts represent a regressive shoal complex (Tanglewood and Millersburg Members) that comprises the Tanglewood buildup, a series of stacked shoals that intertongue in all directions with deeper-water rocks in the Clays Ferry Formation.

Taconic, far-field processes (Ettensohn, 1992; Ettensohn and others, 2002a).

More important, however, the abundance of such putative seismites in the older Phanerozoic record indicates that in many areas seismicity was an important aspect of the fossil sedimentary record. Hence, on this trip we would like to suggest the importance of craton-interior seismicity in marine epicontinental sedimentation, how some of its effects can possibly be quantified from the fossil record, and how its historical significance can contribute to increased understanding of Midcontinental earthquake hazards.

Regional Framework

This trip will examine probable seismites in Middle and Upper Ordovician carbonates deposited on the Lexington Platform (Fig. 2). The platform resulted from collapse of the much larger Blackriverian carbonate platform along old basement lineaments during the Blackriverian-Rocklandian transition, probably due to bulge-related reactivation of basement structures and later far-field, tectonic adjustments related to coeval inception of the Taconic tectophase of the Taconian Orogeny (Ettensohn and others, 2002a). Reactivation of old structures across the Black River Platform apparently generated a series of structural lows and highs. The highs acted as the foundation for the extensive buildup of carbonates found on the Galena Shelf and Lexington Platform (Figs. 2–3), whereas intervening low areas like the Sebree Trough were sufficiently depressed to make contact with open seas to the south, which in the existing paleogeographic and paleoclimatic setting promoted quasi-estuarine circulation. This circulation funneled deep, cold, mineral-rich waters, inimical to carbonate deposition, from the southern margin of Laurentia into structural lows between the platforms, resulting in the suppression of carbonate deposition there. This circulation also promoted upwelling of nutrient-rich waters into adjacent, shallow platform waters, not only affecting proliferation of fauna, but also rapid upward accretion of the skeletal, platform carbonates that comprise most of the Lexington Limestone. The presence of phosphatic limestones and mineralized hardgrounds, which we will also observe at several stops, similarly relates to brief episodes of upwelling and cessation of carbonate deposition that accompanied periods of regional deepening or changing climatic regimes. The growing Lexington Platform not only deepened and canalized waters in intervening lows, but also formed a barrier to major clastic influx from the east, thereby enhancing sediment starvation in the lows. Hence, the interplay of reactivated structures and paleogeography stimulated a major cold-water influx onto the platform, which changed broad sedimentary and faunal regimes, and during 3 million years of mid-Kirkfieldian to late Shermanian time generated carbonate platforms and an intervening Trenton surface of omission and corrosion, expressed as a trough-like corridor of sediment starvation called the Sebree Trough (Figs. 2–

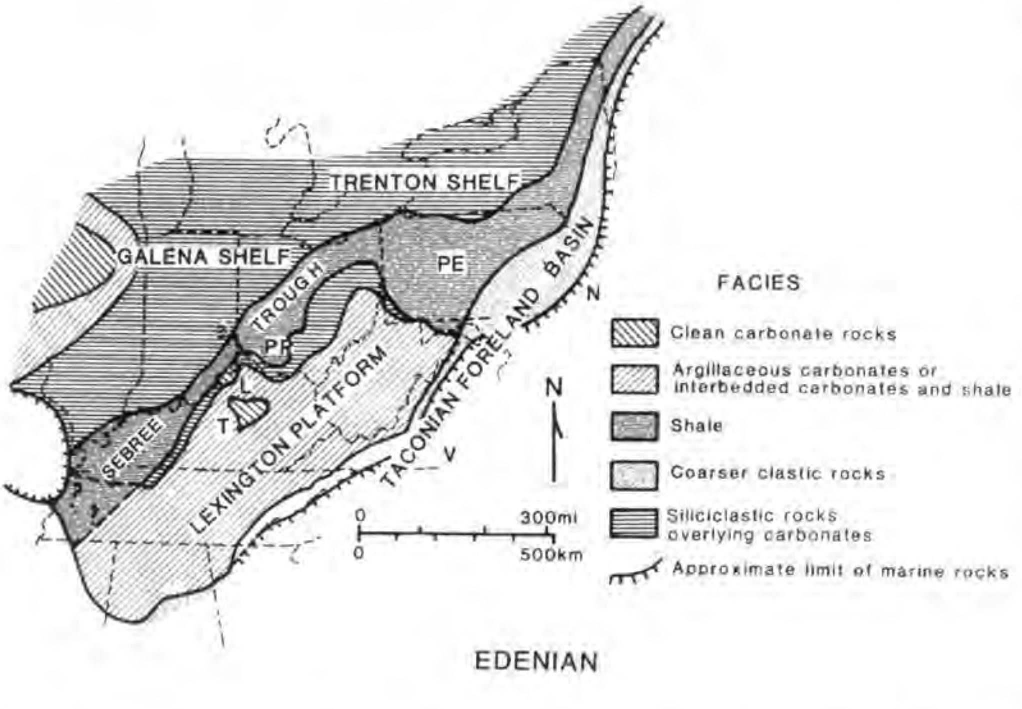

Figure 2. Schematic reconstruction of east-central United States during Late Ordovician (early Edenian) time, showing major paleogeographic features, most of which developed along basement structural lineaments (compare with Fig. 4). The Tanglewood buildup (T) and Louisville High (L) were important areas of local uplift. PP=Point Pleasant Basin; PE=Pennsylvanian Embayment; V=Virginia Promontory; N=New York Promontory. Adapted from Keith (1989).

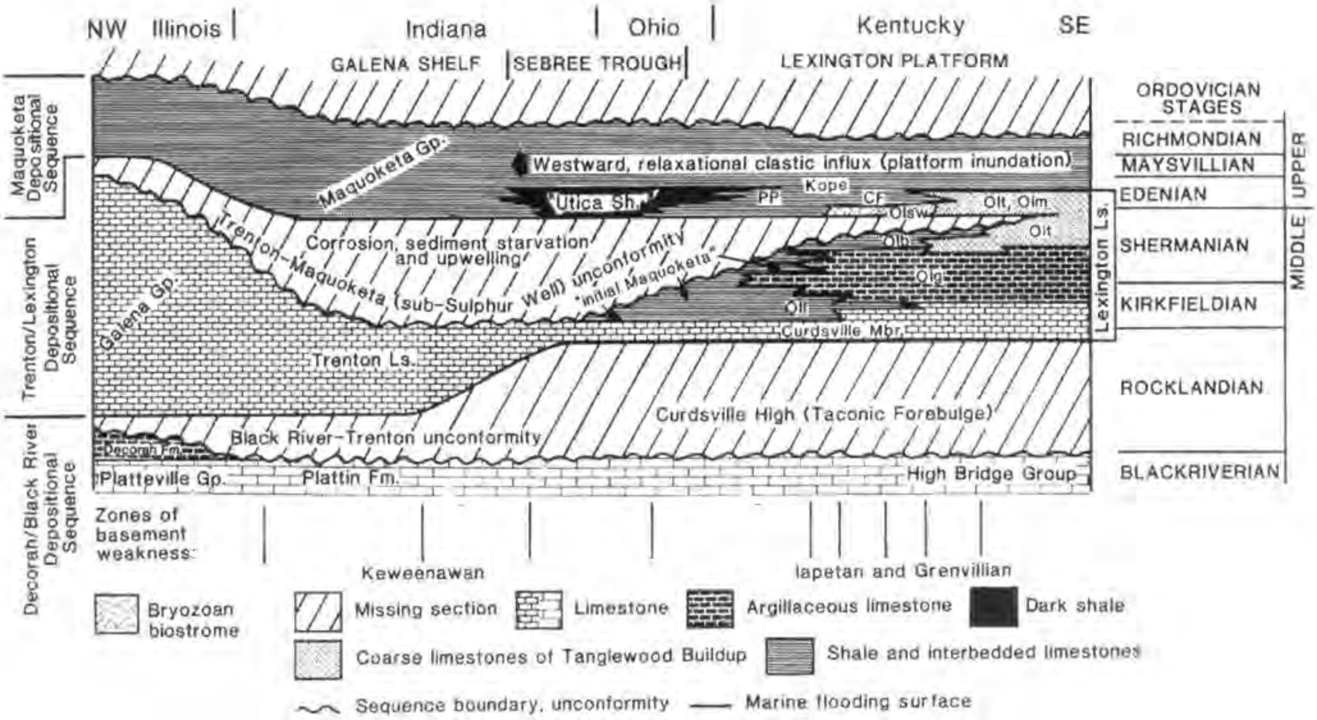

Figure 3. Schematic chronostratigraphic section from the Galena Shelf in central Illinois to the Tanglewood buildup in central Kentucky. Vertical lines below the section are relative positions of basement faults that influenced stratigraphic configuration above (see Fig. 4). Diagonally hatched gaps are unconformities. PP=Point Pleasant Fm.; CF=Clays Ferry Fm. Adapted from Hohman (1998).

3). This surface has been called the Trenton-Maquoketa or sub-Sulphur Well unconformity (Cressman, 1973; Ettensohn and others, 1986, 2002a; Hohman, 1998) (Fig. 3), and we will examine it at several stops. Although the surface does not reflect as much time on the platform as it does in the Sebree Trough (Fig. 3), it is important for our seismite study, because it bounds seismite horizons and provides an important temporal reference.

In latest Shermanian time, an episode of far-field tilting and related deepening allowed siliciclastics to overflow from the foreland basin into the Sebree Trough and onto the Lexington Platform. We will examine the vanguard of that influx in a tongue of the Clays Ferry Formation at stop 5.

Aside from the regional conditions they generated, far-field responses are equally important on more local scales, because it was during reactivation of local structures that earthquakes and resulting seismites were produced, and, in addition to horizons of widespread seismically induced liquefaction, more local responses include the development of a smaller carbonate buildup, the Tanglewood buildup, in the central Kentucky area (Fig. 2), and a plethora of facies changes related to structural trends (Ettensohn, 1992; Ettensohn and Kulp, 1995). Hence, the diversity of responses across wide areas like the Lexington Platform during narrow intervals of time, as well as coincidence and repetition of responses along basement structures, indicate the significance of far-field effects, even in distal areas, during craton-margin orogenies.

Structural and Stratigraphic Framework

The central Kentucky or Bluegrass area is located in a culmination on the Cincinnati Arch called the Jessamine Dome (Fig. 4), but based on lithofacies trends, the arch was not present or active until latest Ordovician time (Borella and Osborne, 1978; Weir and others, 1984). However, evidence does support the presence of more local, Ordovician structural highs related to basement structures at both the Jessamine and Nashville Domes (Borella and Osborne, 1978; Ettensohn, 1992; Ettensohn and Kulp, 1995). The Bluegrass area in particular is underlain by a series of Late Precambrian to Early Cambrian basement structures with surface expression in extant fault zones (Black, 1986; Drahovzal and others, 1992). Many of these faults are associated with anomalous thinning and thickening of units, disjunct unit distribution, and local unconformities, which

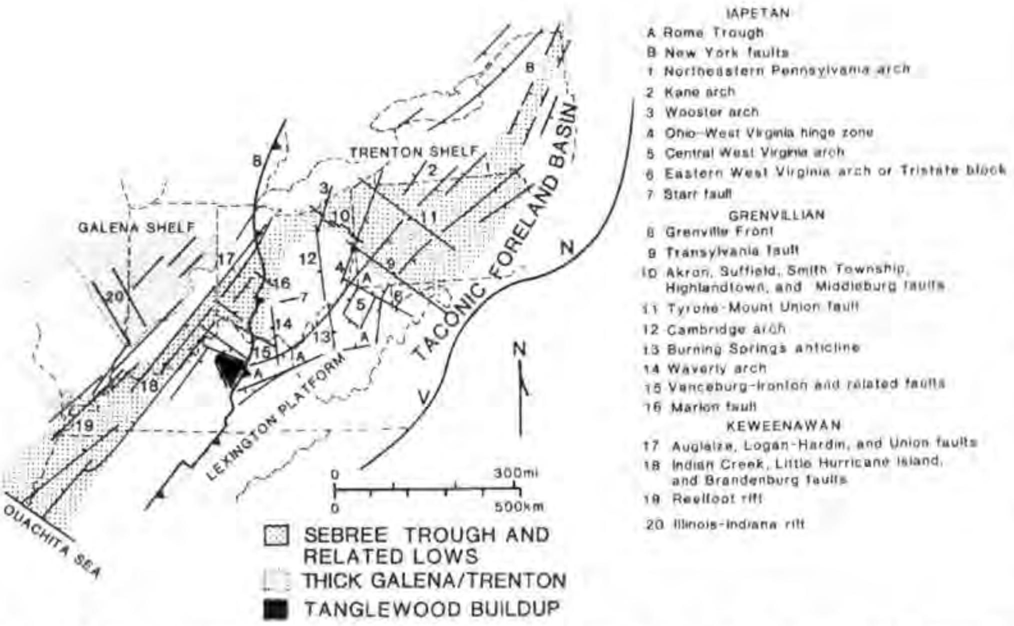

Figure 4. Map showing major basement structural features in east-central United States and their relation to important Middle/Late Ordovician paleogeographic features (see Figs. 2 and 3). V=Virginia Promontory; N=New York Promontory. From Ettensohn and others (2002a).

suggest repeated synsedimentary structural reactivation (Ettensohn and others, 1986; Ettensohn, 1992; Ettensohn and Kulp, 1995; Pope and Read, 1995). In addition, some horizons of contortion and soft-sediment liquefaction structures also seem to be associated with some of these faults.

Exposed Ordovician rocks in Kentucky form parts of two unconformity-bound, third-order sequences, which are apparently related to two Taconian tectophases (Ettensohn, 1991, 1994) (Fig. 5). Parts of the earlier sequence in the Bluegrass region are represented by the Blackriverian High Bridge Group, which includes the Camp Nelson, Oregon, and Tyrone formations. Subsequent structural and stratigraphic differentiation of the Lexington Platform from the larger Black River Platform and initiation of the second third-order cycle that begins with the Lexington Limestone coincided with inception of the second Taconian tectophase during Rocklandian time. Bulge moveout and uplift accompanying this tectophase are probably responsible for the unconformity at the base of the Lexington (Fig. 1), as well as for Middle and Late Ordovician reactivation of basement structures (Borella and Osborne, 1978; Ettensohn, 1991, 1992, 1994; Ettensohn and others, 2002a).

The Lexington Limestone is a complex, generally shallow-water, carbonate unit deposited across the Lexington Platform during late Middle to early Late Ordovician time (Rocklandian-Edenian; mid-Caradocian) (Cressman, 1973; Keith, 1989; Ettensohn, 1992, 1994; Pope and Read, 1997; Pope and others, 1997). Although deposited at 20 to 25° south latitude on the southeast margin of Laurentia, temperate-water carbonates seem to predominate (Pope and others, 1997), and most units are composed of mid- to upper-ramp carbonates that reflect storm reworking.

Overall, the Lexington Limestone is a transgressive unit that generally deepens upward from shallow-ramp calcarenites in the Curdsville Member to mid-ramp, nodular, argillaceous calcarenites in the Grier Member to deep-ramp shales and interbedded calcisiltites and fine-grained calcarenites in the Clays Ferry and Kope formations. However, seemingly out-of-place, local, deep-ramp units like the Logana and Brannon Members (Fig. 1) and the Macedonia and Cane Run beds have lithologies like the Clays Ferry and Kope and represent distal tempestites and background suspension sedimentation during smaller-scale, early, transgressive incursions from the Sebree Trough (equivalent to "initial Maquoketa" in Figure 3); their localized distributions in the Lexington Limestone were in part controlled by structurally related subsidence (Ettensohn and Kulp, 1995; Ettensohn and others, 2002a).

Throughout most of the east-central United States, the Lexington Limestone section and its Trenton equivalents represent this regional, latest Rocklandian to late Shermanian transgressive trend and are generally no thicker than 50 m. In central Kentucky, however, this regionally transgressive trend is disrupted by a regressive buildup of coarse-grained, shallow-ramp calcarenites and calcirudites (Tanglewood Member) and a transitional, shaly, nodular carbonate, mid-ramp facies (Millersburg Member) that extend Lexington Limestone deposition into Late Ordovician (Edenian) time and generate thicknesses in excess of 100 m (e.g., Cressman, 1973) (Fig. 1). Mapping the distribution of this shallow-ramp Tanglewood facies (Tanglewood buildup) shows that it is bounded by major structural lineaments, suggesting that the change in Lexington

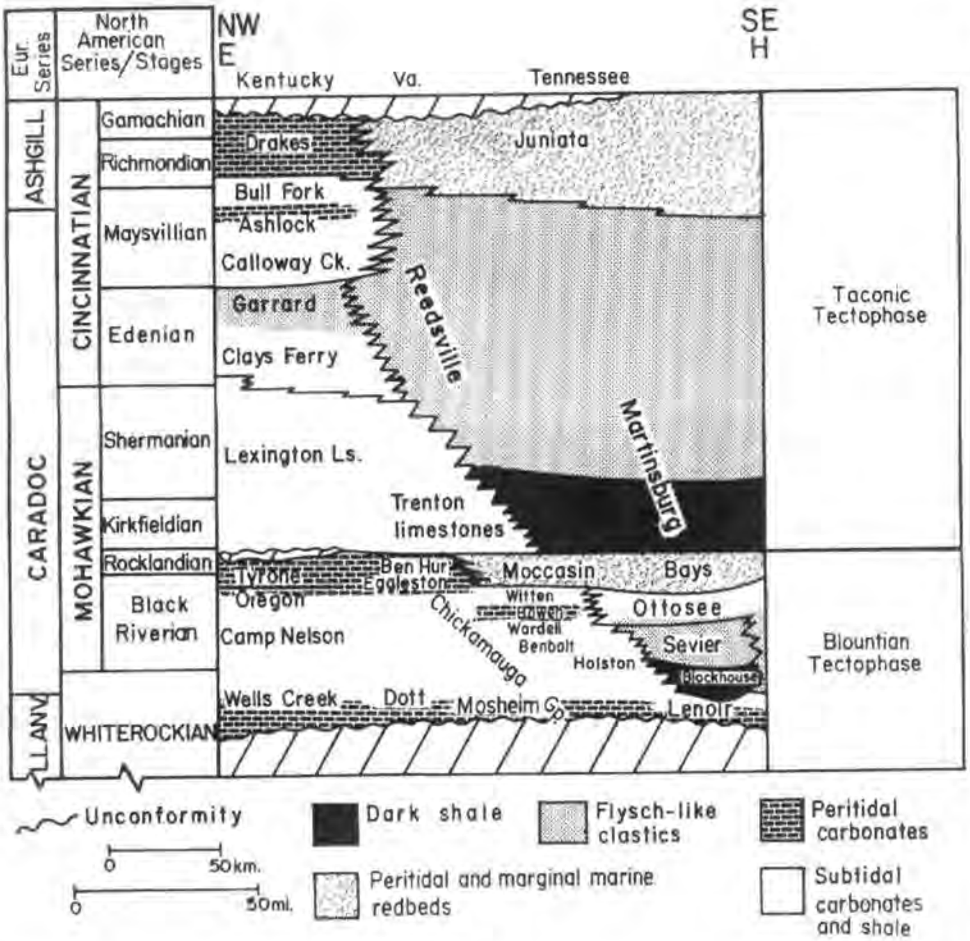

Figure 5. Schematic northwest–southeast section from central Kentucky to northeastern Tennessee perpendicular to the Taconian foreland basin, showing two unconformity-bound stratigraphic sequences and their relationship to Taconian tectophases. On this trip, we will be largely examining Shermanian and Edenian units. Adapted from Ettensohn (1991).

depositional regime and resulting buildup were related to the reactivation of the basement lineaments (Ettensohn, 1992; Ettensohn and others, 2002a) (Fig. 4). We propose here that the abundant soft-sediment deformation that formed both prior to and during development of the Tanglewood buildup may actually reflect seismicity accompanying reactivation of the lineaments. This interpretation is at least partially borne out by mapping the distribution of soft-sediment deformation within the Grier and Brannon Members, which shows that deformation is concentrated along likely lineaments or in actively subsiding areas between them (Jewell, 2001; Ettensohn and others, 2002a, b).

Defining Seismites

Although Seilacher (1969, 1984) coined the term "seismite" as a genetic or interpretive term for post-depositional, soft-sediment deformation inferred to have seismogenic causes, he later realized that the characteristics of seismites are not unique (Seilacher, 1991). Similarly deformed horizons have been attributed to slope-induced mass movement, rapid depositional loading, dewatering, and storm overpressure on marine bottoms, among other causes. As a result, many criteria have been suggested for differentiating the effects of seismicity from those of other causes in soft-sediment deformation, but we suggest differentiation of seismogenic deformation based on the concurrence of four criteria (Ettensohn and others, 2001; Greb and others, 2002) outlined by McAlpin (1996), Obermeier (1996, 1998), and Obermeier and Pond (1999), because these criteria can be reasonably determined in the ancient, marine geologic record. These criteria are (1) deformation that is consistent with a seismogenic origin, (2) widespread occurrence of deformation in temporally and stratigraphically constrained horizons, (3) deformation that shows systematic increases in frequency and intensity toward a likely epicentral area, and (4) the ability to exclude other possible causes. The greater the number of these criteria that can be met, the more likely a seismogenic origin is, and Greb and others (2002) are currently working on a scheme for quantifying this likelihood. An example of the use of these criteria is provided in Ettensohn and others (2002b).

Other reinforcing criteria include presence in a currently or formerly active seismic region and association with a potentially originating fault (Sims, 1975), deformation that crosscuts normal stratification (Rast and others, 1999), and deformation that crosses regional facies boundaries (Ettensohn and others, 2002b).

Quantifying the Effects of Ancient Earthquakes from Seismites

Seismogenic, soft-sediment deformation is controlled by the presence of susceptible sediments (generally water-saturated silts or fine sands) confined below impermeable layers (e.g., Obermeier and others, 1990) and a sudden input of energy sufficient to generate enhanced pore pressure (e.g., Sieh, 1978; Holzer and others, 1989). If thixotropic muds are involved, deformation may occur in unconfined circumstances, especially if the triggering event is abrupt and rapid. However, if sediments were partially consolidated and cohesive, as the coherent layer-segments in most Lexington deformation indicate, burial below impermeable layers may have been essential to generate the overpressuring necessary for deformation; otherwise, deforming pore fluids would seep out at the surface and stress would be dissipated.

Locating Likely Epicentral Areas

Assuming uniform sedimentary conditions and no site effects, increases in pore-fluid pressure and velocity should be proportional to the earthquake energy released through cyclic loading, and the resulting deformation should reflect the amount and location of the energy release, with the greatest energy release, and hence the most intense deformation, occurring near the epicenter. Based on Lowe's (1975) classification and interpretation of water-escape structures, three forms of deformation, each requiring successively higher pore-fluid velocities—and hence energy input—are present in deformed horizons. Lowe (1975) related deformation processes to energy input via the minimum fluidization velocity ($\mathbf{U}_0$), and similar relationships have been noted elsewhere between the severity of earthquakes and resulting soft-sediment deformation (e.g., McAlpin, 1996). At lower energies and resulting pore-fluid velocities well below $\mathbf{U}_0$, hydroplastic deformation is typical and is characterized by the simple contortion or folding of beds with preservation of primary lamination or bedding; elutriation of finer grains is minor. At higher energies and a pore-fluid velocity approaching $\mathbf{U}_0$, liquefaction becomes common and is characterized by vertical piping, dikes, or sand volcanoes that initiate destruction of primary lamination and bedding; flow structures are laminar and elutriation of finer grains becomes more prevalent. At very high energies with resulting pore-fluid velocities that exceed $\mathbf{U}_0$, fluidization predominates and is characterized by complete destruction of primary lamination or bedding and homogenization of the unit; flow structures are turbulent and elutriation of fine grains is ubiquitous. Hence, individual deformation types may reflect differing energy inputs. As a result, if individual deformed horizons can be characterized in exposure by the predominance of one of the three types of deformation, and if the types of deformation can be mapped in well-constrained horizons, then point sources of energy input of the type encountered in seismicity can be recognized by an area of intense deformation (complete homogenization) and a roughly concentric pattern of decreasing-energy deformation bands surrounding it (Ettensohn and others, 2000, 2001, 2002b). Such isoseismal bands of intensity are generally concentric about the epicenters of modern quakes, and the area of most intense deformation—because it likely represents the area of greatest energy input—is inferred to be the epicentral area (e.g., Reiter, 1990). In short, mapping the distribution of deformation types in well-constrained, deformed horizons has the potential for locating ancient epicentral areas.

Approximating Paleoearthquake Magnitude

If deformation can be linked to a seismogenic origin, then the minimum-magnitude earthquake required for liquefaction is generally though to be M=5 or greater (Ambraseys, 1988; Carter and Seed, 1988; Obermeier and others, 1990). This lower limit provides a convenient starting place for subsequent approximations, and such approximations are commonly done in two ways. The first involves determining the distance between the epicentral area and the farthest extent of deformation, and assumes, all things being equal, that the greater the earthquake magnitude, the greater the extent of deformation. In ancient seismites, both the likely epicentral area and extent of deformation can be determined by mapping types of deformation as noted above, provided adequate temporal and stratigraphic control are available (Ettensohn and others, 2000, 2001, 2002b). Moreover, according to Obermeier and others (1990), in any given deformed horizon the number and size of dewatering structures increase toward the epicentral area, and number and size are mappable parameters. Once the epicentral area is located, epicentral distance to the farthest deformation can be measured and plotted on established curves (Ambraseys, 1988; Obermeier and others, 1990) to provide approximate earthquake magnitudes (Fig. 6). Similar methods have been employed in the Lexington Limestone by Pope and Read (1992) and Ettensohn and others (2002b).

A second method is based on well-known statistical correlations among magnitude, fault type, fault-rupture length, and surface displacement from historical earthquakes (Bonilla and others, 1984). At least the fault

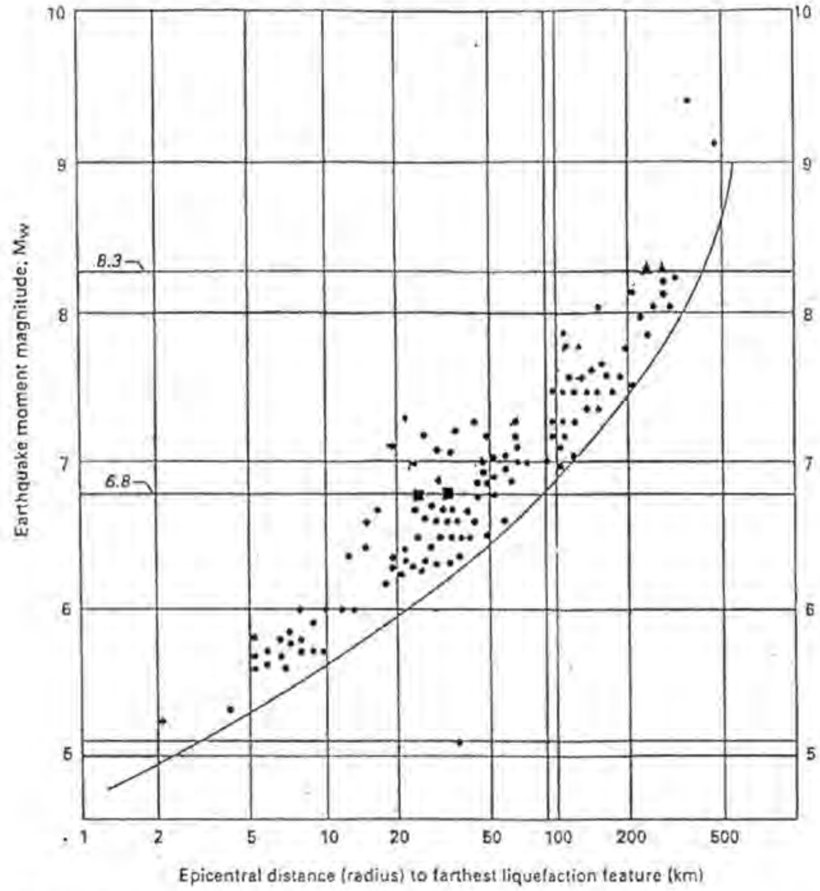

Figure 6. Graphical relationship between earthquake magnitude and epicentral distance to the farthest liquefaction feature. Symbols reflect liquefaction effects for various, historic shallow-focus earthquakes. Adapted from Obermeier and others (1993).

type and either rupture length or displacement must be known. These parameters are more difficult to collect from the fossil record, but if seismites can be related to reactivation of a given fault, and facies changes on either side of the fault allow depth approximations that can serve as a proxy for surface displacement, then this method is available, and in a few situations in the Lexington Limestone we have been able to use this method to confirm other results.

Rating Seismites

In order to map the distribution of deformation types noted by Lowe (1975), a rating scheme was necessary to classify types of deformation in the field. We present in Table 1 a nine-point scale of increasing deformational intensity modified from Jewell (2001). Although mapping individual numbered intervals has proven to be impractical because of extreme variation from locality to locality, we have been successful in mapping distribution of the three major types of deformation: hydroplastic deformation (1–3), liquefaction (4–6), and fluidization (7–9). The "isoseismal maps" shown in Figures 7, 8, and 9 show the results of such mapping for the three well-constrained seismite horizons in the Brannon Member of the Lexington Limestone.

Brannon Member of the Lexington Limestone

At four of today's seven stops, we will examine seismites in the Brannon Member of the Lexington Limestone. The Brannon Member has been chosen for study because a basal, bentonitic shale (Black and others, 1965) provides temporal constraint, and the unit is one of the most widespread and easily identifiable members in the Lexington Limestone. In addition, three contained horizons of deformation are widespread, mappable, and show clear trends of increasing intensity. Hence, based on criteria listed above and the classification of Greb and others (2002), deformed horizons in the Brannon are more probably seismogenic in origin than any others in the Lexington Limestone and equivalent units (Ettensohn and others, 2002b).

The Brannon is a deep-ramp, open-marine unit that probably represents a major eustatic flooding event; the unit is commonly underlain by a corroded, rust-colored hardground that represents the flooding surface and is composed largely of thin-bedded calcisiltites and fine-grained calcarenites interbedded with shale. Its distribution, however, was in part controlled by structure, because its northern pinchout into Tanglewood shoal complexes occurs along a structural lineament (Fig. 10). Moreover, in areas near this lineament, sands are very common in the Brannon (Kulp, 1995), probably owing to downslope transport from shallower shoal environments on the uplifted side of the structure into deeper-water, Brannon environments on the downdropped side. The Brannon is also thicker and contains more seismites in a basinal area outlined by two structures (Fig. 10). The greater abundance of seismites here may reflect the importance of site effects such as basin shape and sediment thickness (Ettensohn and others, 2002b).

Table 1. Subjective scheme for rating occurrence and relative intensity of deformation.

Major Types of Deformation		
Hydroplastic Deformation	*Liquefaction*	*Fluidization*
1. Thinning and thickening of beds; simple folds, contortion, pull-aparts, brecciation; thin and sporadic	4. Sporadic presence of penetrating diapirs	7. Some original bedding remains; widespread channels, intrusions or pockets of fluidization
2. Horizons with channel- or pillow-like, flow-roll deformation; longer expanses deformed but still sporadic	5. Thicker deformed horizons with moderate occurrence of diapirs	8. Moderately thick horizons (~1 m) of largely homogenized sediment; few remnants of original bedding persist
3. Thicker, persistent horizons of simple ball-and-pillow-type deformation without penetrating flame structures	6. Diapirs widespread and persistent throughout interval; local pockets of fluidization associated with diapirs	9. Thick horizons (~2 m) of completely homogenized sediment; rounded clasts floating in structureless matrix; persistent
General Characteristics		
Primary structures and bedding preserved; simple folding, thinning and thickening	Much original bedding preserved; vertical water-escape structures and redistribution of grains; laminar flow	Large-scale destruction of bedding; major homogenization; turbulent flow

Field Trip Route and Stops

Stop 1: Liquefaction in the Brannon Member

After leaving the Hyatt Regency hotel, we will proceed northwest on High Street; turn right onto the Jefferson Street bridge; at the end of the bridge, turn left onto Main Street, which in a short distance becomes Leestown Road (U.S. 421). Proceed northwest on Leestown Road until its intersection with New Circle Road (Ky. 4); on approaching the overpass, move into the left lane and prepare to turn left. After the overpass, turn left onto entrance ramp for New Circle Road and move onto the road. Proceed southwest on New Circle Road about 0.8 mi past the exit ramp for Old Frankfort Pike (Ky. 1681) and pull off to the right just beyond the overpass for Old Frankfort Pike.

The entire exposure (Fig. 11) is almost 0.4 mi long, beginning at the exit ramp for Old Frankfort Pike and continuing southwest beyond the overpass, but we will only examine parts of the exposure at the overpass. As mapped by Miller (1967), the Brannon in this exposure is nearly 23 ft (7 m) thick and is divided by a tongue of the Tanglewood Member. However, regional mapping and correlation by Jewell (2001) indicate that in this exposure, parts of the Brannon below the Tanglewood tongue (near the Old Frankfort Pike exit ramp) are equivalent to the Cane Run Bed and exhibit three horizons of deformation, as is common for the Cane Run (Fig. 11).

The tongue of the Tanglewood is up to 5 ft (1.5 m) thick and capped with a rust-stained hardground. The overlying Brannon begins with a thin bentonitic shale succeeded by 8 ft (2.4 m) of the Brannon proper, which contains the three typical deformed horizons. All three horizons reflect the predominance of liquefaction (Fig. 11), but the middle horizon appears to be more intensely deformed with pockets of fluidization. Locally, the upper surface of each horizon is sharply truncated, but more commonly "reworking" of a lower horizon by its successor makes defining horizons difficult. This exposure has been described in greater detail by Kulp (1995) and Jewell (2001).

Stop 2: Liquefaction in Shaly Carbonates at a Tanglewood-Millersburg Transition

From stop 1, proceed southwest on New Circle Road for 1.5 mi to exit 5B. At exit 5B, exit onto westbound U.S. 60 (Versailles Road) and proceed west for 6 mi to the entrance onto the Blue Grass Parkway. Proceed southwest on the Parkway for 8 mi to the exposure on the north side of the road at mile marker 65.3.

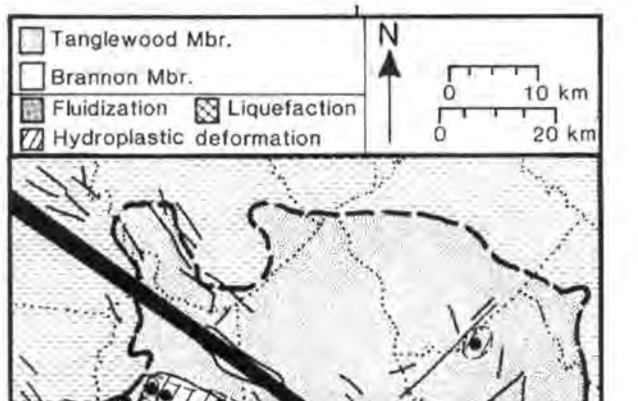

Figure 7. Distribution of deformation mapped by deformation processes (different patterns) for the lower Brannon horizon of soft-sediment deformation (see Fig. 10). From Ettensohn and others (2002b).

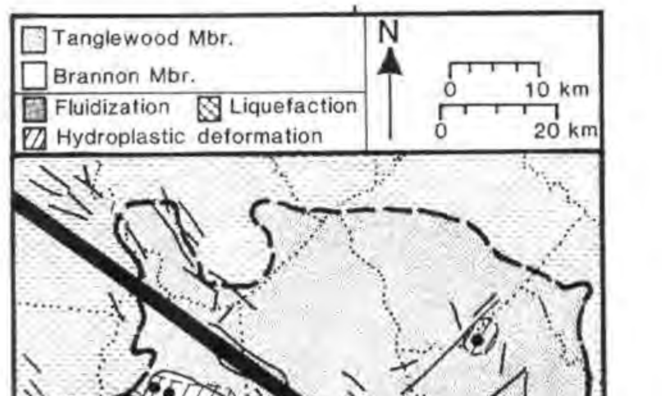

Figure 8. Distribution of deformation mapped by deformation processes (different patterns) for the middle Brannon horizon of soft-sediment deformation (see Fig. 10. From Ettensohn and others (2002b).

This is the first in a series of four stops that show facies changes in a Tanglewood shoal complex apparently related to structural reactivation (Fig. 12) and how those facies influence the seismite manifestation. Although mapped as what would be called the middle tongue of the Tanglewood today (Cressman, 1964, 1968), this series of exposures shows that the middle tongue is actually two superimposed shoal-like bodies separated by the sub-Sulphur Well unconformity (Figs. 12–13), manifested here as a thick, rust-stained hardground. The Tanglewood below the hardground is a typical, massive calcarenite/calcirudite at least 4.8 ft (1.5 m) thick and is underlain by the Brannon Member (Fig. 12). The "Tanglewood" above the hardground, however, is finer grained and much more shaly than typical Tanglewood lithology and contains three horizons of seismites. In fact, rocks above the hardground are much more typical of "Millersburg" facies, which represent the transition from shallow-ramp, shoal calcarenites to deeper-ramp, shallow, open-marine calcarenites and interbedded shales (Fig. 14). Hence, the rocks containing the seismites appear to represent the lee or northwest side of a Tanglewood shoal complex, which was tonguing into sediments from deeper, open-marine waters (Figs. 12 and 14). Each interval of calcarenites containing seismites is replete with small shale partings and separated from the others by major shale breaks (Fig. 13). The former presence of so many beds of water-saturated, fine-grained sands with interbeds of water-saturated, but largely impermeable, muds is an ideal

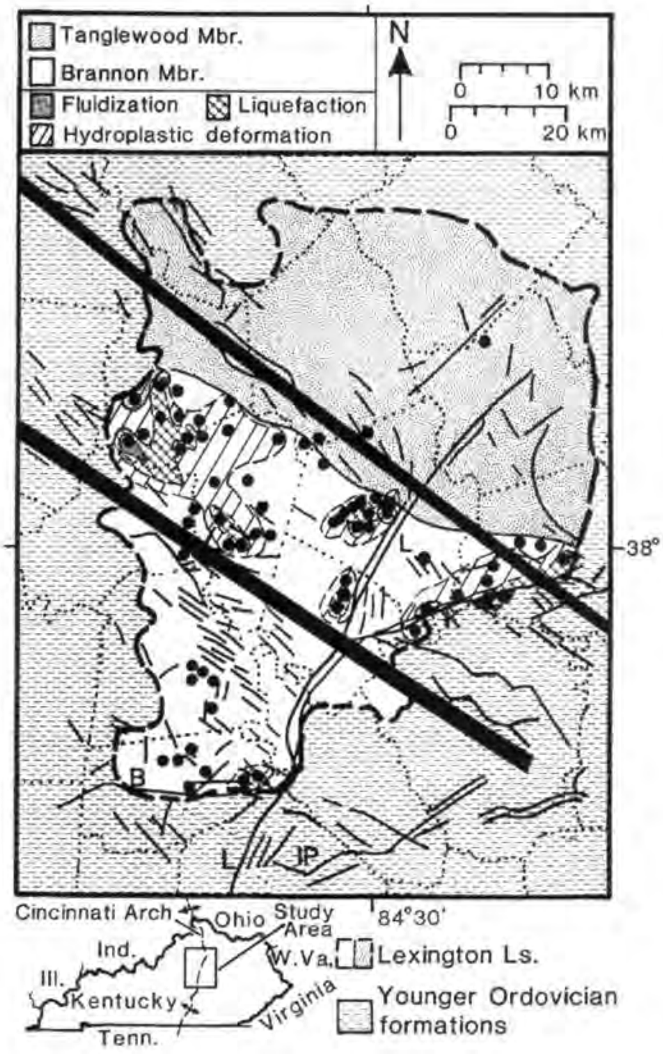

Figure 9. Distribution of deformation mapped by deformation processes (different patterns) for the upper Brannon horizon of soft-sediment deformation (see Fig. 10). From Ettensohn and others (2002b).

situation for failure with the addition of a triggering seismic shock, because argillaceous units can help to confine and enhance pore-fluid velocities beyond the critical level ($\mathbf{U}_0$). Several internal hardgrounds (Fig. 13) may have had similar confining effects before they were finally penetrated.

Probable seismites at this stop and at many other localities like it, which occur above the sub-Sulfur Well unconformity or hardground in the "middle tongue of the Tanglewood," are currently under study. Although we cannot yet call them seismites with the same confidence as we do those in the Brannon (see Greb and others, 2002), at this point their widespread occurrence relative to the hardground below suggests that they are likely seismites. In the lower horizon, laminated to cross-bedded, fine-grained calcarenites have been deformed into gentle folds and flow-rolls, penetrated sporadically by large diapers of fluidized sediment up to 3.8 ft (1.1 m) long and up to 2 ft (0.6 m) thick; micrite dikes occur locally. The middle horizon is largely bounded by hardgrounds and contains persistent deformation on several levels; it is sharply truncated by beds above. Deformation in the uppermost horizon is the thinnest and most sporadic and apparently contains no penetrating diapirs; some of the small nodules in this horizon may represent the pull-apart structures noted by Rast and others (1999). The ratings for each deformed horizon are shown in Figure 13.

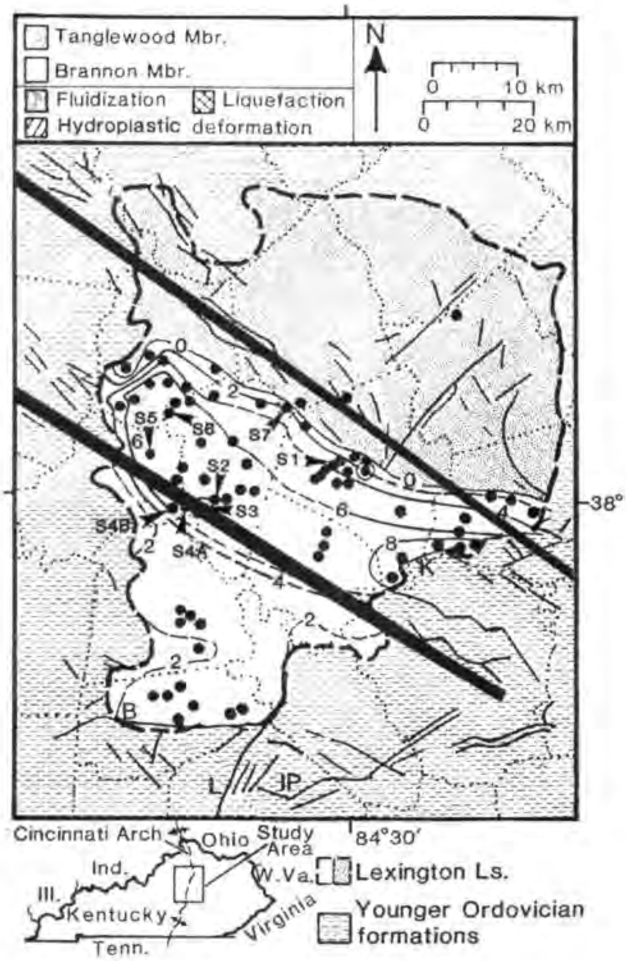

Figure 10. Map from the Bluegrass area of central Kentucky, showing local structures, distribution of Brannon Member (white), and equivalent parts of the Tanglewood Member (stipple), distribution of deformation in the Brannon and equivalent units (black dots), an isopach map of the Brannon, and location of stops (arrows with S numbers). Northwest–southeast-trending black lines represent basement structural lineaments that appear to control facies distribution and Brannon thickness Adapted from Ettensohn and others (2002b).

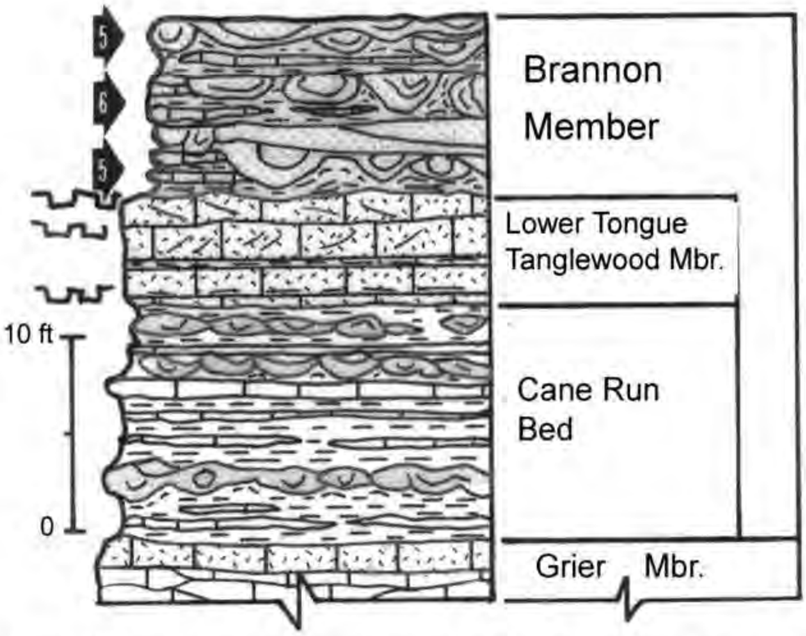

Figure 11. Schematic representation of the section at stop 1 with the rating of Brannon seismite horizons. Symbols as in Figure 13.

Stop 3: Deformation in Coarse Tanglewood Shoal Facies

Proceed southwest on the Blue Grass Parkway another 1.2 mi to mile marker 64.5; the best exposure is on the north side of the highway (Figs. 12 and 15).

The massive, undeformed calcarenite at the base of the exposure overlies the Brannon Member and is the same unit observed at the base of the exposure at stop 2, and similarly, it is capped by rust-colored hardgrounds associated with the sub-Sulphur Well unconformity (Figs. 12 and 15). The deformed unit is up to 6.4 ft (2.0 m) thick and was originally composed of massive-appearing, wavy-bedded calcarenites and calcirudites; based on its occurrence above the unconformity, it is most likely equivalent to the lower deformed horizon at stop 2. Undeformed calcarenites up to 9.4 ft (2.9 m) thick in two distinct units probably represent the middle and upper deformed intervals at stop 2.

Although correlative with the rocks at stop 2, these rocks, in contrast, are thicker, are composed of coarser-grained calcarenites and calcirudites, and are nearly devoid of shales. These differences reflect deposition in a shallow-ramp, high-energy shoal environment, which apparently owes its development to occurrence on the uplifted margin of a reactivated fault zone (Ettensohn and others, 1986); just to the southwest and at the next stop, this shoal facies gives way to a deeper-water, biostromal facies called the Sulphur Well Member (Figs. 1, 3, 12, and 14). The calcarenites and calcirudites at this exposure are typical of Tanglewood shoal environments.

Deformation in such a coarse-grained facies, however, is unusual, because the interconnected porosity typically permits rapid dissipation of pore pressure (Lowe, 1975), and to our knowledge, this is the first report of deformation in such coarse marine carbonates. This deformation is also unusual for carbonates or marine clastics, in that it takes the form of dikes or pipes rather than flow rolls. In fact, it is very similar to the sand volcanoes seen in terrestrial, seismic deformation (Obermeier, 1998), and it seems likely that each of the pipes in this exposure would have terminated at the sea floor in a small, volcano-like mound before they were truncated. Most of the pipes are no more than a foot wide, but they may broaden at the base and top; some bifurcate at the top. Individual beds are rotated upward, and even overturned, along the margins of the pipes, and small sills of intruded material were commonly injected along split bedding planes. The intruded material has a structureless, calcisiltite-like texture, but is clay-rich with angular to rounded clasts of sidewall material floating in it. The intruded dike material emanates from a zone of similar material of varying thickness that overlies the sub-Sulphur Well hardground at the base of the unit. Most likely, this material began as a thin shale with interbedded carbonate lenses like that seen in the same position at the last stop. It was apparently homogenized and injected upward during a seismic event.

The deformation of these coarse-grained sediments probably reflects the fact that they were bounded by hardgrounds or shales that confined or enhanced pore-fluid pressure and velocity, thereby facilitating liquefaction and intrusion during cyclic, seismic loading. In other nearby exposures of the unit, deformation is lacking or only partly developed, suggesting that other factors such as early cementation may have also been important. Horizons of early cementation in the shoal complex may have also compartmentalized it, allowing the buildup of pore pressure in some places and not in others. Nonetheless, deformation in these calcarenites and calcirudites extends the range of occurrence in carbonates and suggests that some combination of extenuating circumstances, such as bounding hardgrounds or shales, early cementation, or extremely large triggering events, is necessary to deform such coarse-grained carbonate rocks (Stewart and Ettensohn, 2001).

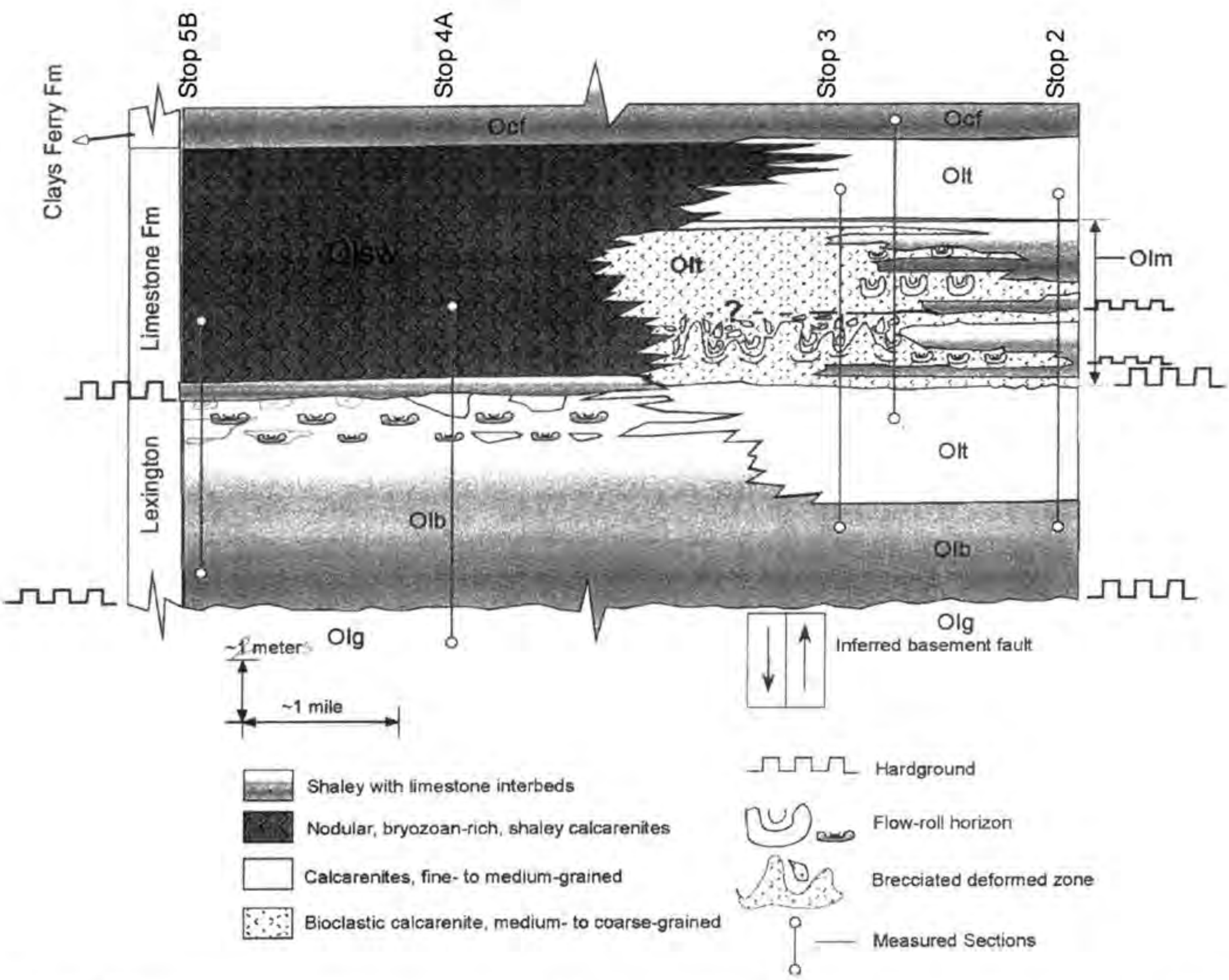

Figure 12. Schematic cross section based on five exposures along the Blue Grass Parkway from mile marker 65 to mile marker 60, showing the change in facies among the middle tongue of the Tanglewood Member, Brannon Member, and Sulphur Well Member and related changes in the nature of seismites. Major facies changes coincide with the crossing of a major structural lineament (Fig. 10), suggesting synsedimentary structural influence.

Stop 4A: Deformed Channel-Like Bodies in the Brannon Member (Optional Stop)

Proceed southwest on the Blue Grass Parkway an additional 2.5 mi to the steep-walled cut on the west side of the Kentucky River. Pull off on the right shoulder and look toward the highwall on the southern side of the road.

This is a well-known and easily viewed exposure, but the deformed parts are inaccessible for close study. Important aspects of the exposure are shown schematically in Figure 16. The key to understanding this exposure is the sub-Sulfur Well unconformity, which is the rust-stained hardground surface that sharply truncates the large, deformed channel-like structures near the top of the exposure. The massive Tanglewood calcarenite below the unconformity at the last two stops has pinched out into deeper-water Brannon shales and calcisiltites, and the deformed sheets and channel-like bodies of fine-grained calcarenite represent deeper-water, distal tongues of sands derived from the shoal to the east (Fig. 12). At about 30 ft (9.1 m) thick, the Brannon is unusually thick here compared to other nearby exposures, apparently reflecting its occurrence on the downthrown side of a synsedimentary fault at the time of deposition and the fact that it includes a section equivalent to the Tanglewood shoal complexes on upthrown sides of the fault (Fig. 12). As is typical of the Brannon at other places, there are three horizons of deformation, but each hori-

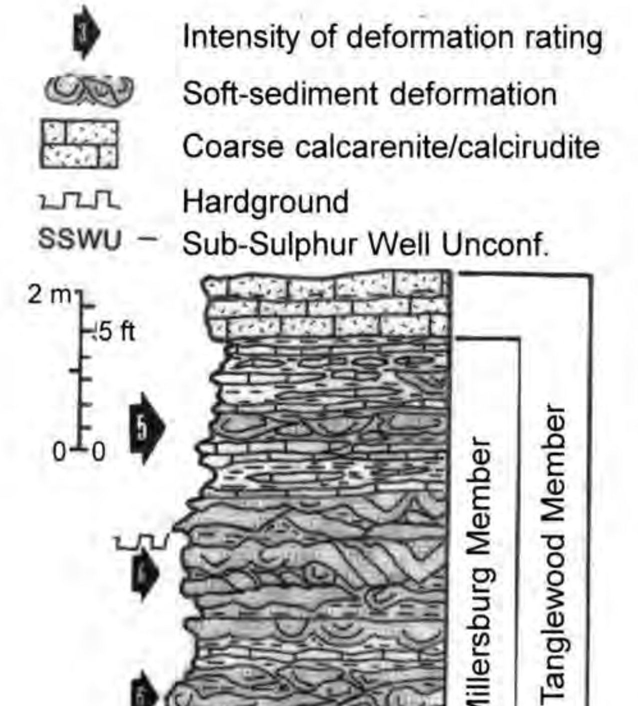

Figure 13. Schematic representation of the section at stop 2 with the rating of seismite horizons.

zon here appears to represent a deformed tongue of Tanglewood-type sands. Despite the large size of the upper deformed horizon, most of the deformation appears to be hydroplastic in nature. The lower horizon comes in at about the middle of the large tilted block and may be truncated by it. The middle horizon occurs just a few feet below the upper horizon and is nearly everywhere truncated by the upper horizon. The upper horizon, which includes the large tilted block, occurs just below and is truncated by the rust-stained hardground. The rubbly, bryozoan-rich unit above the hardground is the Sulphur Well Member, and it is a deeper-water, open-marine, biostromal unit that takes the place of the deformed Tanglewood shoal complexes observed at stops 2 and 3 (Figs. 12 and 14). The facies change between Tanglewood shoal complexes and Sulphur Well bryozoan biostrome again coincides with a fault zone (Figs. 12 and 14), suggesting that fault synsedimentary reactivation was at least partly responsible for the facies changes (Ettensohn and others, 1986). Moreover, the position of the Sulphur Well on the western, exposed side of the shoal complex and the larger Tanglewood buildup put it in a position to intercept deeper, nutrient-rich waters that upwelled out of the Sebree Trough, contributing to the proliferation of the bryozoan biostrome and the upward accretion of nearby shoal complexes from the comminuted skeletal material that resulted (Ettensohn and others, 2002a) (Figs. 3 and 14).

Close examination of the large tilted block shows that it has a channel-like geometry and appears to contain large accretionary crossbeds that thicken toward the center of the "channel." Although the original geometry has been disrupted by deformation, it is possible that these bodies were sheets of sand or channels that reflect the seaward transport of sand from the shoals during storms. Moreover, thickening of crossbeds toward the center of the channel may indicate that the channel complex was already subsiding into underlying Brannon muds during deposition. A final seismic triggering event apparently caused final foundering and deformation.

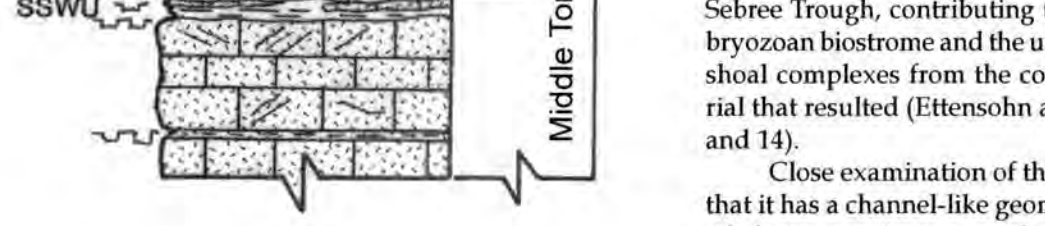

Figure 14. A highly schematic, environmental reconstruction across an approximately 70-km expanse of the Tanglewood buildup for upper regressive parts of the Lexington Limestone, suggesting the influence of structural control on facies development. The facies scenario shown is very similar to that represented by the section in Figure 12. Adapted from Ettensohn (1992).

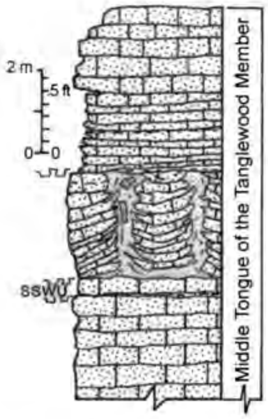

Figure 15. Schematic representation of the section at stop 3. Symbols as in Figure 13.

Stop 4B: Deformed Channel-Like Bodies in the Brannon Member

Proceed southwest another mile on the Blue Grass Parkway and pull off on the right (north) side of the road.

This stop allows us to directly view some of the same deformed, channel-like complexes that were inaccessible in the highwall at stop 4A (Figs. 12, 16, and 18). Approximately 9 ft (2.7 m) of rubbly Sulphur Well is present at the top of the exposure, and it is bounded below by two rust-stained hardgrounds that define the sub-Sulphur Well unconformity. Three horizons of hydroplastic deformation are again present in upper parts of the Brannon Member (Fig. 17). The uppermost horizon is very thin and sporadic and sits just below or is truncated by the hardground; in contrast to the situation at stop 4A, no channel-like bodies are present here in this horizon. However, channel-like bodies are present in the middle and lower deformed horizons, and each body can be traced into a thin bed that eventually disappears into adjacent shales (Fig. 17). Channel-like bodies in the middle horizon are up to 2.3 ft (0.7 m) thick, and the middle horizon truncates the bed out of which the lower channel-like body forms. The lower channel-like body is up to 4.5 ft (1.4 m) thick, and a similar thick-

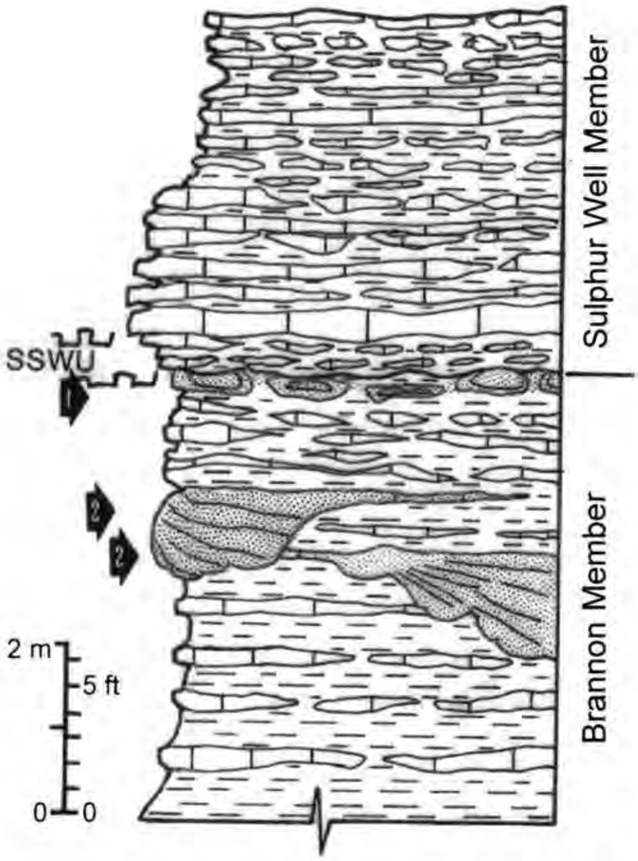

Figure 17. Schematic representation of the section at stop 4B with the rating of Brannon seismite horizons. Symbols as in Figure 13.

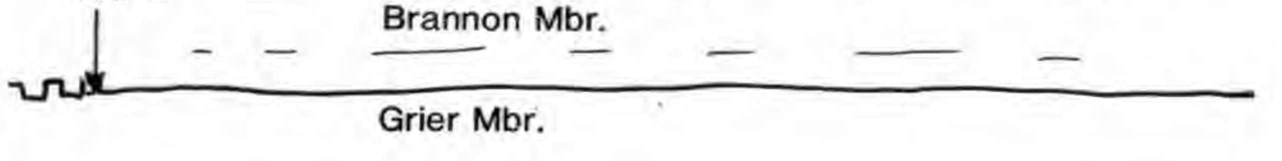

Figure 16. Sketch showing the disposition of the three Brannon deformed horizons at the southern highwall at stop 4A.

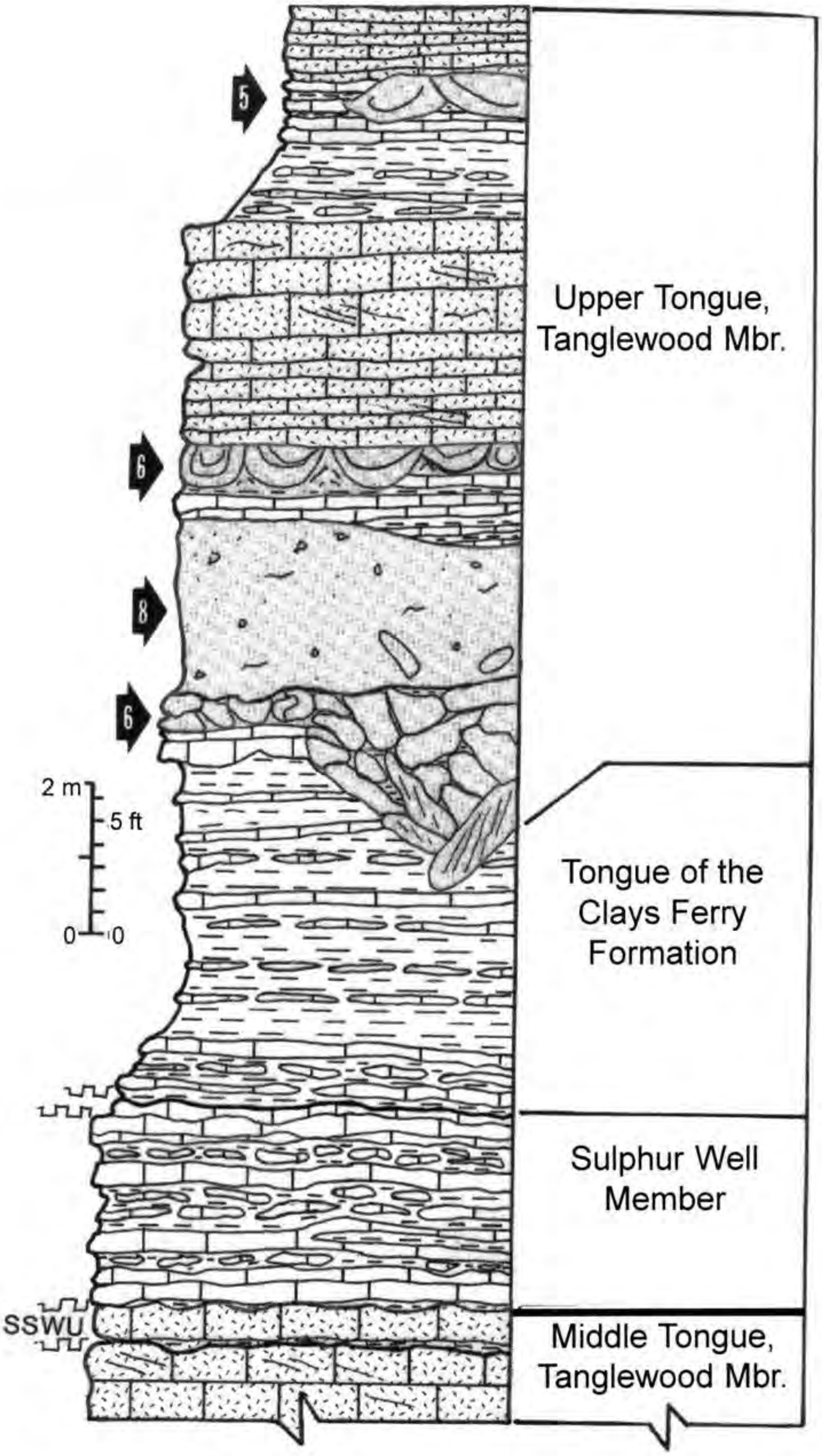

Figure 18. Schematic representation of the section at stop 5 with the rating of seismite horizons. Symbols as in Figure 13.

ening of accretionary crossbeds toward the center of the channel can be seen. Examination of the base of this body shows truncated crossbed laminae, micrite dikes, and faulting, which indicates erosive movement of underlying muds. We would again argue for loading penecontemporaneous with deposition, followed by a triggering seism that led to final foundering and deformation of the body.

Rest Stop

Continue 1.5 mi farther southwest on the Blue Grass Parkway. At exit 59, leave the parkway and enter onto northbound U.S. 127 toward Lawrenceburg, Ky. About 0.2 mi after entering onto U.S. 127, we will pull off into the Shell gas station on the left (west) side of the road.

Stop 5: Four Deformed Horizons in the Upper Tongue of the Tanglewood Member

Proceed 6.7 mi farther north on U.S. 127. Pull off to the right at an exposure on both sides of the road just before the railroad overpass. **Be careful crossing the highway!**

The section begins at the southern end of the cut with the same massive Tanglewood calcarenite that was present at the base of the exposures at stops 2 and 3 (Fig. 18). This is part of the middle tongue of the Tanglewood, and it is underlain by the Brannon Member in the creek bed to the southwest and capped by a rust-stained hardground that defines the sub-Sulphur Well unconformity (Fig. 18). This hardground is overlain by 5.8 ft (1.8 m) of the rubbly, bryozoan-rich Sulphur Well Member, which contains several persistent beds of calcirudite. Of course, the Sulphur Well is equivalent to the deformed Tanglewood/Millersburg interval observed at stops 2 and 3 (Fig. 12). The Sulphur Well is capped with another rust-stained hardground, which shows evidence of corrosion and burrowing. The hardground is also a major flooding surface for a brief period of inundation across the Tanglewood buildup, represented here by a tongue of the Clays Ferry Formation. This Clays Ferry tongue consists of at least 10.3 ft (3.1 m) of calcareous, silty shale with interbedded calcisiltites and fine-grained calcarenites. It represents background suspension sedimentation and deposition of distal tempestites in deeper ramp environments, very similar to those represented by the lower Brannon Member, for which the tongue at this locality has been commonly mistaken (e.g., Hohman, 1998). Near the margins of the Tanglewood buildup, the flooding event is represented by a tongue of the Clays Ferry Formation like this, but toward the interior of the buildup the event has a more shallow-water manifestation in the argillaceous, nodular, or wavy-bedded limestones and shales in one of the tongues of the Millersburg Member (Fig. 1). This tongue of the Clays Ferry and its more shallow-water Millersburg equivalents are partly equivalent to what Brett and Algeo (1999) and Brett and others (in this volume) have called the "Bromley formation."

Four seismite horizons occur here in the upper tongue of the Tanglewood Member (Cressman, 1972), which represents the "last gasp" of the Tanglewood buildup and is early Late Ordovician (Edenian) in age (Figs. 1 and 18). To the south and west, where this Tanglewood tongue pinches out into the Clays Ferry Formation, the late Middle Ordovician (Shermanian) Sulphur Well or equivalents in the middle tongue of the Tanglewood are the highest units of the Lexington Limestone (Cressman, 1972). Although all four horizons are clearly deformed, we can at best call them only "possible seismites" in the terminology of Greb and others (2002), because at present the necessary work of establishing their distribution and temporal framework has not been completed.

The lowest deformed horizon was originally a unit of thin-bedded, fine- to medium-grained, crossbedded calcarenite and interbedded shale about 3.5 ft (1.1 m) thick, which was probably capped by a hardground. Undeformed parts of the unit show crude grading, scours, and amalgamation of beds, suggesting a storm-related origin. Deformation of the unit has created a channel-like thickening or jumble of deformed blocks and flow rolls up to 5 ft (1.5 m) thick in the central part of the "channel" and thinner deformed intervals, 2 ft or less (< 0.6 m) in thickness, on the margins. The main part of the "deformed channel" is about 65 ft (20 m) across, and like the deformation at stops 4A and B, may have originated as a broad, loaded channel such that the most intense deformation occurred where the coarser, denser channel fill was thickest. Blocks in the central jumble have subsided or been erosively emplaced at least 4 ft (1.2 m) into the underlying Clays Ferry tongue. Micrite dikes are present, and the upper surface of the unit has been sharply truncated by overlying deformation.

The middle deformed unit is 2 to 6.5 ft (0.6 to 2.0 m) thick and subtly crosscuts undeformed beds at its upper surface. Deformation has resulted in the nearly complete homogenization of the former unit. Except for reworked flow rolls from the unit below, randomly oriented fossils, randomly oriented clots and clasts of original sediment, and poorly defined, secondary flow lamination, the unit lacks any typical fabric and texture. This manifestation is typical of the very high-energy deformation where pore-fluid velocities in excess of $\mathbf{U_0}$ generate turbulent flow and resulting fluidization. For seismites in this area, such complete fluidization of a unit is very rare, and by the reasoning described earlier (e.g., Ettensohn and others, 2000, 2001, 2002b), if this deformation is seismogenic, then this locale must have been very close to the epicentral area.

The third deformed interval is 2.5 to 4 ft (0.8 to 1.2 m) thick and consists largely of ball-and-pillow structures; deformation thickness decreases to the northwest, where undeformed parts of the interval show that is was originally a swaley-bedded, medium-grained calcarenite with interbedded shales.

The final deformed horizon is inaccessible but can be seen in the western side of the cut about 3 ft (0.9 m) below the top of the exposure. It is sporadic in occurrence and varies from 1.5 to 4.0 ft (0.5 to 1.2 m) in thickness. Each horizon is rated on Figure 18.

Stop 6: Fluidization in the Brannon Member

Proceed 7 mi farther north on U.S. 127 toward Frankfort to its junction with I-64. Enter onto the ramp to eastbound I-64 and continue 0.5 mi to the point where the ramp enters onto the Interstate. Pull off to the right and park. **Be very careful crossing the Interstate, as traffic is coming from two directions.**

The Brannon at this exposure is about 20 ft (6.1 m) thick and also contains three deformed horizons (Fig. 19). There is no capping hardground below the overlying middle tongue of the Tanglewood and above the Brannon at this exposure; hence, the overlying Tanglewood here is probably equivalent to the massive Tanglewood units that occur below the sub-Sulphur Well unconformity at stops 2 and 3. The lower two deformed horizons consist of fine- to medium-grained calcarenites with crossbedding, crude grading, and ripples, and appear to have foundered into underlying shales and calcisiltites. The upper deformed interval, in contrast, is composed of coarse Tanglewood-type calcarenites. Liquefaction predominates in the upper two horizons, and fluidization in the lower one. Each of the units is sharply truncated at its top.

Our purpose here is to view another example of fluidization, this time in the lower Brannon. What is unique about this exposure is that large slabs up to 2.5

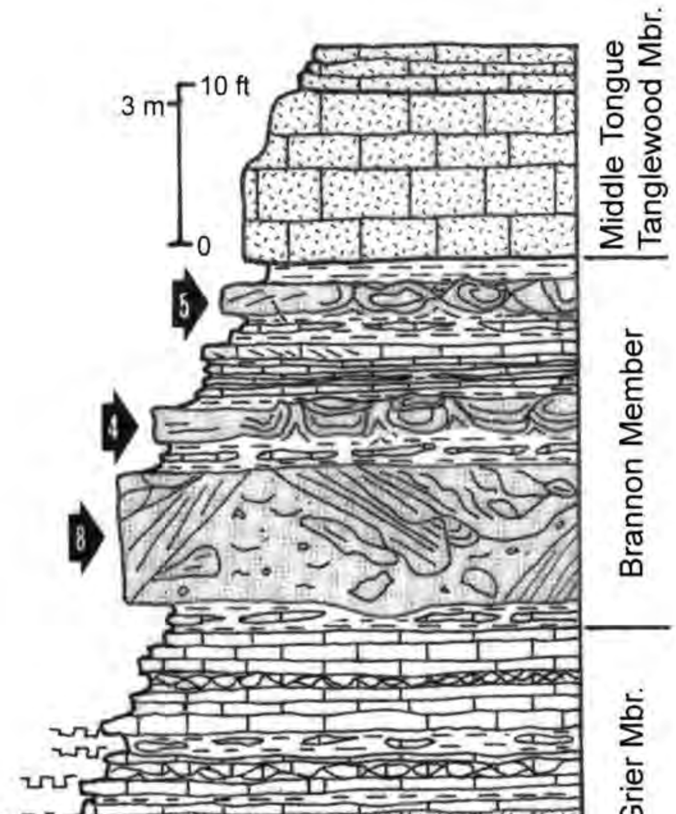

Figure 19. Schematic representation of the section at stop 6 with the rating of Brannon seismite horizons. Symbols as in Figure 13.

ft (0.8 m) thick have foundered into a homogeneous, argillaceous, fluidized matrix below. In addition, large rounded to angular clasts and fossils float randomly throughout the homogenized matrix, which shows only crude flow lamination and dish structures. Moreover, some of the large slabs show brittle deformation in the form of faults. The facts that the slabs and blocks remained intact and deformed brittlely and apparently foundered into underlying fluidized sediments suggest that the upper part of this unit was largely lithified prior to deformation. The combination of a confining lithified cap and likely proximity to the epicentral area may have generated the unusual combination of foundered blocks and intensely fluidized sediment. Deformed horizons are rated on Figure 19.

Stop 7: Brannon Pull-Apart Structures as Possible Indicators of Pre- and Post-Seismic Deformation

Proceed 5.6 mi to the east on I-64. Pull off to the right at mile marker 59, just before the overpass. **Be careful crossing the Interstate!**

The entire Brannon Member at this cut is only 3 ft (0.9 m) thick, as we are near its northern limit of distribution and pinchout into the Tanglewood Member (Pomeroy, 1968; Kulp, 1995) (Fig. 20). This facies boundary is a roughly northwest–southeast line that nearly coincides with a major structural lineament (Fig. 10), suggesting control by the reactivating structure (Ettensohn and Kulp, 1995; Kulp, 1995; Ettensohn and others, 2002a,b).

Despite its thin nature, three thin horizons of deformation are present, the lower one reflecting liquefaction, and the upper two probably reflecting pre- or post-seismic extension (Fig. 20). We are particularly interested in the upper horizons here, because they may show evidence of pre- or post-seismic creep. According to Rast and others (1999), many faults about to slip experience earthquake cycles involving pre-seismic creep, the abrupt co-seismic pulse, and post-seismic afterslip. Only the co-seismic pulse actually produces an earthquake. Although the other two phases are aseismic, Rast and others (1999) indicated that they might produce intermittent strain that is recorded in semi-consolidated sediments as small, pull-apart shear or compressional structures (Fig. 21). Some of the more spindle-shaped nodules in the upper horizons may represent such pull-apart structures. Although every Brannon exposure in the area does not show major soft-sediment deformation, some do show horizons of nodular pull-apart structures in similar positions. Such pull-apart structures may be present here because of proximity to one of the bounding structural lineaments (Fig. 10). Although we do not think that epicentral areas coincided with this lineament, pre- and post-seismic slip on this lineament, related to the main seismic event, may have established nearby strain fields that are recorded in these pull-apart structures.

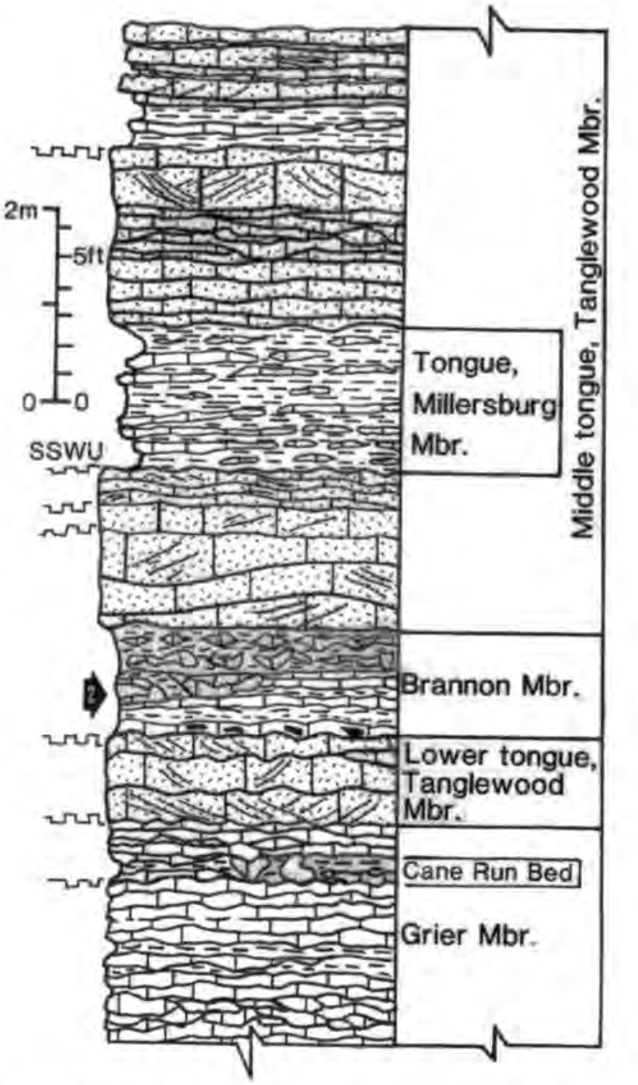

Figure 20. Schematic representation of the section at stop 7 with the rating of Brannon seismite horizons. Symbols as in Figure 13.

Return Trip

Continue east on I-64 to exit 65; exit here to U.S. 62/421. Proceed southeast on U.S. 421 (Leestown Road) for 13.2 mi in Lexington. The Hyatt Regency hotel sits on the south side of Leestown Road, which in town changes its name to Main Street.

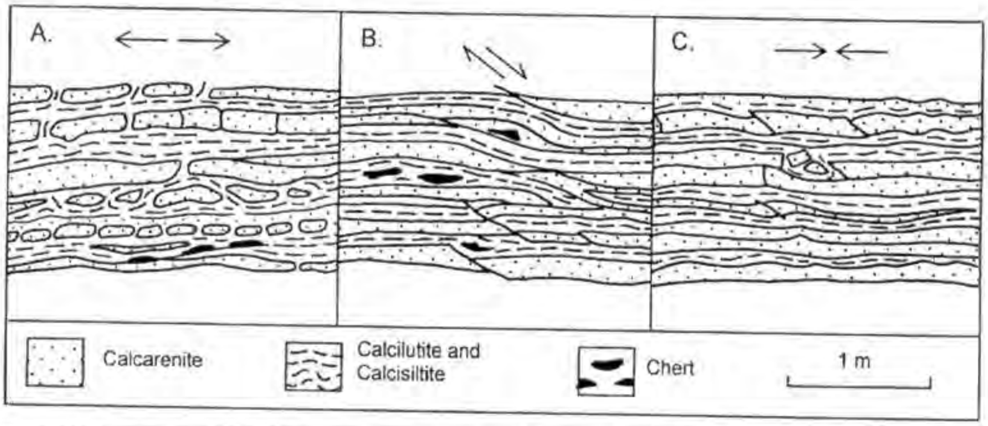

Figure 21. Sketches showing examples of minor aseismic, extensional (A), shear (B), and compressional (C) structures related to pre- or post-seismic creep from various places in the Lexington Limestone. From Rast and others (1999).

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Upper Ordovician Facies, Depositional Environments, and Sequence Stratigraphy of the Lexington-Frankfort Area, Central Kentucky

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Introduction

The Middle to Upper Ordovician strata exposed near the crest of the Jessamine Dome in north-central Kentucky are richly fossiliferous and record a broad spectrum of carbonate litho- and biofacies. This paper will examine facies, depositional environments, and sequence stratigraphy of the Lexington Limestone and immediately adjacent units along a transition from more proximal depositional environments near Lexington and Frankfort, Ky., to more distal, deeper-water environments northward toward the Sebree Trough. A spectacular series of exposures, including newly created cuts along U.S. 127 from Frankfort to Monterey, provide a transect of facies approximately perpendicular to depositional strike (Fig. 1). In this paper and on the accompanying field trip, we will illustrate the use of sequence and event stratigraphy, including faunal epiboles and seismites, in interpreting the transition. Middle to Upper Ordovician stratigraphy in the Jessamine Dome area has been the subject of many studies (Foerste, 1905; Miller, 1905; McFarlan and Freeman, 1935; McFarlan and White, 1948; Black and others, 1965; Weir and Greene, 1965; Cressman, 1973; Borella and Osborne, 1978; Weir and others, 1984; Ettensohn, 1992; Holland, 1993; Pope and Read, 1997; Hohman, 1998; Brett and others, 2000; Algeo and Brett, 2001; Holland and others, 2001a), resulting in a plethora of terms. The most recent comprehensive lithostratigraphic works are those of Cressman (1973) and Weir and others (1984), and the most recent large-scale sequence-stratigraphic analysis was done by Pope and Read (1997). We have developed a slightly different sequence-stratigraphic interpretation and present it here.

Geologic Setting of the Lexington Limestone and Adjacent Units

Facies of the Lexington Limestone and Adjacent Units

The Lexington Limestone and the overlying Bromley, Point Pleasant, and Kope formations span a range of siliciclastic and carbonate depositional facies. These range from dark gray to olive shales, through a spectrum of nodular calcareous mudstones and argillaceous limestones, to carbonate wacke-, pack-, and grainstone facies. Minor amounts of fenestral micrite are also present very locally within this interval.

In the following sections we will briefly discuss these facies, in order of most distal (deepest water) to more proximal. In each case, we will note predominant aspects of litho- and biofacies and give an inferred depositional environment.

Facies 1. Dark Gray Shales, Calcisiltites, and Argillaceous Concretionary Limestones. The most distal facies represented by the Logana, Macedonia, Faulkner, Brannon, Bromley, and Kope stratigraphic units consists of dark gray, slightly organic-rich, sublaminated shales, with interspersed thin laminated calcisiltites, and, in some cases, argillaceous concretions (rhythmite cycles of Pope and Read, 1997). In the Bromley and Kope stratigraphic intervals, this facies grades laterally into black laminated "Utica" shale facies near the center of the Sebree Trough.

Shales are typically sparsely fossiliferous and show laminated interbeds. Fossil assemblages are dominated by low-diversity associations of sponges, inarticulate brachiopods, ostracods, and nautiloids, and a few species of trilobites, notably *Isotelus*. Above the Lexington Limestone *Triarthrus* trilobites and *Merocrinus* crinoids are occasionally present. Small *Chondrites* traces may also be present.

Most fossil material is well preserved but disarticulated, and there is typically substantial biasing toward certain parts; for example, cranidia of *Triarthrus* may occur virtually to the exclusion of pygidia on certain bedding planes. Such taphonomic evidence indicates long-term processing of skeletal remains by intermittent current action and/or scavenging organisms. Lamination of sediments (a general absence of burrowing), and the sparse, relatively small fauna indicate low-energy, dysoxic conditions, below the effects of all but the deepest storm waves. Occurrence of thin, sorted layers of fossil debris suggests occasional distal storm wave/current effects. Thin calcisiltites are interpreted to be the distal expression of storm-generated gradient currents, which imported carbonate silt from shallower shelf areas. Rarely, bedding planes show suites of well-preserved fossils, including articulated specimens of trilobites or echinoderms. For example, molt clusters of the trilobite *Triarthrus* occur at several levels in the lower Kope; also, complete *Isotelus* are found in a few concretionary horizons of the Kope and Bromley shales. These layers indicate rapid burial by mudflows.

The presence of small carbonate concretions indicates the development of alkaline conditions intermittently within the sediment column, probably associated with the development of a zone of sulfate reduction within overlying sediments. This is also supported by the occurrence of pyritic burrows, commonly as the cores of carbonate nodules.

Facies 2: Nodular, Calcareous Mudstone and Argillaceous Limestone. This facies is dominated by medium to dark gray, calcareous mudstones with nodular- to wavy-bedded limestones. The latter are typically wacke- to packstones. These lithologies are interbedded with more continuous, graded packstone beds. The general aspect of these facies is moderately burrow mottled or bioturbated.

Fossil assemblages are characterized by low to moderate diversity, typified by small brachiopods, including *Zygospira*, *Dalmanella*, and small specimens of *Rafinesquina*. Certain beds contain abundant mollusks, particularly the gastropods/belerophonts *Lophospira* and *Sinuites*, as well as small bivalves such as *Modiolopsis* and *Ambonychia*. Trilobites are common to very abundant in these beds, typically heavily dominated by *Isotelus*. Ichnofossils, especially *Chondrites* and *Planolites*, are common.

Fossils are well calcified, but disarticulated and commonly fragmented. A notable feature of this facies is discontinuous wacke- to packstone beds, composed primarily of fragments of the large trilobite *Isotelus*.

The dark gray color of much of the mudstone and lateral gradation into dark shale facies suggests that this setting represents somewhat organic-rich, upper dysoxic to lower oxic environments. Nodular bedding indicates a rather strong degree of bioturbation.

Graded beds and the high degree of fragmentation of fossils in certain layers suggest intermittent, but common, storm action on the sea floor. Edgewise stacking or nesting of brachiopod and trilobite remains in preferred convex-upward position also suggests processing by storm currents.

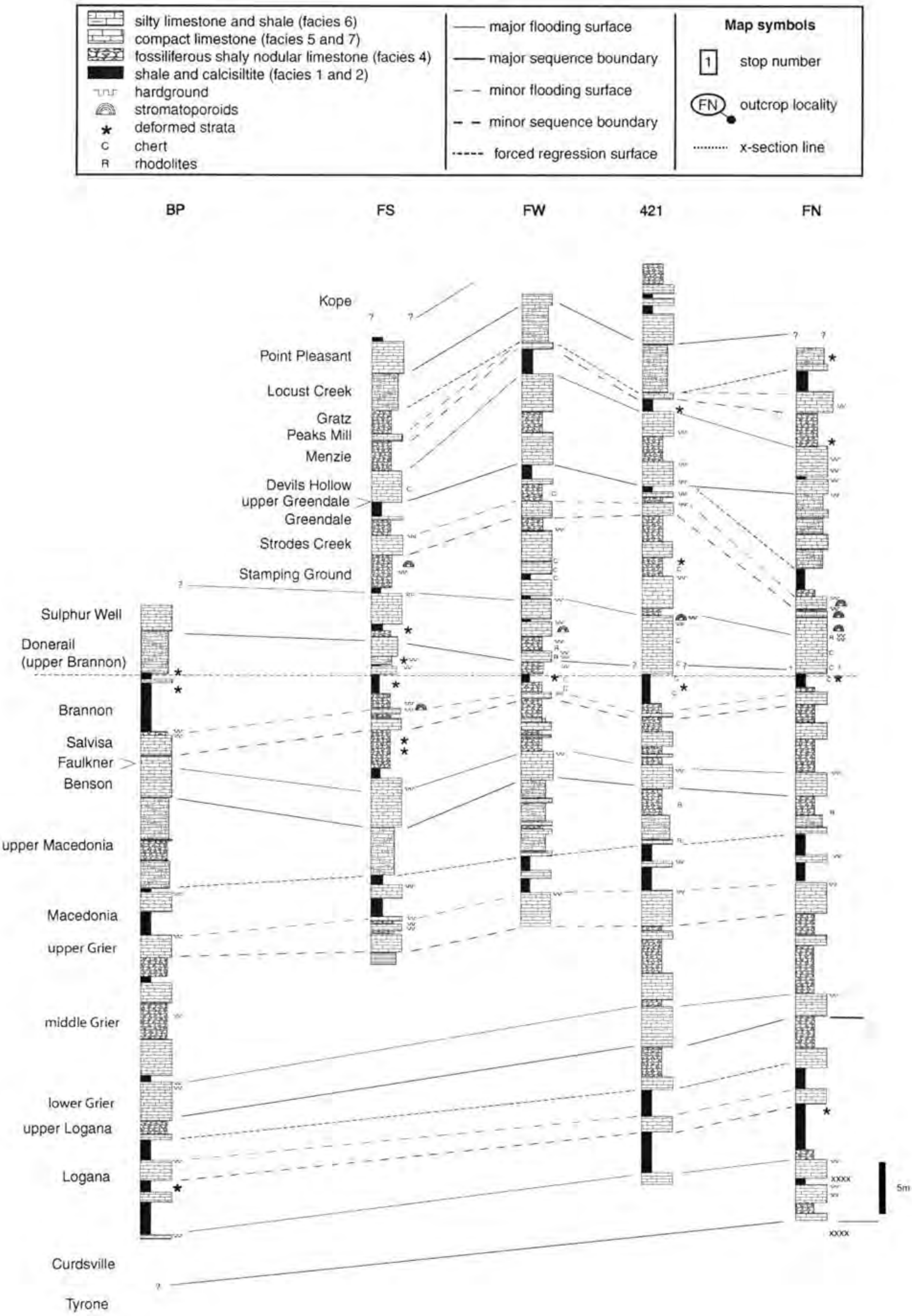
This facies is particularly typical of the more proximal portions of the Bromley, Greendale, and rarely portions of the lower Kope or Clays Ferry. It appears to grade down-ramp into shales (facies 1) and up-ramp into nodular packstones.

Facies 3: Medium to Olive Gray Mudstone with Thin Packstone to Grainstone: "Point Pleasant-Kope Facies." This facies is characterized by medium to pale olive-gray claystones and mudstones that are typically soft and noncalcareous. These beds are sparsely fossiliferous, but may be interbedded with layers of skeletal pack- or grainstone, which have sharp bases and contain very abundant, although typically fragmented, fossils.

Faunas of the mudstones tend to be typified by small brachiopods, such as *Onniella* and *Sowerbyella*, a few trilobites, including *Flexicalymene*, *Cryptolithus*, and *Isotelus*, as well as small crinoids with relatively long stems and slender small crowns like *Merocrinus*, *Ectenocrinus*, *Cincinnaticrinus*, and *Iocrinus*. Graptolites are present on certain bedding planes. Fossils in the shales are commonly articulated. The limestones are composed predominantly of bryozoans and fragmentary brachiopods.

The limestone beds have sharp bases, are up to 20 cm thick, and may contain rip-up clasts of mudstone. In some instances, small ellipsoidal concretions may underlie the grainstone and packstone layers.

These facies in their depositional settings are discussed thoroughly in Algeo and Brett (2001). Mudstones are believed to represent relatively quiet dysoxic to lower oxic conditions. Relatively rapid deposition of muds may have led to both low faunal abundance as well as the excellent preservation of fossils seen in some beds.


silty limestone and shale (facies 6)
compact limestone (facies 5 and 7)
fossiliferous shaly nodular limestone (facies 4)
shale and calcisiltite (facies 1 and 2)
hardground
stromatoporoids
deformed strata
C chert
R rhodolites
major flooding surface
major sequence boundary
minor flooding surface
minor sequence boundary
forced regression surface
Map symbols
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FN outcrop locality
x-section line
BP
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FW
421
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Kope
Point Pleasant
Locust Creek
Gratz
Peaks Mill
Menzie
Devils Hollow
upper Greendale
Greendale
Strodes Creek
Stamping Ground
Sulphur Well
Donerail
(upper Brannon)
Brannon
Salvisa
Faulkner
Benson
upper Macedonia
Macedonia
upper Grier
middle Grier
lower Grier
upper Logana
Logana
Curdsville
Tyrone
5m

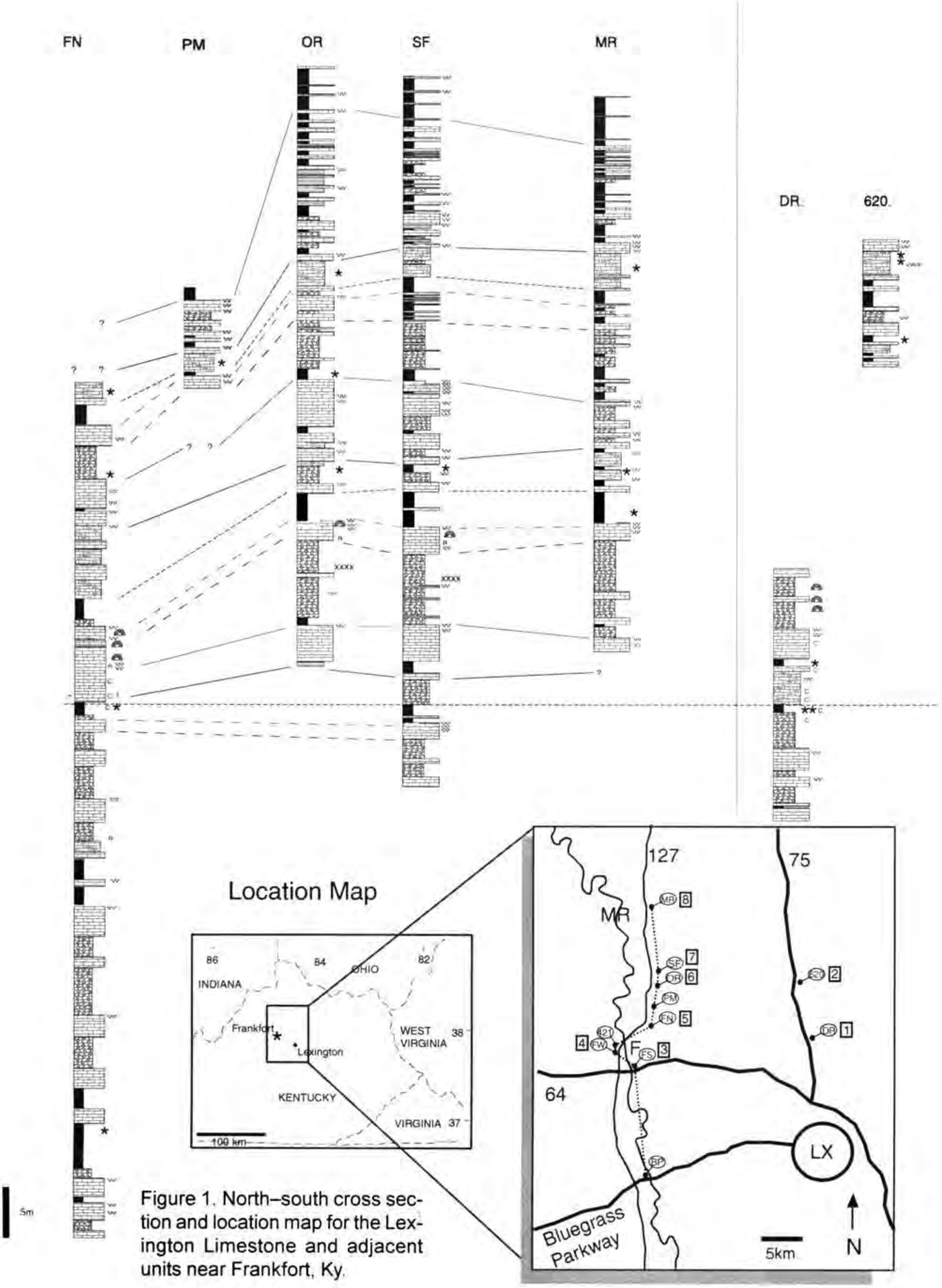

Figure 1. North–south cross section and location map for the Lexington Limestone and adjacent units near Frankfort, Ky.

Thin pack- and grainstone beds are believed to represent storm-winnowing events, but the thicker beds have been interpreted to be long-term amalgamated stacks of beds formed during periods of generally slow sedimentation. Indeed, these beds are believed to represent the transgressive bases of small-scale cycles (Algeo and Brett, 2001) or the winnowed products from periods of increased storm activity (Holland, 2001). The facies shows both decameter- and meter-scale cyclicity. The decameter-scale cycles are represented by large packages of shale-dominated strata, which alternate with more tightly bundled, meter-scale cycles of alternating shales and pack- or grainstone beds. For discussion, see Algeo and Brett (2001) and Holland and others (2001a,b).

This facies is particularly typical of the Point Pleasant and Kope formations in the Cincinnati region and appears to pass up-ramp into more tightly stacked packstones. It is less typical of lower units, although it can be found in portions of the Bromley formation.

This facies somewhat resembles the rhythmically bedded mudstones and grainstones in facies 2 but is distinctly less shale-rich.

Facies 4: (Millersburg Facies) Rhythmically Bedded, Shaly, Wavy-Bedded Packstone and Grainstone. This facies is characteristic of several of the more shale-rich intervals of the Lexington Limestone where it has commonly been termed "Millersburg Member." It is characteristic of portions of the Grier, Faulkner, Brannon, Stamping Ground, Greendale, and Bromley. This facies consists of medium to dark gray, shaly packstones, with some thin grainstones and alternating thin (1 to 5 cm) partings of calcareous shale (Fig. 2). In weathered outcrops this facies typically has a rhythmic appearance because of the rather regular spacing of decimeter-scale beds of wavy-bedded, nodular limestone with alternating shale partings. Decimeter-scale beds also may be bundled in groups of 10 to 20 between thicker or more persistent pack- to grainstone beds up to 20 cm thick; these beds typically show sharply defined bases and graded bedding.

The fossil content of this facies is somewhat more varied, but within the Lexington Limestone it is characterized particularly by the brachiopods *Rhynchotrema*, *Zygospira*, *Rafinesquina*, *Hebertella*, and *Platystrophia*. Larger crinoids are more common in this facies than in facies 1 to 3 and include *Glyptocrinus*, commonly associated with *Cyclonema* gastropods, which lived symbiotically on the crinoids. Trilobites are less common than in the previous facies, but are still dominated by *Isotelus*. Bryozoans are exceptionally common in certain layers and are dominated by rather thickly branched ramose, lumpy, and encrusting forms. In the unique case of the Stamping Ground Member, these bryozoans are joined by abundant, large, dome-shaped coenostea of the stromatoporoid *Labechia* (Cressman, 1973; Hudson, 1984; Taha and others, 2001), up to nearly a meter in basal diameter.

Rhynchonellids and *Zygospira* are typically articulated, closed, silicified, and filled with calcite spar. This undoubtedly reflects the robust arrangement of hinge teeth in these brachiopods rather than rapid burial. Most other fossils in this facies are disarticulated, and many are fragmentary. The occurrence of fossils, including large stromatoporoids that have been overturned, suggests intermittent strong turbulence from storm waves in this facies. Conversely, the abundance of muds within this setting suggests generally low-energy conditions. Occasional mud burial layers occur within stromatoporoid colonies. Partial smothering of the organisms retarded the growth of the stromatoporoid; subsequently, the skeleton grew outward over the mud layer. This proves the occurrence of episodic pulses of fine-grained sediment input, probably following storms in more proximal or shoreward directions.

The occurrence of *Solenopora*, a red alga, indicates deposition within part of the photic zone, although possibly toward the lower end. A variant of this facies in the Point Pleasant Formation, however, has yielded abundant cyclocrinitids. These are green algae that provide an excellent depth indicator for this facies. Modern dasycladacean green algae occur only at depths of about 10 to 15 m, with an absolute maximum in clear water of 30 m (Beadle and Johnson, 1986). Hence, these settings, although clearly below normal wave base, probably record depths no greater than about 15 to 20 m.

Figure 2. Facies 4; note the rhythmic banding in the Menzie member of the Bromley formation on U.S. 127, SF locality.

Facies 5. Tanglewood Facies A: Coarse Grainstone-Rudstone. This facies is characteristic of the shallower portions of the Lexington Limestone, typically assigned to the "Tanglewood Member" of the Lexington Limestone. They grade upslope into well-sorted and somewhat finer crinoidal grainstones. Predominant lithology of facies 5 is a crinoid-, brachiopod-, and bryozoan-fragment grainstone to rudstone. Sorting in these beds is relatively poor and, in places, the beds may grade into packstones. Bedding varies from medium to massive. Fossils range in size from sand to large cobble size.

Fossil associations here are varied and include particularly robust and dome-shaped bryozoans. The Sulphur Well Member of the Lexington is a bryozoan-rich variant of this facies (Ettensohn and others, 1986). Brachiopods, such as *Rafinesquina* and *Platystrophia,* and fragments of the large trilobite *Isotelus* may be common. In the upper Stamping Ground interval, this facies may carry large numbers of stromatoporoids. In the more proximal sections, stromatoporoid heads are jumbled in varied orientations and some are fragmented. The surrounding fauna tends to be heavily disarticulated, broken, and abraded.

This facies was undoubtedly deposited in relatively shallow waters between average and normal wave base. Frequent agitation by major storms is evident in the occurrence of broken and abraded fossils, as well as in the overturning and fragmentation of stromatoporoids (Stamping Ground Member). Large-scale trough crossbedding may be present in some sections, suggesting a development of large bedforms. Studies by Hudson (1984) showed that crinoid grains within this facies are typically micritized. This micritization, together with the occurrence of solenoporid algae, indicates deposition within the euphotic zone, presumably shallower than in facies 4, and thus, perhaps in 10 to 15 meters of water.

The tops of skeletal limestone beds may show sharp, typically limonite- or rust-stained hardgrounds. These appear to be most prevalent at contacts with overlying shaly nodular facies (facies 2 or 3) and reflect flooding surfaces on top of shallow-water or shoal grainstones.

Facies 6: Tanglewood Facies B: Well-Sorted, Laminated, Crinoidal Grainstone. This facies is characteristic of a major portion of the "Tanglewood Member" of the Lexington Limestone, particularly in more proximal areas near Lexington and Frankfort, Ky. It consists of fine- to medium-sand size, crinoidal calcarenite. Bedding planes may show limonitic staining, which accents their appearance in weathered outcrops (Fig. 3). Planar to trough crossbedding is common. Certain sections exhibit bimodal or "herringbone" cross-stratification, although some of these sections may actually be oblique views through small trough crossbeds.

Fossils, other than well-worn crinoid ossicles, are uncommon. Fragmentary brachiopods are present in some sections and may show considerable abrasion. A variant of this facies in the Devils Hollow is composed largely of gastropod shells.

Facies 6 is considered to represent the shallowest-water environments commonly present during deposition of the Lexington Limestone. The well-sorted, winnowed nature of this facies and the occurrence of trough and planar crossbeds suggest a high-energy environment, associated with crinoidal shoals. The appearance of bimodal or herringbone crossbedding in some sections suggests tidal influence in deposition.

This facies characterizes much of the so-called "Tanglewood buildup" (Hrabar and others, 1971; Ettensohn, 1992) in the Lexington and Frankfort areas.

Facies 7: Fenestral Micrite. Facies 7 is composed of gastropod- and ostracod-rich micrite. Few sedimentary features are present short of laminae, mud cracks, and bird's-eyes. There is little sorting or abrasion of skeletal material (Etter, 1948; Cressman, 1973). This suggests a low-energy environment indicative of peritidal mud flats and lagoons.

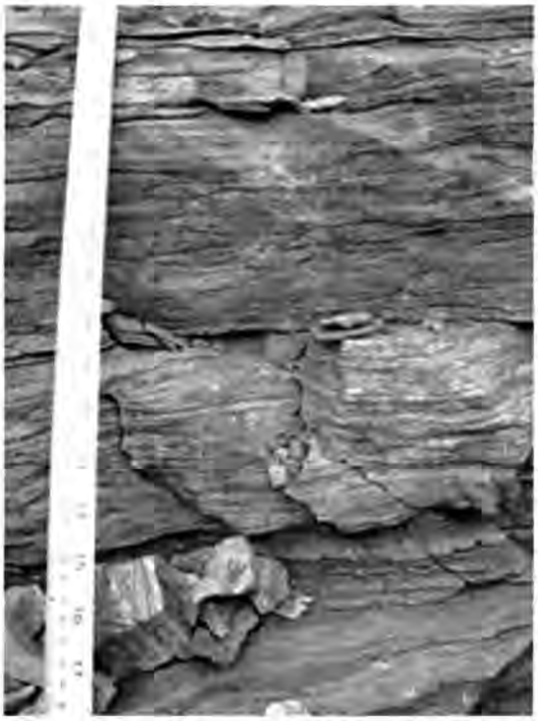

Figure 3. Pinstriped, silty, fine-grained grainstones of facies 6 in the Locust Creek member of the Bromley formation on U.S. 127, locality ML.

Overview of Lexington, Bromley, Point Pleasant, and Lower Kope Lithostratigraphy

Figure 1 shows a north–south cross section from the Blue Grass Parkway near its intersection with the Kentucky River in the south to Monterey, Ky., in the north. The cross section is composed of a series of large roadcuts that are well exposed and easily accessible. These exposures (especially the three northernmost) have allowed for detailed correlation of the Lexington Limestone and adjacent units for up to 35 km along this north–south transect. Key marker horizons (i.e., K-bentonites, faunal epiboles, and hardgrounds), abrupt changes in lithofacies, and mapping of litho- and biofacies were incorporated in correlation. Figure 4 illustrates a generalized stratigraphic column for the Lexington Limestone (derived from the cross section, Figure 1), in addition to the overlying Bromley, Point Pleasant, and lower Kope formations. As no two sections are identi-

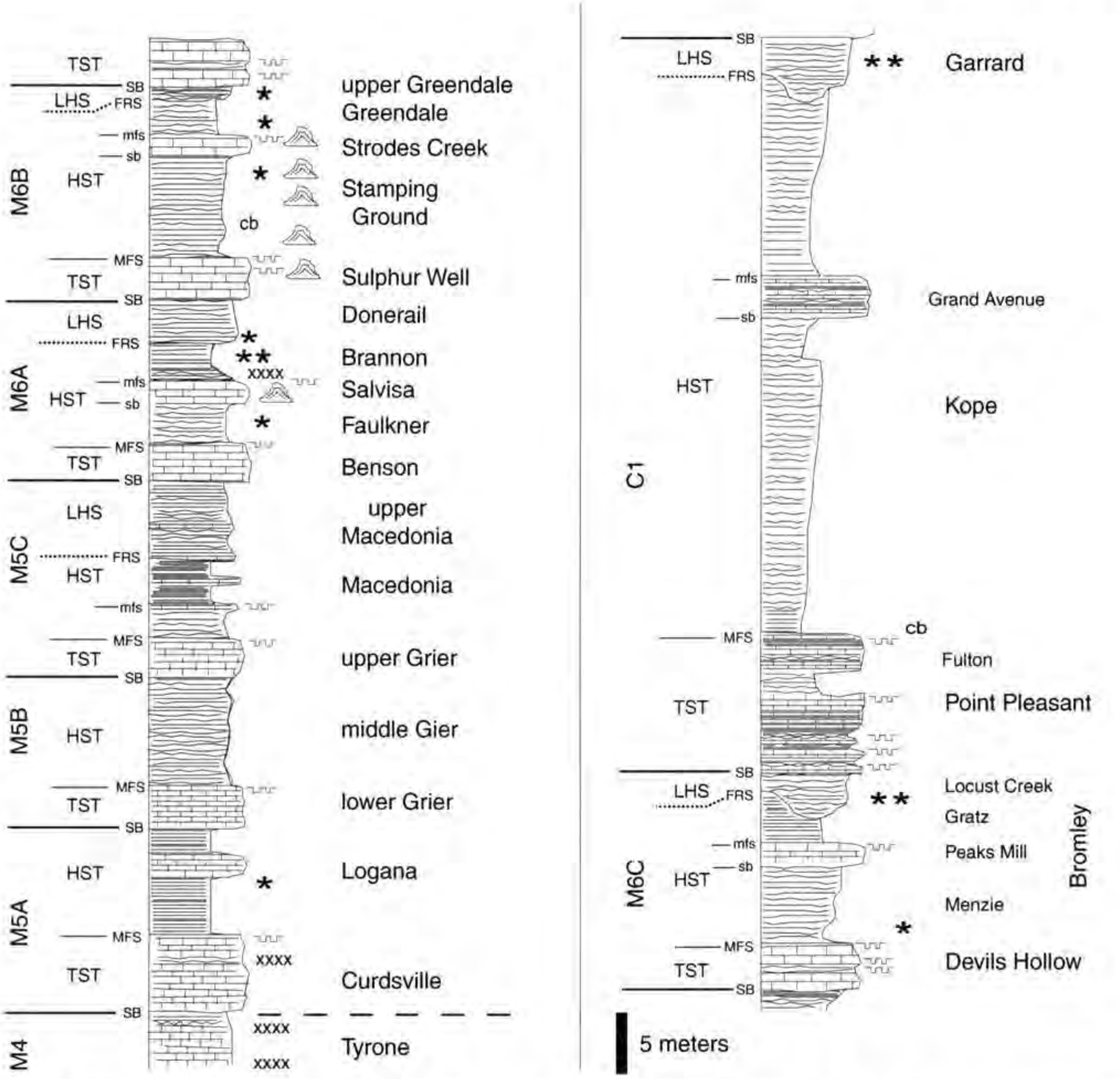

Figure 4. Generalized stratigraphic column for Lexington Limestone and adjacent units. SB—major sequence boundary; MFS—major flooding surface; sb—minor sequence boundary; Mfs—minor flooding surface; FRS—forced regression surface.

cal, this is only intended as a "model" column, and the reader should realize that the thicknesses and facies of given units are subject to substantial variation. The stratigraphic subdivision used herein generally follows Cressman (1973), except that in the upper third of the Lexington we have been able to recognize and consistently trace out several individual bracketed intervals and to determine gradual lateral facies changes within them. Because of this, we have found it useful to designate informal names for these units. Where possible, we have simply extended names that Cressman applied locally to a given package; we propose informal "submember" names for a few other distinct packages

Overall, the Lexington formation is about 70 m thick; it is approximately age-equivalent to the Trenton Group of New York state (Cressman, 1973) and thus encompasses the upper Mohawkian Series (Rocklandian to Shermanian stages, now typically lumped as the Chatfieldian Stage). The Lexington Limestone sharply and unconformably overlies the Tyrone Limestone of the Turinian (Blackriveran) High Bridge Group, and is in turn overlain by shales and thinner-bedded limestones of the Bromley, Point Pleasant, and Kope formations (locally lumped as Clays Ferry Formation; Weir and Greene, 1965).

The associated field trip will focus heavily upon strata of the upper third of the Lexington Limestone and the Bromley, Point Pleasant, and lower Kope formations. Therefore, we will only give brief treatment to the lower two-thirds of the Lexington Limestone here (for further discussion, see Cressman, 1973), reserving the bulk of the discussion to those units to be visited on the field trip.

Curdsville Member

The lowest unit of the Lexington Limestone is the Curdsville Member. It is variable in thickness from 7 to 13 m and is composed of skeletal pack- and grainstone. The unit rests with sharp unconformity on the underlying Tyrone ("Black River") limestone. Above this sharp boundary, the Curdsville is a relatively massive, crinoid-rich grainstone to packstone unit with *Tetradium* corals. It typically exhibits three divisions: a lower massive grainstone, a middle shaly zone containing ball-and-pillow deformed shale and calcisiltite, and an upper pack- to grainstone division. Conkin and Dasari (1986) identified the middle interval as the Capitol metabentonite, named for its occurrence in the Capitol District near Frankfort, Ky. The presence of phenocrysts within this shale indicates a probable contribution of volcanic ash. The Curdsville has been assigned to the Kirkfieldian because of affinities of its echinoderm fauna with that of the Kirkfield (Bobcaygeon) Limestone of Ontario (Cressman, 1973); however, the unit also contains fossils, such as *Sowerbyella curdsvillensis* and *Hesperorthis tricernaria*, that suggest assignment to the Rocklandian Stage of Kay's (1937, 1968) terminology.

Logana Member

The Logana Member abruptly overlies the Curdsville and contains approximately 8 to 12 m of rhythmically thin-bedded calcisiltites and dark gray shales (facies 1 and 2). The Logana Member is consistently divisible into two major packages, separated by a middle bundle of dalmanellid brachiopod-rich grainstones. The age of the Logana has been debated. Recent discovery of the Guttenburg C-13 anomaly in both the Logana and the Napanee Limestone of New York (Bergström, 2001) further supports a Rocklandian age for both units.

Grier Member

The Grier Member as referred to in this report overlies the Logana and is overlain by the Macedonia beds interval (see below). The Grier is a 12- to 17-m-thick, seemingly monotonous interval of thin- to medium-bedded, nodular- to wavy-bedded pack- and grainstone with minor shale and calcisiltite. We have divided it into lower, middle, and upper portions based on lithology. It has a diverse fauna typified by the domal bryozoan *Prasopora*; faunal data suggest that this interval is of Kirkfieldian to early Shermanian age.

Macedonia Beds

The Macedonia interval, designated as a "bed" of the Grier Member by Cressman (1973), consists of 4 to 5 m of rhythmically bedded shale and calcisiltite, resembling the Logana. We treat the Macedonia as an informal submember of the Grier, although it probably should be considered a member in its own right. It is one of the most laterally persistent and diagnostic units of the entire Lexington Limestone. The Macedonia is split by a 0.5-m-thick brachiopod grainstone. The upper division of the Macedonia varies greatly in thickness, as it is truncated by an overlying erosion surface.

Unnamed Submember (Upper Macedonia)

In the past referred to as a tongue of the Grier Member, the upper Macedonia interval is not stratigraphically equivalent to the Grier Member (as we have defined it). The post-Macedonia interval ranges from 5 to 10 m in thickness and is commonly composed of a 0.5-m-thick grainstone that sharply overlies the Macedonia, followed by a few meters of shaly, nodular packstone containing *Prasopora*. The shaly, nodular strata (Grier facies) may grade upward into wavy-bedded, silty limestone split by thin shale partings.

"Benson Interval" (Submember)

The name "Benson" was suggested by Foerste (1905) for an interval (30 to 40 ft) of limestones that was located below the Brannon Member. Cressman (1973) included this interval within the Grier because, despite its grainstone lithology, he did not think it was continuous with the rest of the Tanglewood limestones. However, placing a 10-m-thick grainstone package in a member defined by the presence of shaly, nodular, skeletal packstone is not justifiable on the basis of lithostratigraphy. This grainstone interval is distinctive and traceable (as noted by Cressman, 1973). Therefore, we refer to it here informally as the Benson limestone. As thus defined, the Benson is composed of 5 to 8 m of compact skeletal grainstone. It sharply overlies the upper Macedonia interval and rests on an erosion surface that may remove up to 3 m of the underlying upper Macedonia interval.

Faulkner Beds (Submember) Equivalent

This 0- to 7-m-thick interval of fossiliferous, shaly, nodular packstones and calcisiltites (Grier and Millersburg facies) has in the past also been assigned as a tongue of the Grier Member, but was acknowledged to be stratigraphically equivalent to the Faulkner Bed (submember) of the Perryville Member to the south (Cressman, 1973).

Salvisa-Cornishville Beds (Submember) Equivalent

A compact interval of skeletal grainstones 1.5 to 2 m thick forms the "Salvisa equivalent," which sharply overlies strata equivalent to the Faulkner Bed. The Salvisa equivalent often displays long low-angle planar crossbedding. These beds pass upward into thin, shaly, nodular pack- and grainstones (facies 4), probably equivalent to the Cornishville Bed. Near Frankfort, this interval has abundant stromatoporoids near the top and may be capped by a thin dolomitic bed with a rusty-stained hardground at the contact with the overlying Brannon Member.

Brannon Member

The Brannon Member is another distinctive fine-grained marker interval, resembling the Logana and Macedonia. It is approximately 1 to 5 m in thickness, is generally dark gray, rhythmically bedded, and locally contains cherty calcisiltites and shales. These beds are typically highly deformed and toward the top may develop a deformed, brecciated fabric referred to as Cane Run Bed (Cressman, 1973) near Lexington. Cressman originally placed the Cane Run Bed in the Grier Member; however, our mapping indicates that the Cane Run Bed is part of the Brannon.

"Donerail Submember" (Upper Brannon)

The shaly, thin-bedded Brannon is sharply overlain by a thin, compact grainstone bed followed by 0 to 5 m of thin, wavy-bedded, fine-grained grainstones with minor cherty calcisiltites. This "upper Brannon" (informally named Donerail submember for exposures on I-75 near Donerail, Ky.; stop 1) package is locally absent where it has been truncated by erosion under the overlying grainstones. This interval has been combined with the subtly different overlying grainstone and termed "lower tongue of the Tanglewood" in the past.

Upper Lexington

The upper portion of the Lexington, previously of middle to late Shermanian age, has been viewed as a complex intertonguing of two broadly defined members: the Tanglewood and Millersburg. We consider the terms "Tanglewood" and "Millersburg" to be generalized facies names for thick-bedded skeletal grainstone and nodular shaly packstones, respectively. In some cases, we also have found particular units to be much more widely traceable than was supposed. For example, the shaly, nodular ("Millersburg") intervals that Cressman (1973) termed "Stamping Ground Member" and "Greendale Lentil" have proven to be widespread marker intervals.

Lower Tongue of Tanglewood (Including Sulphur Well Member)

As noted, we subdivide the lower tongue of Tanglewood into two parts, the Donerail and the Sulphur Well equivalents. We have found evidence that an important disconformity, the sub-Sulphur Well unconformity of Cressman (1973), actually separates these units. An unusual succession occurs near the base of this interval where a compact 0.4- to 1-m-thick bed (herein termed "Switzer Road bed") of grainstone or locally fenestral micrite rests sharply and apparently unconformably on the underlying "upper Brannon." This bed is typically followed by a thin interval of fine-grained grainstone/calcisiltite that is commonly deformed into overturned folds and ball-and-pillow structures.

The main body of the interval, herein considered to be a Sulphur Well equivalent, consists of 2.6 to 4 m of thick-bedded to massive crinoidal, bryozoan, and *Rafinesquina*-rich grainstone that may be split into two intervals by a shaly packstone interval about a meter below the top. The "Sulphur Well" is sharply demarcated at the top by a rusty-stained, pyrite-coated discontinuity; another rusty-weathering bed commonly occurs about 60 cm lower.

Stamping Ground Member

Proposed by Cressman (1973), this unit consists of 4 to 5 m of medium gray, typically shaly, nodular packstones and grainstones near the top of an abandoned quarry near Stamping Ground, Ky. Our studies have shown that this is an incomplete section of the unit, which is actually about 7 to 8 m thick and typically culminates with intervals of coarser pack- and grainstone. The interval has been variably identified as Millersburg or Tanglewood (in part), but recent studies show that it is consistently mappable. Bryozoans and brachiopods, notably *Rhynchotrema*, are especially common in the lower shaly beds of the Stamping Ground. Large coenostea of the stromatoporoid *Labechia huronensis* are also abundant at many localities, this being the most prolific occurrence of these fossils in the Lexington Limestone (stop 1; Taha and others, 2001). Near Lexington, Ky., *Labechia* occurs in the base of the Stamping Ground; northward, however, *Labechia* becomes consistently higher in the section until eventually becoming absent north of Swallowfield along the U.S. 127 transect (Fig. 1). About six meter-scale, shallowing-upward cycles, each capped by thicker grainstones, have been traced in the Stamping Ground (Taha and others, 2001). At least two unctuous clays, one of which has been shown to contain expandable-lattice clays typical of K-bentonites, occur locally in the upper Stamping Ground. In addition, a spectacular obrution/condensation deposit of conodonts and echinoderms occurs about 2 m above the base at one locality (stop 7).

Middle Tongue of Tanglewood (Strodes Creek Equivalent)

The Stamping Ground Member proper is abruptly overlain by about 2 m of Tanglewood facies; this could be simply designated the middle tongue of Tanglewood, but recent correlations suggest that it is equivalent to the Strodes Creek Member of the Lexington Limestone recognized to the southeast of Lexington. This is a compact skeletal pack- to grainstone resembling the lower Tanglewood (Sulphur Well tongue of this report). In northerly localities this interval bears abundant stromatoporoids and prolific bryozoans and solenoporids (Fig. 5). The upper surface of this unit shows pyritic hardgrounds and is sharply overlain by an interval of shale and nodular packstones.

Greendale Member

We identify the thin (2 to 4 m thick) interval of medium gray shales and thin, nodular wacke- and packstone or calcisiltite (facies 2 and 4), which overlies the "Strodes Creek equivalent," as the Greendale member. The term "Greendale" has been used in many senses; however, Cressman (1973) redefined the Greendale Lentil of shaly nodular packstones between two tongues of his Tanglewood Member at Greendale Station near Lexington. Our correlations show that this shaly, brachiopod- and bryozoan-rich unit is very widespread and identifiable, and we have termed it Greendale member. Near Frankfort, this interval is exceptionally rich in thick ramose bryozoans; to the north as the interval becomes shalier, its fauna becomes dominated by rhynchonellid and *Zygospira* brachiopods. The Greendale consistently contains a skeletal pack- to grainstone bed 10 to 30 cm thick that often divides the unit nearly in half.

Figure 5. Stromatoporoid in *Solenopora* conglomerate, Stamping Ground Member on U.S. 127, locality OR (stop 6).

Upper Tongue of Tanglewood (Including Devils Hollow Member)

The Greendale interval is abruptly, and probably disconformably, overlain by 3 to 10 m of the "middle tongue of the Tanglewood." This interval can be divided into four parts. The lower interval (informally termed "post-Greendale") is composed of thin, wavy, amalgamated, silty limestones that may show ball-and-pillow deformation. The Devils Hollow Member disconformably overlies the "post-Greendale" interval and is composed of three parts over much of the study area, as described by Cressman (1973). The lower division of the Devils Hollow is composed of nearly a meter of coarse-grained, stylolitic, gastropod grainstone displaying large-scale cross-stratification that grades into fenestral micrites. The micrites are overlain by an interval of finer crinoidal grainstones, packstones, and minor shales a few meters in thickness, which may show ball-and-pillow deformation. The top of the "middle tongue of the Tanglewood" is composed of a thick interval of tabular skeletal grainstone, which shows an abrupt contact with the overlying dark shales or argillaceous calcisiltites of the lower Bromley formation (the informal Menzie member) and is marked by several rusty-weathering discontinuity surfaces.

Bromley Formation

The Bromley formation (officially termed the Bromley Bed of the Point Pleasant tongue of the Clays Ferry Formation) was originally named by Ulrich (1888) and comprises about 8 to 10 m of shales, thin- to medium-bedded calcisiltites, and nodular wacke- to grainstones. The term corresponds in large part, though not entirely, with Cressman's Millersburg Member of the Lexington Limestone. The lower Bromley formation (informally termed the Menzie member) is predominantly dark shale and calcisiltite in the Cincinnati area; Ulrich (1888) reported that in former exposures of the lower Bromley shale along the bank of the Ohio River near Cincinnati, these dark shales yielded a "Utica" fauna composed of small inarticulates (*Leptobolus*), the trilobite *Triarthrus*, and the cladid crinoid *Merocrinus*. Southward toward the Jessamine Dome, the percentage of shale in the Menzie decreases, and the unit becomes calcareous gray shale and wavy to nodular wackestone with thin pack- and grainstone beds. The Menzie comprises at least two 2-m-thick intervals separated by a middle grainstone package. At a finer scale there are as many as eight to 10 half-meter-scale packages, which grade up from shale or calcareous nodular mudstone to thin compact limestones. Locally, the upper portion of the Menzie member is truncated and partially removed by erosion. The contact appears flat in any given outcrop, but regionally there is evidence for removal of over a meter of strata. This is particularly notable in the area of Frankfort, where as much as 2 to 3 m of upper Menzie may have been removed. A thin bed showing possible fenestral fabric was located at the base of the "Peaks Mill beds" in a large outcrop on the northern end of Frankfort (Pope and Read, 1997; stop 5). The presence of this bed indicates an abrupt shift in facies from subtidal to peritidal.

The newly recognized "Peaks Mill beds" (McLaughlin, in prep.) are 1 to 3 m thick and are composed of compact, sparry, light gray brachiopod- and gastropod-rich grainstone and fenestral micrite (in the base, facies 5 and 7), which sharply overlie the "Menzie." The white limestones of the "Peaks Mill beds" are in turn sharply overlain by the "Gratz" interval.

The "Gratz" interval consists of a thin, but rather monotonous, succession of shales, calcisiltites, and, in more proximal sections, *Isotelus* and brachiopod (mostly *Rafinesquina*) pack- and grainstones (facies 1 and 2). The Gratz varies greatly in thickness from 0 to 3 m. The "Gratz" interval has been variably truncated by subsequent erosion, as near Frankfort where silty limestones of the "Locust Creek beds" rest directly on white sparry grainstones of the "Peaks Mill beds."

The "Locust Creek beds," also newly recognized (McLaughlin, in prep.), comprise rhythmically laminated fine- to medium-grained, generally sparsely fossiliferous grainstones. These beds rest sharply on truncated Gratz shales and calcisiltites. These beds locally appear to occupy distinct channel fillings up to tens of meters across, and cut up to 2 m into the subjacent Gratz. These fillings are almost invariably strongly deformed (see Ettensohn and Stewart, this volume). The laminated and generally deformed grainstones are actually subdivided into a series of packages, each capped with a skeletal hash bed (dominated by *Rafinesquina*); these are capped by mineralized (rusty-weathering) hardgrounds, interpreted as minor flooding surfaces of meter-scale cycles.

The top of the Locust Creek beds (top of Bromley formation) is everywhere sharply defined at a disconformable contact with the Point Pleasant Formation. Variable removal of up to several meters of upper Locust Creek shales is evident from regional mapping.

Point Pleasant Formation

The Point Pleasant Formation, named for exposures along the Ohio River in southern Ohio, consists of 7 to 9 m of bryozoan- and brachiopod-rich pack- and grainstones with intervals up to about a meter thick, dominated by gray shales and calcisiltites. Beds of the Point Pleasant are arranged into about eight 0.5- to 1-m-scale shale-limestone bundles. In the upper half of the Point Pleasant, these cycles exhibit progressive diminution in thickness with a reduction of shaly portions. The brachiopod *Rafinesquina* and the archaeogastropod *Cyclonema* are abundant in lower Point Pleasant beds, whereas upper beds show abundant *Ectenocrinus*, *Dendrocrinus*, and *Merocrinus*, the trilobite *Cryptolithus*, and the brachiopods *Onniella*, and rarely *Sowerbyella* (typical of lower Edenian, deeper, dysoxic facies; see ordination studies of Holland and others, 2001a). Throughout the Point Pleasant, there are a number of irregular, encrusted/bored and phosphate-coated firmgrounds and hardgrounds (Fig. 6). Stacking of hardgrounds and firmgrounds on and just above compact, amalgamated grainstone bundles in meter-scale cycles (Fig. 1) further indicates condensation in this portion of the section. The abrupt upper contact of the Point Pleasant is locally marked by an irregular conglomeratic pyrite-stained hardground.

Lower Kope Formation

The lowest unit of the Kope Formation, termed the "Fulton submember," consists of brownish-gray shales and olive mudstones with carbonate concretions alternating with thin (10 to 25 cm), sharply bounded, skeletal pack- and grainstone beds (facies 1 and 2; Algeo and Brett, 2001). The darkest Fulton shales bear a dysoxic fauna, including small inarticulates (*Lingula, Leptobolus*), the trilobite *Triarthrus*, small *Isotelus, Cryptolithus*, and the cladid crinoid *Merocrinus*. Skeletal limestones carry abundant crinoidal debris (mostly *Merocrinus* columnals), the brachiopods *Dalmanella* and *Sowerbyella*, and small ramose bryozoans. The Fulton displays an excellent correlatable framework of meter- and half-meter-scale, shale-limestone bundles (Fig. 1). It is divisible into about four 1- to 2-m-thick shale-based cycles with superimposed smaller 10- to 50-cm shale-limestone alternations toward the top. A condensed bed ("Duck Creek bed") containing abundant conodont elements, and disseminated and moldic pyrite occurs at its top. Dark shales and siltstones of the Brent submember (facies 1) abruptly overlie the "Duck Creek bed."

Figure 6. Lumpy, bryozoan-crinoid hardground in the Point Pleasant Formation on I-75 North, locality 620 (stop 2); pencil for scale.

Sequence Stratigraphy of the Lexington Limestone

Sequence-Stratigraphy Generalizations

The Lexington and overlying units are subdivisible into a series of bounded packages, each delimited at its base by a sharp surface, which we interpret to be sequence boundaries (SB). Each sequence boundary shows evidence of erosion of subjacent beds and an abrupt facies dislocation (i.e., evidence for disjunctive juxtaposition of shallower over deeper facies; Figs. 1 and 7). The basal transgressive systems tracts (TST) are primarily skeletal grainstones or packstones, apparently representing shallow-water, high-energy settings; the upper parts of these packages show a change toward more muddy, packstone facies and stacked hardgrounds, in addition to a change of major faunal constituents from shallow-water faunas to those indicative of deeper water, suggesting retrogradation. Flooding surfaces (FS) are readily identifiable by abrupt changes in color (light yellow or pink to dark gray), grain size (coarse sand to mud and clay), bedding (medium bedded to massive to thin-bedded), and fossil content. Flooding surfaces may be marked with mineralized crusts—typically pyrite, which oxidizes to form a rusty parting. These intervals may also contain condensed beds containing a high density of pelagic elements (conodonts, etc.) and K-bentonites. Overlying dark gray shales and nodular wacke- and packstones record increased siliciclastic input and apparently deeper-water offshore environments and are considered highstand systems tracts (HST). Typically, highstand intervals will contain a thin carbonate package in their upper half, likely representing a period of sea-level rise. These thin TST's rest upon erosion surfaces and are capped by hardgrounds interpreted to represent a flooding surface. Typically, the strata that lie above this upper flooding surface are rhythmic calcisiltites and shales of facies 1. Most sequences also show a yet higher interval, herein considered to be a late highstand (regressive) systems tract (LHST), which is locally composed of wavy-bedded, laminated calcisiltite to fine-grained grainstone beds and which occasionally have undergone extensive

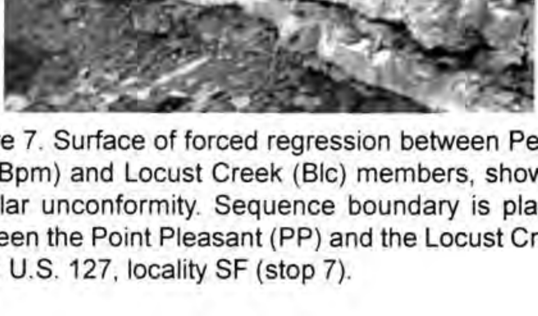

Figure 7. Surface of forced regression between Peaks Mill (Bpm) and Locust Creek (Blc) members, showing angular unconformity. Sequence boundary is placed between the Point Pleasant (PP) and the Locust Creek (Blc); U.S. 127, locality SF (stop 7).

deformation. These LHST's are bounded at their bases by a surface of forced regression and at their tops by a sequence boundary (Fig. 7). There appear to be sequences of different scales developed at thicknesses or scales of a few meters and tens of meters. The sequences described above display the opposite pattern in contrast to parasequences that are bounded by flooding surfaces and show primarily shallowing-upward patterns. Parasequences occur within these sequences at the meter scale.

In following sections, we briefly describe the major sequences as presently recognized in the Lexington Limestone and adjacent units. It should be noted that certain of the sequence boundaries overlap with those previously recognized by Holland (1993), Holland and Patzkowsky (1996), Pope and Read (1997), and Hohman (1998).

Sequence M5A (Curdsville-Logana)

At the base, the Lexington Limestone is bounded by a major unconformity at the contact with the underlying Tyrone Formation. This is a sharp, slightly wavy surface, which demonstrably cuts out several meters of the underlying upper Tyrone Formation (Miller, 1925). The typically fenestral micrites of the upper Tyrone contain a series of useful markers in the form of K-bentonites (Conkin and Dasari, 1986; Huff and others, 1992). The lowest, the Pencil Cave K-bentonite, a middle unnamed bentonite, and the Mud Cave or Millbrig, form useful markers that demonstrate the regional truncation at the base of the Lexington (Cressman, 1973). In the area of Frankfort, for example, the upper of these three bentonites, the Mud Cave or Millbrig, has been removed, and the sequence boundary or basal surface of the Lexington rests close to the position of the middle, unnamed bentonite.

The Curdsville grainstone facies represents a transgressive systems tract (Pope and Read, 1997). The upper contact of the Curdsville is inferred to represent a maximum-flooding surface, overlain by shales and thin calcisiltites (lutites) of the Logana Member, herein interpreted to be the highstand systems tract of sequence M5A.

Sequence M5B ("Lower and Middle Grier")

The "lower Grier" is a grainstone-dominated interval that seemingly lies disconformably upon the "upper Logana" interval. The "lower Grier" is sharply overlain by the "middle Grier." This unit of shaly, nodular, *Prasopora*-rich packstones has not been intensely scrutinized in the course of this study and may yield additional divisions with further study.

Sequence M5C ("Upper Grier"–Macedonia Bed–"Upper Macedonia")

The "upper Grier" seemingly rests unconformably on the "middle Grier." It is in turn overlain by shaly nodular packstones of the Macedonia interval at a likely maximum-flooding surface marked by a mineralized hardground. An additional flooding surface occurs at the base of the Macedonia beds (facies 1). The Macedonia beds are in turn overlain by a forced-regression surface at the base of silty, wavy "upper Macedonia" limestones.

Sequence M6A ("Benson"–"Faulkner Equivalent"–"Salvisa-Cornishville Equivalent"–Brannon–"Donerail")

Limestones of facies 5 make up the "Benson" interval." It rests upon an erosion surface that chops out a few meters of the underlying "post Macedonia" interval. It is commonly overlain by shaly, nodular strata of the Faulkner equivalent. This contact is marked by a mineralized hardground and is interpreted to be a flooding surface. The Faulkner equivalent is in turn sharply (erosionally) overlain by strata equivalent to the Salvisa (facies 5). Shaly, nodular packstones of the Cornishville equivalent overlie the Salvisa at a mineralized flooding surface and are in turn sharply overlain by the Brannon Member at an additional mineralized flooding surface. The rhythmic calcisiltites and shales (facies 1) are often highly deformed in the upper few meters of the Brannon Member (Cane Run deformational facies). This bed is generally sharply overlain by up to 4 m of grainstones of facies 6, herein provisionally termed "Donerail" submember. These beds show a generally upward-coarsening pattern and are interpreted to be late highstand deposits. The rather sharp contact at the top of the Brannon Member (or Cane Run Bed) may represent a forced-regression surface. The Faulkner and Salvisa equivalents, Brannon Member, and "Donerail" submember can be interpreted as components of a highstand systems tract of a third-order depositional sequence. This highstand interval is truncated by a surface of prominent erosion, which occurs beneath the massive grainstones of the Sulphur Well; this erosion surface locally removes the "upper Brannon" and may even cut into the Brannon Member. Hence, it is considered to be a major sequence boundary.

Sequence M6B1 (Sulphur Well–Stamping Ground–"Strodes Creek Equivalent"–"Greendale Member"–"Upper Greendale")

We interpret the sharp basal contact of the Sulphur Well–equivalent, lower Tanglewood Member, as a third-order sequence boundary. Areas in which truncation is extreme are presumed to have been topographic highs. The overlying Sulphur Well Member (and equivalents) is interpreted to be a transgressive systems tract. The basal Switzer Road beds show oncolites, ostracod wackestones, and possible flaser bedding, all evidence of deposition in shallow-water to peritidal environments near the base of this succession. The overlying 2 to 3 m of grainstone record amalgamated, high-energy, shoal facies. These grainstones interfinger with finer-grained, typically cherty grainstones to calcisiltites.

The closely spaced, commonly pyrite-coated (rusty-weathering) discontinuities near the top of the Sulphur Well Member are thought to record hardgrounds associated with sediment starvation. Clustering of these hardgrounds near the top of the Sulphur Well indicates a condensed section associated with a maximum flooding zone (Fig. 8).

The basal shaly beds of the Stamping Ground represent some of the deepest-water facies of the succession. They seem to coarsen stepwise upward and thus are interpreted to be part of the highstand systems tract.

The sharp and possibly unconformable contact of the middle Tanglewood (Strodes Creek) grainstones represents a minor sequence boundary; this disconformity appears locally to truncate much of the Stamping Ground Member in the north Frankfort area. This compact middle Tanglewood grainstone contains large stromatoporoids as far north as the large cut on U.S. 127 near Swallowfield, Ky.; north of this area, it contains abundant large bryozoans and solenoporid algae.

The sharp, mineralized upper contact of the "Strodes Creek," similar to the top of the Sulphur Well, is a flooding surface. The gray shales and thin nodular wacke- and packstone of the Greendale member occupy the upper part of the highstand. The Greendale is then overlain by the late-highstand, silty limestones of the "upper Greendale."

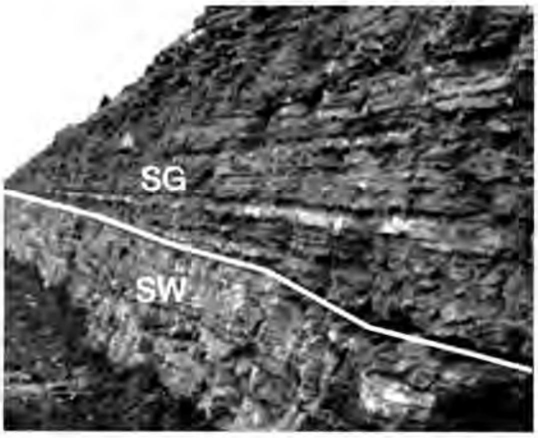

Figure 8. Rust-stained, maximum-flooding surface at the Sulphur Well/Stamping Ground contact, sequence M6B, on I-75, DR locality.

Sequence M6C-1 (Devils Hollow–Menzie–Peaks Mill–Gratz–Locust Creek)

The top of this interval is considered to be equivalent to the upper part of the highest Mohawkian sequence (M6) of Holland and Patzkowsky (1996). It is inferred to begin with the sharply based grainstones of the Devils Hollow Member, which have been studied in detail (Etter, 1948; Cressman, 1973; Kasl, 2001) and appear to show three small-scale cycles (parasequences).

The Devils Hollow is interpreted to represent a transgressive systems tract. It overlies the "upper Greendale" at a major erosion surface (sequence boundary), which removes it entirely in many exposures south of the FN exposure (Fig. 1). The contact of the Devils Hollow with the overlying Menzie member of the Bromley formation is interpreted to be a maximum-flooding zone of no more than 0.5 m in thickness, containing up to four tightly stacked mineralized hardgrounds.

The Menzie member exhibits several meter-scale, coarsening-upward packages interpreted to represent parasequences. These parasequences seem to roughly coarsen (shallow) upward though the Menzie, and therefore are considered part of the highstand systems tract.

The sharply based succession of pack- and grainstones of the "Peaks Mill" interval represents a minor transgressive systems tract. The Peaks Mill member erosionally overlies the Menzie member at an inferred minor sequence boundary. Its upper surface is a mineralized flooding surface, upon which the Gratz member (facies 1) rests, and is inferred to be a minor flooding surface. The Locust Creek member (facies 7) erosionally overlies the Gratz at an inferred forced-regression surface. The increased proportion of silt and fine-grained calcarenite/sandstone of the "Locust Creek" is suggestive of progradation. In particular, deformed beds of fine calcarenite of the Locust Creek member appear to record rapid progradation of near-shore sediments into offshore areas followed by their seismic deformation.

The upper boundary of the M6 sequence is marked by the sharp, erosional contact of the Point Pleasant Formation, which variably truncates upper beds of the Bromley (Locust Creek member; see below).

Sequence C1 (Point Pleasant–Lower Kope–Grand Avenue–Upper Kope–Garrard)

The last large sequence comprises the Point Pleasant, Kope, and Garrard formations. The overall sequence architecture is similar to that of the underlying sequences, although the proportion of shale is greatly increased. This sequence has been designated as C-1 (first Cincinnatian sequence) by Holland (1993) and Holland and Patzkowsky (1996); in fact, it probably spans uppermost Shermanian through Edenian stages of the North American Cincinnatian Series, an interval of some 2 to 3 million years.

Holland (1993) did not specify the precise placement of the C1 sequence boundary. However, we place this boundary at the sharp base of the Point Pleasant Formation, as defined herein. There are several justifications for this placement: (1) this is a sharp and demonstrably erosional contact, (2) the basal bed of the Point Pleasant is roughly a half meter of coarse skeletal pack- to grainstone, typically rich in gastropods and resembling a transgressive lag deposit, (3) at the scale of single outcrops, this bed shows an erosional relief of several centimeters and typically contains abundant clasts of the subjacent shales and calcisiltites, and where this contact rests on the Locust Creek deformed zone it drapes irregularities of the convoluted calcarenite and may contain eroded clasts of the deformed beds, (4) at a regional scale this unconformity clearly shows discordance (regional angularity) with underlying beds, and (5) the base of the Point Pleasant overlies a generally shallowing-upward succession of the Bromley and is overlain by a maximum-flooding surface near the base of the Kope. Hence, the base of the Point Pleasant occupies the position of a transgressive systems tract. Moreover, toward the top of the Point Pleasant Formation and in the Fulton submember of the Kope (included here in the TST), there are a number of irregular, encrusted/bored and phosphate-coated firmgrounds and hardgrounds. Stacking of hardgrounds and firmgrounds toward the tops of meter-scale cycles further indicates condensation in this portion of the section. We interpret the relative condensation as resulting in part from progressive siliciclastic starvation during the later transgressive systems tract.

The abrupt upper contact of the Point Pleasant, locally marked by an irregular pyrite-stained hardground, is interpreted to be a flooding surface and time of sediment starvation. The lower Fulton in the Cincinnati area shows a number of concretionary horizons that may also indicate a condensed section associated with transgression.

Brownish-gray shales and olive mudstones of the lower Fulton submember appear to record some of the most dysoxic facies in the Cincinnatian, at least comparable in environment to the brownish-gray, *Triarthrus*-bearing shales of the lower Bromley (lower part of the informal Menzie member). The recurrent *Triarthrus* fauna of the Fulton signals a second onlap of dysoxic water from the Sebree Trough onto the margin of the Lexington Platform.

Following the interpretation of Ettensohn and others (2002), we infer that the abrupt influx of Kope muds, as with the Bromley shales, indicates rising sea level and perhaps tectonic tilting that opened a passageway from the Taconic foreland basin into the Sebree Trough. This highstand permitted an influx of siliciclastics, derived from Taconic highlands to the northeast, to be deposited in the Sebree Trough and up onto the Lexington Platform. We further suggest that the relatively deep water enabled larvae of typical Utica Trough (dysoxic "*Triarthrus* fauna") to invade the margin of the Lexington Platform temporarily.

The thin (1 to 3 cm) but widespread pyrite- and conodont-rich Duck Creek bed at the top of the Fulton may record overall maximum flooding and condensation of the larger, third-order cycle. Overlying the Duck Creek bed, the Brent submember (facies 1) forms the base of the C1 highstand systems tract. The remainder of the Kope Formation is interpreted to represent the later highstand systems tract. The Grand Avenue beds may indicate a small transgression located within the Kope. Near the top of this highstand in the vicinity of the Jessamine Dome is the Garrard Siltstone. The Garrard is a 20- to 30-m-thick bundle of siltstones and fine-grained sandstones that appear channelized and extensively deformed as seismites. We interpret this package as being analogous to the Locust Creek calcarenite deformed zone of sequence M6. That is, the Garrard records the seaward progradation of coarser sediments during a sea-level drop. We suspect that a fourth-order subsequence boundary underlies the Garrard, and that it can be interpreted as a forced-regression surface. Hence, although it is much thicker, sequence C1 shows many features analogous to lower sequences, including division of the third-order highstand into subsequences.

Summary Discussion: Regional Patterns and Implications

Figure 1 shows the regional stratigraphic cross section of the Lexington Limestone and adjacent units along a north–south transect from the Blue Grass Parkway south of Frankfort, north to Monterey, approximately

35 km. It is notable that most units, including intervals of skeletal grainstone, herein interpreted as TST's, and shaly nodular intervals, interpreted as HST's, can be traced in at least the upper Lexington, Bromley, Point Pleasant, and lower Kope through all outcrops. Moreover, the units maintain relatively similar thicknesses, especially in the lower half of the Lexington. The lateral persistence of distinctive surfaces and major facies offsets (inferred sequence boundaries and flooding surfaces) suggests a widespread, allocyclic control on the development of these sequences. Moreover, preliminary work suggests that many of the sequences recognized here may correlate with those found in the Appalachian Basin (Brett and others, 2000).

However, some notable changes in thickness and facies do occur, especially in the upper units in the area of north Frankfort. Especially notable is the dramatic thinning of the middle Tanglewood (Sulphur Well–Stamping Ground equivalents) in the FN exposure on U.S. 127. At this section the exact relationships are still slightly uncertain. However, a thin interval of deformed fine- to medium-grained, cherty grainstones appears to represent the Brannon equivalent. This interval of grainstones is abruptly overlain by thin- to medium-bedded, coarse, crinoidal grainstones inferred to be the Sulphur Well equivalent, and a succession of cross-stratified, bryozoan-rich grainstones (some with herringbone crossbeds), capped by an exceedingly densely packed interval of fragmented stromatoporoids and a final grainstone. As the latter appears clearly to be overlain by thin nodular limestones correlative with the Greendale member both north and south of this area, we infer that the underlying beds should be assigned to the middle tongue of the Tanglewood (or Strodes Creek equivalent). The sharp surface below the stromatoporoid conglomerate beds appears to be an erosion surface at which the bulk of the Stamping Ground Member has been truncated. Nearby outcrops east and west of this area (i.e., FW and 421) show a substantially thicker interval of fine- to medium-grained, somewhat argillaceous pack- and grainstones in the position of the Stamping Ground Member.

The marked thinning, coarsening, and probable truncation of the lower to middle Tanglewood (interval equivalent to the Sulphur Well–Strodes Creek) at north Frankfort relative to sections both north and south of this area suggest that this area was a local high that developed perhaps slightly prior to deposition of the Brannon Member. Truncation is also evident at a higher level within the lower Bromley, which is thinner and coarser in this area than elsewhere.

While uncertainties remain regarding the interpretation of these stratigraphic patterns, they seem to indicate that shallower areas were characterized by thinner sections of stacked grainstones, representing the transgressive systems tracts, and locally coarsened, thinned, and partially truncated highstand deposits. This telescoping of units contrasts with the implications of the term "Tanglewood buildup," which seemingly would imply a local thickened area of high skeletal production and/or pileup of wave-winnowed debris. Instead, skeletal-shoal areas seem to be characterized by winnowing, truncation, and amalgamation of beds.

Other trends, apparent from the cross section, include the converse effect of thickening of shaly, nodular intervals both to the north and south of Frankfort. Generally, the deepest-water facies of the Stamping Ground, Greendale, Menzie, and Gratz occur near Monterey (the northernmost locality on the cross section). Both intervals exhibit a south–north change from facies 6 or 5 (grainstones) to 4 then to 2 or 1 (shaly calcisiltites). In the older terminology, this would be designated as a lateral change from Tanglewood to Millersburg to Clays Ferry members. However, it is important to note that these changes can be observed *within* bracketed packages. Also, they appear more extreme in the intervals interpreted herein as highstands, whereas transgressive systems-tract grainstones (e.g., Salvisa, Sulphur Well, Strodes Creek, and Devils Hollow equivalents) remain more nearly similar in thickness and facies (showing, at most, a transition from facies 6 to 5 across this same profile). This could imply that the grainstones are somewhat diachronous blanket-like deposits. Nonetheless, an exception to this occurs in the Point Pleasant Limestone. The upper portion of this interval shows a marked change from skeletal grainstones (facies 5 and 6) near Frankfort to mixed grainstones and packstones (facies 3 or 4) near Swallowfield, and finally into shaly nodular carbonates (facies 2) near Monterey. This trend affects only the upper half of the Point Pleasant, and we suspect that it represents a brief pulse of local subsidence along the margin of the Sebree Trough during latest Shermanian time. Surprisingly, it does not appear to similarly affect the overlying Fulton beds, which appear limestone-rich and rather proximal at Monterey.

Several zones of soft-sediment deformation can be mapped over a good deal of the Frankfort-Lexington area (Pope and others, 1997). The lowest such widespread interval is in the Brannon, which shows varying degrees of deformation over the Lexington-Frankfort area. This interval is dealt with in detail by Ettensohn and Stewart elsewhere in this volume. We interpret the Cane Run Bed as highly disrupted fabrics near the top of this interval; we have observed this type of deformation from Swallowfield (stop 8) southward to Frankfort.

A second rather widespread interval of overturned folds occurs near the base of the Sulphur Well (within the lower tongue of the Tanglewood), at least from Lexington through south Frankfort. Deformed, cherty calcisiltites, closely resembling those of the Brannon, also occur locally in the lower Stamping Ground west of Frankfort, in the upper Tanglewood (Devils Hollow equivalent north of Frankfort to Monterey), and in the Greendale member near Monterey and Gratz.

The most extensive disturbed zone occurs within fine-grained, "pinstriped" grainstones, herein referred to as the Locust Creek member of the Bromley. This interval is strongly deformed, with convolute bedding, ball-and-pillow deformation, and foundered slabs at three to four levels, up to the sharp erosive base of the Point Pleasant Formation. Deformation occurs at all localities examined in northern Kentucky and southern Ohio. This interval is accessible in eight exposures along U.S. 127 between Frankfort and Monterey, and the three to four intervals of deformation are present at all of these outcrops, with the singular exception of the long outcrop along U.S. 127 near Swallowfield (stop 7), where the strata appear completely undeformed along nearly 1 km of exposure.

We infer that these extensive zones of ball-and-pillow deformation are seismites recording very large earthquakes that affected faults in the Jessamine Dome area. They also occur nonrandomly in interbedded shales and fine-grained grainstone to calcisiltite facies, but crosscut other facies patterns to some extent. We infer that most of the extensive deformed zones occur within rapidly deposited late-highstand ("regressive") carbonates.

Faunal zonation is also evident within the Lexington Limestone. The bryozoan *Prasopora* sp. occurs abundantly throughout much of the Grier and Perryville members up to the level of the Brannon Member, but rarely above. Its abrupt loss appears to be a regional extinction tied to that seen in the Appalachian Basin. A second example involves the persistence of the stromatoporoid *Labechia* in the lower to middle Tanglewood (Sulphur Well–Stamping Ground–Strodes Creek equivalent) interval. This interval appears to represent an epibole, or the peak development of this stromatoporoid. Less common occurrences of *Stromatocerium* occur above and below, but nearly all of the abundant *Labechia* occur in this interval. The genus is rare or absent above the level of the Greendale flooding surface, again suggesting regional extinction.

Finally, there is evidence for incursion of faunal elements, including the trilobite *Triarthrus*, the rhombiferan *Cheirocystis*, and various crinoids and brachiopods into the Lexington Platform area during deposition of the Bromley formation (late Shermanian). These taxa appear to have originated in the northeast where they are present considerably earlier in strata of Shermanian age. This influx is coincident with extension of the Sebree Trough and Point Pleasant Basin to the northeast, and we suggest that the yoking of this area with the Appalachian Basin may have permitted the influx of new taxa as well as increased siliciclastics via the Sebree Trough.

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