2011

# DEPOSITIONAL AND STRATIGRAPHIC SIGNIFICANCE OF MARINE, GREEN-CLAY, MINERAL FACIES IN THE LOWER-MIDDLE MISSISSIPPIAN BORDEN AND FORT PAYNE FORMATIONS, WESTERN APPALACHIAN AND EASTERN ILLINOIS BASINS, KENTUCKY

Devi Bhagabati Prasad Udgata
*University of Kentucky*, devi.udgata@uky.edu

ABSTRACT OF DISSERTATION

Devi Bhagabati Prasad Udgata

The Graduate School

University of Kentucky

2011

DEPOSITIONAL AND STRATIGRAPHIC SIGNIFICANCE OF MARINE, GREEN-CLAY, MINERAL FACIES IN THE LOWER-MIDDLE MISSISSIPPIAN BORDEN AND FORT PAYNE FORMATIONS, WESTERN APPALACHIAN AND EASTERN ILLINOIS BASINS, KENTUCKY

---

ABSTRACT OF DISSERTATION

---

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the College of Arts and Sciences at the University of Kentucky

By

Devi Bhagabati Prasad Udgata

Lexington, Kentucky

Director: Dr. Frank R. Ettensohn, Professor of Earth and Environmental Sciences

Lexington, Kentucky

2011

# ABSTRACT OF DISSERTATION

## DEPOSITIONAL AND STRATIGRAPHIC SIGNIFICANCE OF MARINE, GREEN-CLAY, MINERAL FACIES IN THE LOWER-MIDDLE MISSISSIPPIAN BORDEN AND FORT PAYNE FORMATIONS, WESTERN APPALACHIAN AND EASTERN ILLINOIS BASINS, KENTUCKY

Detailed study of strata associated with the glauconite-rich Floyds Knob Bed in the western Appalachian and eastern Illinois basins have corroborated previous interpretations that the unit is a widespread, largely synchronous marker horizon. However, in some areas there are multiple glauconite beds; in others a distinct bed is lacking, but the glauconite is dispersed throughout many beds, forming an interval rather than a distinct bed. In Kentucky and adjacent states, the Floyds Knob interval, in upper parts of the Lower-Middle Mississippian Borden-Grainger delta sequence and in lower parts of the Fort Payne carbonate sequence, was deposited at the end of loading-type relaxation during a flexural cycle in the Neoacadian (final) tectophase of the Acadian Orogeny. Tectonic influence, combined with a major late Osagean sea-level lowstand, created conditions that generated sediment starvation and shallower seas across widespread parts of the western Appalachian and eastern Illinois basins. In the absence of major sediment influx, glauconite was deposited uniformly across many major depositional settings, ranging from delta-platform to basinal environments. Especially important, however, is the newly reported occurrence of the Floyds Knob interval in basinal Fort Payne environments from south-central Kentucky, where it is represented by a thick, pelletal, glauconite-rich horizon that separates clastics at the base of the Fort. Payne Formation from carbonates at top. The study also provides the first-ever radiometric dating of the Floyds Knob glauconites, which suggests a late Osagean origin. These results support the existing biostratigraphic studies that point to a late Osagean origin for the Floyds Knob interval.

KEYWORDS: Floyds Knob, Glauconite, Mississippian, Borden Formation, Fort Payne Formation.

<u>Devi Bhagabati Prasad Udgata</u>
Student’s Signature

<u>July 18, 2011</u>
Date

DEPOSITIONAL AND STRATIGRAPHIC SIGNIFICANCE OF MARINE, GREEN-CLAY, MINERAL FACIES IN THE LOWER-MIDDLE MISSISSIPPIAN BORDEN AND FORT PAYNE FORMATIONS, WESTERN APPALACHIAN AND EASTERN ILLINOIS BASINS, KENTUCKY

By

Devi Bhagabati Prasad Udgata

Dr. Frank R. Ettensohn
Director of Dissertation

Dr. Alan E. Fryar
Director of Graduate Studies

July 18, 2011
Date

RULES FOR THE USE OF DISSERTATION

Unpublished dissertation submitted for the Doctor's degree and deposited in the University of Kentucky Library are as a rule open for inspection, but are to be used only with due regard to the rights of the authors. Bibliographical references may be noted, but quotations or summaries of parts may be published only with permission of the author and with the usual scholarly acknowledgements.

Extensive copying and publication of the thesis in whole or in part also requires the consent of the Dean of the Graduate School of the University of Kentucky.

A library that borrows this thesis for use by its patrons is expected to secure the signature of each user.

| Name | Date |
| --- | --- |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |
| | |

DISSERTATION

Devi Bhagabati Prasad Udgata

The Graduate School

University of Kentucky

2011

# DEPOSITIONAL AND STRATIGRAPHIC SIGNIFICANCE OF MARINE, GREEN-CLAY, MINERAL FACIES IN THE LOWER-MIDDLE MISSISSIPPIAN BORDEN AND FORT PAYNE FORMATIONS, WESTERN APPALACHIAN AND EASTERN ILLINOIS BASINS, KENTUCKY

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Arts and Sciences at
the University of Kentucky

By

Devi Bhagabati Prasad Udgata

Lexington, Kentucky

Director: Dr. Frank R. Ettensohn, Professor of Earth and Environmental Sciences

Lexington, Kentucky

2011

# ACKNOWLEDGMENTS

It is a pleasure to thank many people and organizations who made this dissertation possible.

First and foremost, I want to thank my advisor Dr. Frank R. Ettensohn. It has been an honor to be his Ph.D. student. With his enthusiasm, his inspiration, and his great efforts to explain things clearly and simply, he helped to make geology enjoyable for me. Throughout my dissertation, he provided encouragement, sound advice, good teaching, good company, and lots of good ideas. I would have been lost without him. I appreciate all his contributions of time, ideas, and financial assistance to make my Ph.D. experience productive and stimulating. The joy and enthusiasm he has for his research was motivational for me, even during tough times in the Ph.D. pursuit. I am also thankful for the excellent example he has provided as a successful geologist and professor.

Deepest gratitude are due to the members of the supervisory committee, Dr. William A. Thomas, Dr. Stephen F. Greb, Dr. Alan E. Fryar, Dr. William M. Andrews Jr., and Dr. Hans Gesund, without whose knowledge and assistance this study would not have been successful. My dissertation committee members have contributed immensely to my personal and professional time at the University of Kentucky. My committee members have been a source of good advice and collaboration. I would like to thank Dr. Alan E. Fryar for all his help as the director of graduate studies.

I gratefully acknowledge the funding sources that made my Ph.D. work possible. I was partly funded by the student grant-in-aid of research from the Geological Society of America (GSA). My work was also supported by the student research Brown-McFarland and Ferm funds from the Department of Earth and Environmental Sciences, University of Kentucky.

Sincere gratitude to Dr. James A. Drahovzal, Kentucky Geological Survey, Lexington, for interesting and stimulating discussion on basement tectonics in western Appalachian and eastern Illinois basins in Kentucky.

I am grateful to Mr. Henry Francis and Mr. Jason Backus at the Kentucky Geological Survey, Lexington for providing assistance, guidance, and help with mineralogical studies of glauconites.

In regards to the radiometric dating of glauconites, I thank Dr. Chris M. Hall at the University of Michigan, Ann Arbor, for taking his time out to discuss procedures and intricacies of Ar-Ar system with me.

I gratefully acknowledge Dr. David K. Brezinski, Maryland Geological Survey, Baltimore, for his help in trilobite identification and biostratigraphy.

I am grateful to Mr. Matthew Crawford, Kentucky Geological Survey, Lexington, for his invaluable help with ArcGIS and digital geologic maps.

I would like to thank Ms. Pamela Stephens, Mr. Peter Idstein, and Mr. George T. White Jr. from the Department of Earth and Environmental Sciences for their invaluable help and support during my graduate student life at the Department of Earth and Environmental Sciences, University of Kentucky.

I thank Mr. Timothy O'Brien, graduate student in geology at the University of Michigan, Ann Arbor, for his considerable help and support. His help has been invaluable and has ranged from lodging and meals to fixing my car in the dead winter.

I want to express my gratitude to Mr. Ralph Campbell, Russell County, Kentucky for providing free boat rides to examine the carbonate-mud mounds deep inside the Lake Cumberland.

I would also like to thank Mr. Brook E. Brosi, US Army Corps of Engineers, for his help in providing borehole images for my study.

Lastly, and most importantly, I wish to express my love and gratitude to my family for their understanding and endless love. They raised me, supported me, taught me, and loved me. To them I dedicate this dissertation.

Thank you.

Devi Bhagabati Prasad Udgata
University of Kentucky
July 2011

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

# CHAPTER 1: INTRODUCTION

## 1.1 Importance of Green Marine-clay Mineral Facies

Clay minerals are the most important and most common mineral phase that occurs at the surface and in the shallow-subsurface on Earth. They are prime indicators of a large variety of geochemical processes at the surface and in the subsurface on Earth, and they are widespread and diverse in marine environments throughout geologic history. Among clays in the marine realm, authigenic green, marine, clay-mineral facies (glauconite and verdine) are very important because they precisely reflect the surrounding physical and chemical environments at the sediment-water interface at the time of formation. Glaucony and verdine facies commonly occur with phosphates, dolomite, siderite, silica, and calcite in mudstone-dominated successions and are important indicators of accommodation-space availability and background sedimentation rates.

## 1.2 Glaucony Facies

The mineral ‘glauconite’, also  known as glaucony and the major constituent in the ‘Glaucony facies’, is a common authigenic green clay mineral that occurs within glauconite-smectite and glauconite-mica end members.  Glauconite is the iron-magnesium-rich equivalent of aluminum-rich illite. The transition into the smectite-glauconite trend is similar to smectite-illite trend and ends with progressive incorporation of potassium into the system forming a glauconite-mica end member. Glauconite is a common constituent of modern, as well as of Precambrian-to-Pleistocene continental-shelf environments, predominantly in water depths from 60 to 250 m, ranging from mid-shelf to upper-slope regions (McRae, 1972; Odin and Letolle, 1980; Chafetz and Reid, 2000). These areas are known to have slow sedimentation rates. The glauconitization process occurs mostly in passive shelf-margin environments in sediment-starved states that have low terrigenous-sediment input, suitable substrates, high organic activity, and suitable physical-chemical conditions (e.g., low turbulence, sub-oxic to reducing conditions, and an abundant supply of dissolved iron, potassium, and magnesium) (McRae, 1972; Odin and Matter, 1981). Because glauconite is a sensitive indicator of low sedimentation rates and is widespread in the sedimentary record, it constitutes a powerful tool for the study of depositional environments, the geologic time scale, and stratigraphic correlation (McRae, 1972; Odin and Matter, 1981; Amorosi, 1997). Glauconite is easy to recognize in the field and easy to separate in the laboratory because of its characteristic green color, pelletal shape, and high magnetic susceptibility. It can also be dated easily by several methods (e.g., K-Ar, Ar-Ar, Rb-Sr, and K-Ca) with good analytical precision (Morton and Long, 1980; Odin and Hunziker, 1982; Grant et al., 1984; Smith et al., 1993; Amireh et al., 1994; Smith et al., 1998; Gopalan, 2008; Conrad et al., 2010).

### 1.3 Verdine Facies

Another important, authigenic, green, marine clay mineral that is commonly reported from modern-day, wide, continental-shelf to upper slope environments is the light- to dark-green, chloritic-clay-rich, verdine facies, now commonly referred to as the mineral ‘odinite’. This mineral is part of the kaolinite-serpentine group. Like glauconite facies, verdine facies are widely found in modern-day, passive-margin, shelf environments in areas known to have slow sedimentation rates (Odin, 1988; Odin and Masse, 1988; Odin and SenGupta, 1988; Rao et al., 1993; Rao et al., 1995). Because of its susceptibility to alteration to chlorite through weathering, verdine facies occurrences from geologic horizons older than Quaternary age are rare (Proust and Hosu, 1996; Albani et al., 2004; Ettensohn et al., 2004; Udgata and Ettensohn, 2008). Authigenic verdine facies are notably pristine and commonly occur as relatively well-preserved, green, clay minerals that infill primary intraparticle porosity, especially the microcavities of bioclasts (Odin and Masse, 1988; Rao et al., 1993; Rao et al., 1995). Modern day, verdine-bearing sediments have been reported from both reefal and continental-margin environments where clastic input is very low (Odin, 1988; Odin and SenGupta, 1988; Rao et al., 1995; Kronen and Glenn, 2000). There are also verdine grains that show the effects of reworking and transport, such as abrasion, fragmentation and grain destruction. The reworked nature of these particles is commonly attributed to a higher energy depositional setting, where loss of accommodation space, seaward progradation, or sediment reworking have occurred. Verdine facies are iron-rich, but because they contain iron in both oxidized ($Fe^{3+}$) and reduced ($Fe^{2+}$) states, it has been suggested that the facies forms in association with mildly reducing, suboxic solutions from which both ferric and ferrous iron may be supplied (Odin et al., 1988). It has also been suggested that the *in situ* formation of verdine minerals is rare in water depths exceeding 60 m due to their poor preservation potential, but contrary to these suggestions, verdine facies have been reported in a few situations from water depths of 200 m near reefal to sub-reefal environments around the Great Barrier Reef (Kronen and Glenn, 2000).

### 1.4 Purpose of Study

Though geologic records of vertical transitions from clastic-dominated facies to carbonate-dominated facies or vice versa are common and well studied, the lateral transition between the above-mentioned facies so far is poorly understood. As many as five glauconite horizons are present in the Lower-Middle Mississippian (Kinderhookian and Osagean) rocks of the Borden, Fort Payne, and Grainger formations in the western Appalachian and eastern Illinois basins in Kentucky and across intervening areas on the Cincinnati Arch (Fig. 1.1). These rock units have been the topic of many previous studies and are thought to be well understood; however, questions remain concerning details of the depositional framework and the lateral stratigraphic relationships among these three formations. Across the Appalachian Basin in eastern and east-central Kentucky, the Borden interval forms a thick, prograding, sub-aqueous deltaic sequence, which grades into a succession of more distal, deeper water marine shales and carbonate intercalations of the Fort Payne Formation in south-central Kentucky and north-central Tennessee. In south-central Kentucky, however, the Borden sequence thins across the Cincinnati Arch (Fig. 1.1) and thickens west of the arch in west-central Kentucky and southern Indiana in the Illinois Basin, where it was deposited as a separate Borden delta lobe. In southeastern Kentucky and northeastern Tennessee, a succession of shale and siltstone, strikingly similar to and equivalent to the Borden Formation, known as the Grainger Formation, is exposed along the Pine Mountain Thrust Fault. The Grainger Formation intertongues with, and disappears to the southwest by gradation into the carbonate-dominated Fort Payne chert in the Jellico Mountain area of northeastern Tennessee.

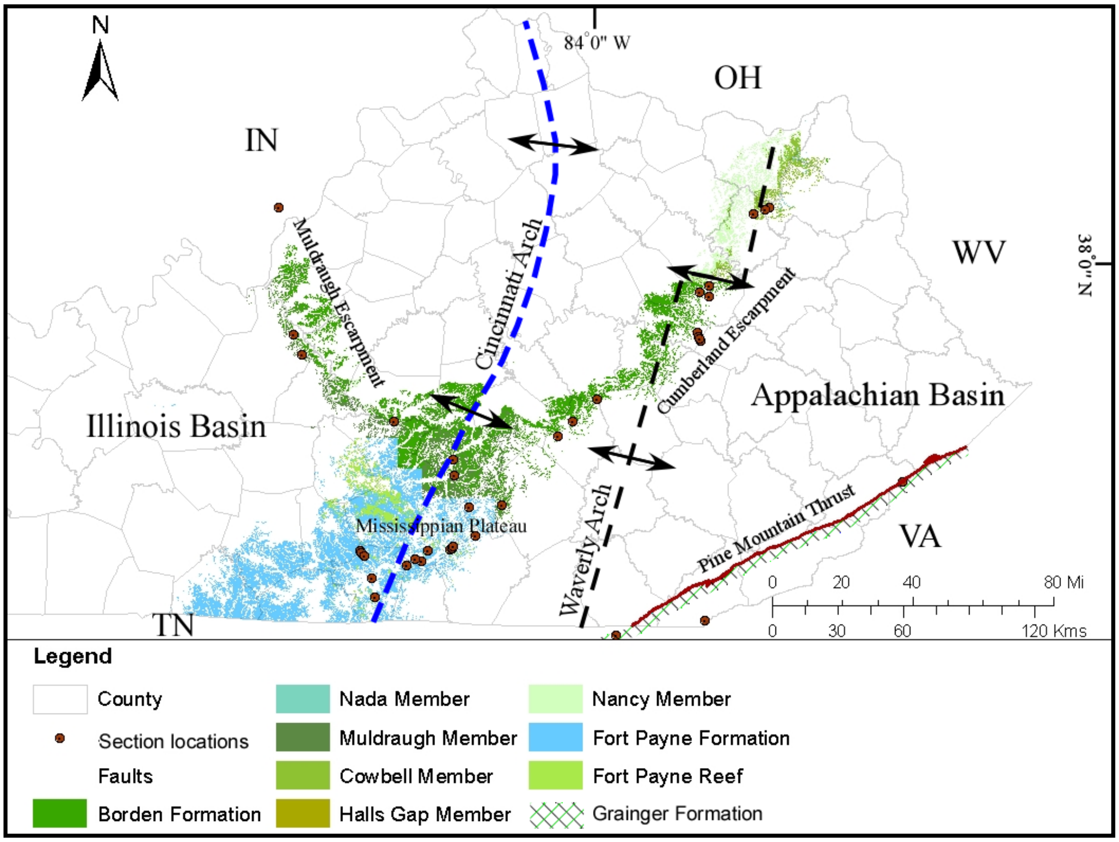



Figure 1.1 – Map showing regional geological outline of the Lower-Middle Mississippian Borden, Fort Payne, and Grainger formations in Appalachian and Illinois basins in Kentucky. The Cincinnati Arch is the boundary between the Appalachian and Illinois basins. Map also shows section locations, and physiographic regions in Kentucky and adjacent states. Note: Fort Payne Reefs on geological quadrangle maps are carbonate-mud mounds, rather than true reefs.

These three formations in the western Appalachian and eastern Illinois basins in Kentucky are associated by complex lateral facies architecture. Several different models have been suggested for lateral facies associations between the units (Sedimentation Seminar, 1972; Kepferle and Lewis, 1975; Lewis and Potter, 1978; Kepferle et al., 1980; Sable and Dever, 1990; Meyer et al., 1992; Meyer et al., 1995; Khetani and Read, 2002). Nonetheless, a key unit in all of the interpretations is the Floyds Knob Bed, a thick, widespread glauconite-rich horizon that is known in all three formations. In this horizon, the glauconite is pelletal and occurs with intense bioturbation and phosphorite. Additional glauconite horizons also occur that may or may not be associated with the Floyds Knob Bed. These horizons occur in upper parts of the Borden-Grainger deltaic sequence and in the lower part of Fort Payne Formation at the transition between coarser clastics and carbonate-rich silt and shale. This study has focused on a detailed sedimentological and geochemical examination of the Floyds Knob Bed and the associated, green marine chloritic-clay-rich-verdine facies, especially relative to the sedimentology of the facies and units above and below the Floyds Knob glauconite horizon. In addition, this study has attempted to trace the distribution of the Floyds Knob into areas and units, like the Fort Payne Formation. The position and distribution of the Floyds Knob Bed in the Fort Payne Formation was poorly known especially in relation to the economically significant Fort Payne carbonate-mud-mound facies (Sedimentation Seminar, 1972; Kepferle and Lewis, 1975; Lewis and Potter, 1978; Kepferle et al., 1980; Sable and Dever, 1990; Meyer et al., 1992; Meyer et al., 1995; Khetani and Read, 2002). Finally, I examined the regional depositional, eustatic, tectonic, and paleogeographic framework of the Lower-Middle Mississippian rocks in the western Appalachian and eastern Illinois basins to understand the conditions that permitted the widespread deposition of the chloritic-clay-rich-verdine facies.

Bright blue-green shales (chloritic-clay-rich-verdine facies), and dark-green marine clays (glauconite facies) are common on some distal, continental shelves and reflect the formation of iron-rich clays in sediment-poor settings (Odin and Masse, 1988; Rao et al., 1993). Shales of similar color are locally common in distal parts of the Appalachian Basin and in the eastern part of the Illinois Basin, especially in the Lower-Middle Mississippian Borden and Fort Payne formations, Kentucky. The major problems addressed in this study include: 1) testing the hypothesis that the widespread, fossiliferous, dark-green, phosphate- and glauconite-rich Floyds Knob Bed in the Borden, Fort Payne, and Grainger formations is a chronostratigraphically equivalent surface; 2) characterizing and determining the origin of these green, marine, clay-mineral facies in the upper part of the Borden-Grainger deltaic sequence and in the distally equivalent marine shales and carbonate intercalations of the Fort Payne Formation; 3) determining whether or not this Paleozoic facies helps us identify depositional, tectonic, and global eustatic patterns in the Mississippian rock record, like the verdine facies from modern continental platforms,; 4) determining whether or not these green marine-clay facies reflect a distal sedimentary response to the end of Neoacadian and/or Ouachita orogenies and subsequent global sea-level fall in a sediment-poor, carbonate-dominated setting; 5) determining what role regional and local tectonics, and global eustasy played in the lateral transition between the clastic-dominated upper Borden-Grainger deltaic sequence and carbonate-dominated Fort Payne sequence; and 6) examining the possible controls on localization and deposition of Early Mississippian (early Osagean) carbonate-mud mounds in the Fort Payne Formation.

### 1.5 Study Methods

All the above-mentioned objectives were achieved via detailed field and laboratory investigations. Vertical sections were measured and described for 39 outcrops and one core (total 40 sections) (Fig. 1.1). Where possible, lithologies both above and below the Floyds Knob Bed were described relative to lithofacies and current stratigraphic nomenclature. Outcrop and core data were supplemented by surface-mapping information from 7.5-minute U.S.G.S. quadrangle maps. In the field, representative sections were carefully measured, described, and photographed to collect sedimentological, paleontological, and stratigraphic data, including general lithologies, textures, physical and biogenic structures, and associated body fossils, especially in units above and below the Floyds Knob Bed. The occurrences of different sedimentary features (e.g., hardgrounds and unconformities), paleontological features (biostromal accumulations), and trace-fossil occurrences were also noted for possible correlation. Because the Floyds Knob Bed is associated with multiple granular glauconite-rich horizons and glauconite-rich clay, it is described as a bed where it occurs as a single glauconite-rich bed; however, it is described as the Floyds Knob interval where it is represented by multiple glauconite horizons, or dispersed glauconite-rich clay. Representative samples were collected from measured sections for laboratory studies and to produce standard thin sections for petrographic analyses. Studies designed to assess the green marine-clay facies include: 1) petrographic examination in thin sections, 2) identification of clay-mineral phases using x-ray diffraction, and 3) analyses of major oxide contents using x-ray fluorescence. Isotopic ages of the Floyds Knob glauconite bed from Borden Formation were determined by $^{40}Ar/^{39}Ar$ radiometric methods to provide time constraints. The radiometric dating technique is particularly important, as it has shown promising results in glauconite beds from different parts of the world (Morton and Long, 1980; Odin and Hunziker, 1982; Grant et al., 1984; Smith et al., 1993; Amireh et al., 1994; Smith et al., 1998; Gopalan, 2008; Conrad et al., 2010). However, this is the first time that it has been tested on glauconite-bearing strata in the Appalachian and Illinois basins.

**1.6 Study Area**

The study area includes the prominent belts of Mississippian rocks exposed in the Muldraugh Hill/Escarpment, Mississippian Plateau, and Cumberland Escarpment physiographic regions (Fig. 1.1). Outcrops were examined as far as Cumberland County, Kentucky, to the south, Carter County, Kentucky, to the northeast, Floyd County, Indiana, to the north, Letcher County, Kentucky, and Campbell County, Tennessee, to the southeast. The study area includes the distribution of Nada and Muldraugh members of the Borden Formation, exposed in eastern, east-central, west-central, and south-central Kentucky and southern Indiana, and the Fort Payne Formation exposed in south-central Kentucky both east and west of the Cincinnati Arch in the western Appalachian and eastern Illinois basins (Fig. 1.1). Field studies also included the Borden-equivalent Grainger Formation, exposed in southeastern Kentucky and northeastern Tennessee along the Pine Mountain Thrust Fault (Fig. 1.1).

# CHAPTER 2: GLAUCONITE AND RADIOMETRIC DATING

## 2.1 Glauconite Mineralogy

Minerals placed into the glauconite group, or glaucony facies, are iron- and potassium-rich alumino-phyllosilicates having the general chemical composition of (K, Na) $(Fe, Al, Mg)_2$ $(Si, Al)_4O_{10}(OH)_2$. These minerals constitute a continuous family series with smectite and micaceous end members (Odin and Fullagar, 1988). Glauconite mica is a Fe- and K-rich dioctahedral mica with tetrahedral Al usually comprising >0.2 atoms per formula unit and octahedral $Fe^{3+}$comprising >1.2 atoms per formula unit (Huggett, 2005). Typically, 5–12% of the total iron is ferrous. Glauconite mica is chemically distinguished from ferric illite by having higher total iron content, and from celadonite, by having higher levels of aluminum substitution for silicon in the tetrahedral layer and by a higher octahedral charge (Duplay and Buatier, 1990). Glauconitic smectite is a mixed-layer clay that has lower K and Fe contents, but higher Al content than glauconite mica. As will be described in subsequent sections, the spectrum of glauconite smectite to glauconite mica reflects mineralogic maturity (Thompson and Hower, 1975; Odin and Matter, 1981; Odin and Fullagar, 1988).

## 2.2 Glauconite Formation

The formation of glauconite occurs via authigenesis under a relatively narrow range of environmental conditions. It forms at or near the sediment-water interface in oxygenated to mildly reducing marine environments, wherein sedimentation rates are very low (McRae, 1972; Odin and Matter, 1981; Amorosi, 1997). Glauconization mainly occurs in fine-grained muds, deposited in shelf and slope settings at depths between 30 m to 500 m (Bornhold and Giresse, 1985; Amorosi, 1997; Kelly and Webb, 1999). Glauconite may precipitate as coatings or films on the walls of fissures, borings, and in other semi-confined microenvironments associated with carbonate hardgrounds (Pemberton et al., 1992; Kitamura, 1998; Ruffel and Wach, 1998). However, it forms most commonly in granular siliciclastic substrates via replacement, infilling, or coating of individual grains. Fecal pellets are the most common type of precursor substrate. Aggregation of clay-rich sediment during passage through the digestive tracts of the organisms creates microenvironments that are favorable for glauconitization (Anderson et al., 1958; Pryor, 1975; Chafetz and Reid, 2000). In addition to pellets, glauconite may replace a variety of other grain types, including micas, quartz, chert, feldspar, calcite, dolomite, phosphate, and volcanic rock fragments (McRae, 1972; Pryor, 1975; Odin and Matter, 1981). Glauconite also may precipitate as cements within microfossil cavities or as coatings or films on other grains (Triplehorn, 1966; McRae, 1972; Odin and Matter, 1981).

**2.3 Glauconite Maturity**

Odin and Matter (1981) recognized four common varieties of glauconite that reflect different levels of maturation: nascent, slightly evolved, evolved, and highly evolved grains. The level of maturity attained by glauconite depends on the residence time of grains at or near the sediment-water interface and, hence, on sedimentation rate. The glauconitization process normally ceases after burial beneath several decimeters of sediment, and formation of fully mature grains may require residence times of $10^5$-$10^6$ years (Odin and Matter, 1981). Levels of maturity of glauconite can be assessed on the basis of chemical composition, grain color, and morphology (Table 2.1).

Table 2.1 – Characteristics of glauconite at different stages of maturity (after Odin and Matter, 1981; Amouric and Parron, 1985; Amorosi, 1995; Huggett and Gale, 1997; Kelly and Web, 1999).

| **Glauconite types** | **Maturity** | **$K_2O$ content** | **Mineralogical structure** | **Color** | **XRD peak position** |
|---|---|---|---|---|---|
| *nascent* | low | < 4% | glauconite smectite | pale green | 14Å |
| *slightly evolved* | moderate | 4-6% | ↓ | light green | ↓ |
| *evolved* | high | 6-8% | ↓ | green | ↓ |
| *highly evolved* | very high | > 8% | glauconite mica | dark green | 10 Å |

## 2.4 Radiometric Dating: The $^{40}Ar/^{39}Ar$ Method

The $^{40}Ar/^{39}Ar$ dating technique is a sophisticated variation of the $^{39}K/^{40}Ar$ dating technique. Both techniques rely on the measurement of a daughter isotope ($^{40}Ar$) and a parent isotope. While the K-Ar technique measures $^{39}K$ as the parent, the $^{40}Ar/^{39}Ar$ technique uses $^{39}Ar$. $^{39}K$ transforms to $^{39}Ar$ by fast-neutron irradiation in a neutron-capture proton-emission reaction [$^{39}K$ (n, p) $^{39}Ar$] in a nuclear reactor. The amount of $^{39}Ar$ produced in the nuclear reactor depends upon the known relative abundance of $^{39}K$, time-length of irradiation, neutron-flux density, and neutron-capture cross section for $^{39}K$ (Albarede, 1982; Foland et al., 1984, 1992; Layer et al., 1987); thus, $^{39}Ar$ can be used as a proxy for $^{39}K$. The comparatively long half-life of $^{39}Ar$ ($t_{1/2}$ = 269 years) enables it to be used as a stable isotope for mass-spectrometric analyses (Merrihue and Turner, 1966).

The Ar-Ar method is frequently used instead of K-Ar for geochronological studies of fine-grained minerals such as glauconite and illite, which are made up of fine crystallites (Brereton et al., 1976; Halliday, 1978; Foland et al., 1984; Hess and Lippolt, 1986; Smith et al., 1993; Dong et al., 1995; Hassanipak and Wampler, 1996; Conrad et al., 2011), because multiple aliquots of the same sample can be analyzed and compared to avoid possible sample inhomogeneities for better results (Albarede, 1982; Layer et al., 1987), and the better precision of ±0.1% to which $^{40}Ar/^{40}K$ ratios can be measured (Samson and Alexander, 1987). However, serious complications of $^{39}Ar$ recoil loss can arise while analyzing fine-grained clay minerals. The loss of $^{39}Ar$ in this method occurs because the recoil energy, following production by irradiation, is sufficient to displace an atom to a distance of ~0.1 µm, which is a significant distance relative to the small grain size (~500-1000 nm thick) of clay minerals (Turner and Cadogan, 1974). The recoil loss leads to underestimation of the K content, and is responsible for anomalously high $^{40}Ar/^{39}Ar$ ratios in cryptocrystalline materials, which results in anomalously old ages (Brereton et al., 1976; Foland et al., 1984). $^{39}Ar$ loss in cryptocrystalline materials can also occur by thermal degassing of low-retentive sites which pick up recoiling nuclides (Dong et al., 1995). These low-retentive sites are the two free surfaces of a clay-mineral grain, and the amount of $^{39}Ar$ loss is inversely proportional to grain thickness. $^{39}Ar$ loss in clays also occurs with $H_2O$ loss during laboratory heating. $^{39}Ar$ loss from clay minerals occurs much more rapidly during vacuum heating due to structural disruption caused by $H_2O$ loss than by heating during diagenesis (Evernden et al., 1960). Another manner in which Ar may be lost during irradiation is caused by the different phases of unstable alteration products or poorly crystalline material present inside clay minerals, especially if elevated temperatures are attained (Hess and Lippolt, 1986). Alteration phases may lose significant $^{39}Ar$ as a result of recoil capture as well as radiogenic $^{40}Ar$ during neutron bombardment. The loss of $^{40}Ar$ may result in an anomalously low $^{40}Ar/^{39}Ar$ ratio and low apparent age.

Several workers have suggested a modified technique to minimize Ar loss during vacuum heating and neutron irradiation (Foland et al., 1992; Smith et al., 1993). The technique involves encapsulating and sealing glauconite grains in a small evacuated ampoule prior to irradiation. The recoiled Ar inside the ampoule and Ar from the solid sample can then be collected for analysis together by breaking the ampoule in an evacuated system. The vacuum-irradiation method significantly reduces recoil loss, and glauconites dated using this method show agreement between $^{40}Ar/^{39}Ar$ (total gas age) and K-Ar ages.

## 2.5 Experimental Method for $^{40}Ar/^{39}Ar$ Analysis of Glauconites

Previous studies of glauconite in other areas have shown that only highly evolved glauconite grains with ~6% K are suitable for radiometric studies because the possibility of inheriting radiogenic $^{40}Ar$ from less evolved grains is minimal (Odin and Dodson, 1982; Smith et al., 1993), and hence, such grains provide reliable geochronometers. In the absence of any reliable instrument for elemental-composition studies, however, the grains analyzed in this study were selected purely on the basis of prior experience with glauconite studies. Only grains with dark-green color and smooth peloidal external morphology were collected for radiometric analysis, as these grains tend to have high K-content. In total, 12 samples were analyzed for this study; 11 came from the Floyds Knob Bed and associated glauconite horizons, and one came from the glauconite-rich, Kinderhookian Maury Shale in south-central Kentucky (Fig. 2.1). This is the first attempt at the Ar-Ar dating of glauconite from the Maury Shale.

Three to four grains per sample, ~0.1-0.2 mm in diameter and weighing ~0.1 mg, were collected. The grains were placed in a quartz tube and evacuated under pressure. Because glauconite grains start degassing at very low temperatures, the bottom of the tube was dipped in water while the top was heated to detach the ampoule in order to keep the grains from overheating. The ampoules were placed in an evacuated crushing apparatus within a high-sensitivity mass spectrometer and were crushed mechanically. After collecting and measuring the ampoule gas, the samples were step-heated with a continuous laser for 60 seconds. Integrated $^{40}Ar/^{39}Ar$ ages for samples were calculated by combining the data for recoiled Ar in the ampoule gas fractions and the gas from the corresponding step-heated grains.

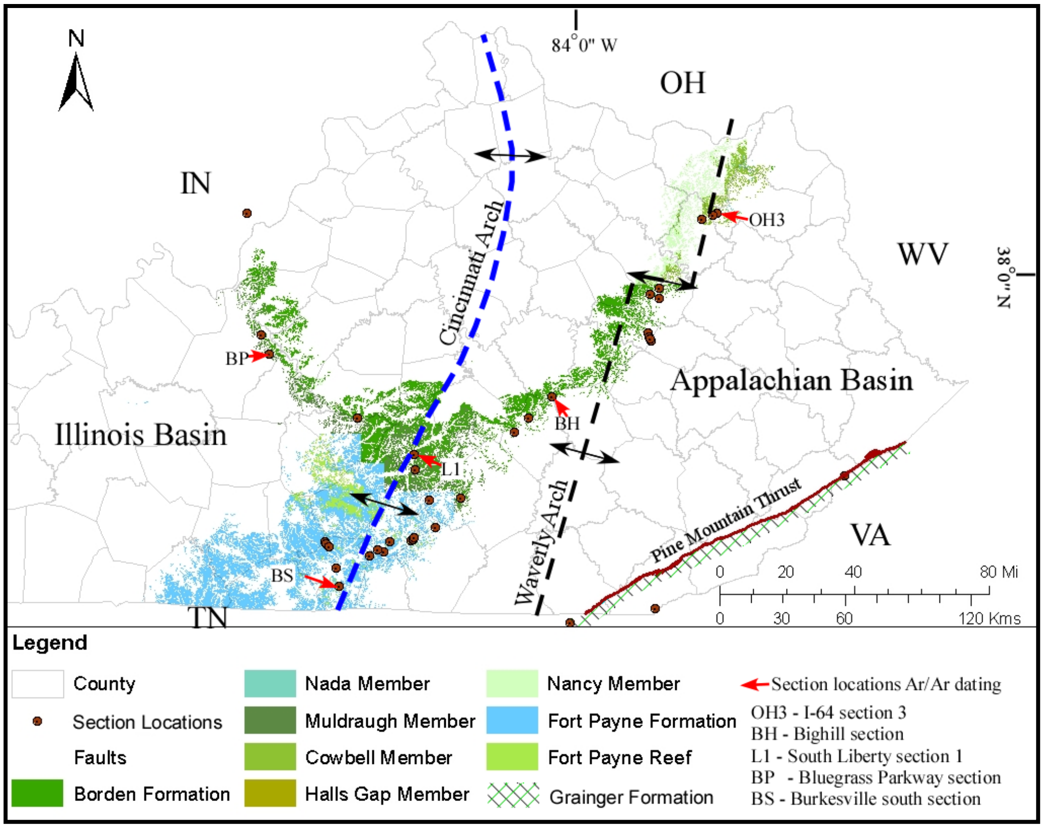



Figure 2.1 – Sampling locations for Ar/Ar dating. Three samples each were collected from the Bluegrass Parkway (BP), Big Hill (BH), and I-64 (OH3) sections, and two samples from the South Liberty (L1) section, respectively. A sample from the Burkesville south (BS) section was collected from the glauconite-rich Kinderhookian Maury Shale. Please note that the Bluegrass Parkway and Burkesville south sections are in the Illinois Basin west of the Cincinnati Arch, whereas South Liberty, Big Hill, and I-64 sections are in the Appalachian Basin east of the Cincinnati Arch.

In order for an age to be calculated by the $^{40}Ar/^{39}Ar$ technique, the neutron-flux density parameter must be known. For the neutron-flux density to be determined, a standard of known age must be irradiated with the samples of unknown age. The primary standard must be a mineral that is homogeneous, abundant, and easily dated by the K/Ar and $^{40}Ar/^{39}Ar$ methods. Once an accurate and precise age is determined for the primary standard, other minerals can be dated relative to it by the $^{40}Ar/^{39}Ar$ method. For this study, a hornblende from the McClure Mountains, Colorado (MMhb-1), with a recommended age 520.4±1.7 Ma was used as the primary standard (Samson and Alexander, 1987).

# CHAPTER 3: PALEOGEOGRAPHY, PALEOCLIMATE, AND EUSTATIC FRAMEWORK DURING MISSISSIPPIAN TIME

Important factors that control regional climate, which subsequently controls sediment supply and sedimentation pattern, include the geographic position of the area with respect to adjacent mountain belts and orogens (Hoffman and Grotzinger, 1993), and global and zonal climate belts through which the continents migrate (Heckel and Witzke, 1979; Ettensohn et al., 2002; Cecil and DuLong, 2003; Cecil et al., 2004).

Paleozoic sedimentary successions in the Appalachian Basin are divided into three major sedimentation patterns: Late Precambrian–Early Cambrian clastic-dominated, Early Cambrian–Middle Mississippian carbonate-dominated and Late Mississippian–Permian clastic-dominated. These three Paleozoic sedimentation patterns of the Appalachian Basin were controlled in part by global and zonal climate changes during the northward movement of Laurentia/Laurussia from the southern temperate belt into the tropics (Scotese, 1997; Cecil et al., 2004). In particular, the Appalachian Basin had migrated through the humid, temperate, 60°–40°S latitudinal belt during Late Precambrian–Early Cambrian time, where clastic sediments dominated due to high moisture content. In turn, Middle Cambrian–Middle Mississippian time saw the basin migrating through the subtropical, high-pressure, arid climatic belt inside the 35°–15° S latitudes, where evaporites and carbonate sediments dominated due to decreased humidity. Late Mississippian–Permian time saw the basin migrating into the low-pressure, humid, tropical climate belt of the equatorial region (equator–5° N latitude) (Scotese, 1997), where clastic sediments dominated because of high humidity and enhanced weathering rates.

The Lower–Middle Mississippian study interval in the western Appalachian and eastern Illinois basins is dominated by Borden-Grainger deltaic sediments and Fort Payne carbonate sediments with localized occurrences of black shales, cherts, phosphates, evaporites, iron-rich sediments, sandstones, and siltstones (Ettensohn, 1985a, 2008; Kepferle, 1971, 1977; Kepferle and Lewis, 1975; Kepferle et al., 1980; Whitehead, 1978; Warne, 1990). These varied lithologies in a carbonate-dominated regime reflect interactions among climate, eustasy, paleogeography, and tectonics (Ettensohn, 1985a, 1985b, 1994, 2004, 2008).

### 3.1 Laurussia

During the Early–Middle Mississippian transition, the Laurussia continent was made up of North America and western Europe, and the Appalachian and Illinois basins were situated in sub-tropical latitudes south of the equator (Fig. 3.1). Deposition of the Borden and Fort Payne formations took place in a cooler climate with a low sea-level stand (Popp et al., 1986; Mii et al., 1999). However, the cooling event in central Laurussia was preceded by a warmer climate with high sea-level stands as evident from the thick, widespread Devonian–Mississippian black-shale deposition (Fisher, 1984; Ettensohn, 1995, 1998, 2008), and succeeded by warmer Late Mississippian climates with low sea-level stands, as evident from thick Upper Mississippian carbonates and Pennsylvanian coal deposits (Popp et al., 1986; Mii et al., 1999). Gondwana, the other major continent at that time, was positioned near the south pole throughout much of Paleozoic time (Caputo and Crowell, 1985) (Fig. 3.1). The position of Gondwana during Early—Middle Mississippian time was favorable for widespread glaciation, although evidence for the extent and magnitude of glaciation is limited (e.g., Veevers and Powell, 1987; Diaz et al., 1993). However, much of Laurussia was cooler (Mii et al., 1999; Ettensohn et al., 2009) and sea-levels dropped, which led to a global icehouse state and inception of Gondwana glaciation (Fisher, 1984). The glaciation event certainly influenced the global sea-level, which showed pronounced cyclicity thereafter (Ross and Ross, 1988).

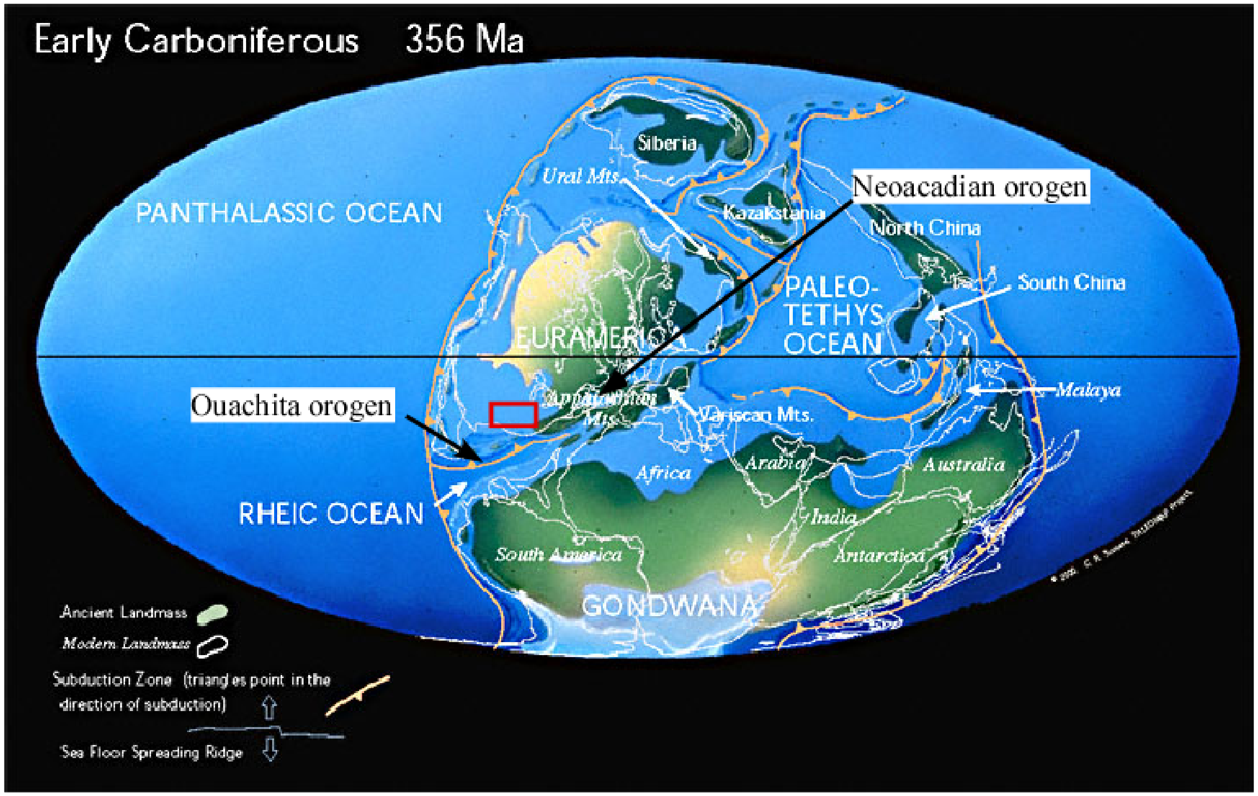



Figure 3.1 – Paleogeographic map showing approximate position of Euramerica (Laurussia) and Gondwana supercontinents with respect to major orogenic and climate belts during Early Mississippian time (from http://www.scotese.com/newpage4.htm). Note that much of Laurussia was positioned in the sub-tropical climate belt, whereas Gondwana was positioned near the south pole. Red rectangle shows approximate position of the study area in Appalachian and Illinois basins.

Oxygen (O), carbon (C), and strontium (Sr) isotopes from marine carbonate rocks and unaltered brachiopods from the Paleozoic era have been studied extensively to understand changes in sea-water composition and related changes in global climate patterns (e.g., Popp et al., 1986; Grossman et al., 1993), but none of the studies has adequately explained global climate changes during Mississippian time. Mii et al. (1999) first published results of isotopic studies of unaltered North American brachiopod shells from Carboniferous (Mississippian and Pennsylvanian) strata (Fig. 3.2). The study shows that there was a major positive shift in $\delta^{13}C$ and $\delta^{18}O$ values during Early Mississippian (Kinderhookian–Osagean) time (stage C1, Fig. 2.4) across the Devonian-Mississippian boundary. The positive shift in $\delta^{13}C$ has been attributed to a increase in the global carbon reservoir (Popp et al., 1986) and changes in the marine-circulation pattern due to closure of a seaway (Rheic Ocean) between Laurussia and Gondwana (Mii et al., 1999, 2001), whereas the increase in $\delta^{18}O$ has been attributed to cooling and glaciation in Kinderhookian-Osagean time (Mii et al., 1999, 2001). Although none of the analyzed brachiopod shells were from the Appalachian Basin (the majority were from the Illinois Basin and epeiric seas covering the North American platform), the changes in isotopic composition and climate in adjacent areas during Mississippian time might help to explain the decrease in sedimentation rates at the Devonian-Mississippian boundary (Maury Shale) and in the Floyds Knob Bed (Osagean) of the Fort Payne Formation, and at the transition between the Borden and Slade formations in the Appalachian Basin during deposition of the Floyds Knob Bed (Osagean) and correlative rocks.

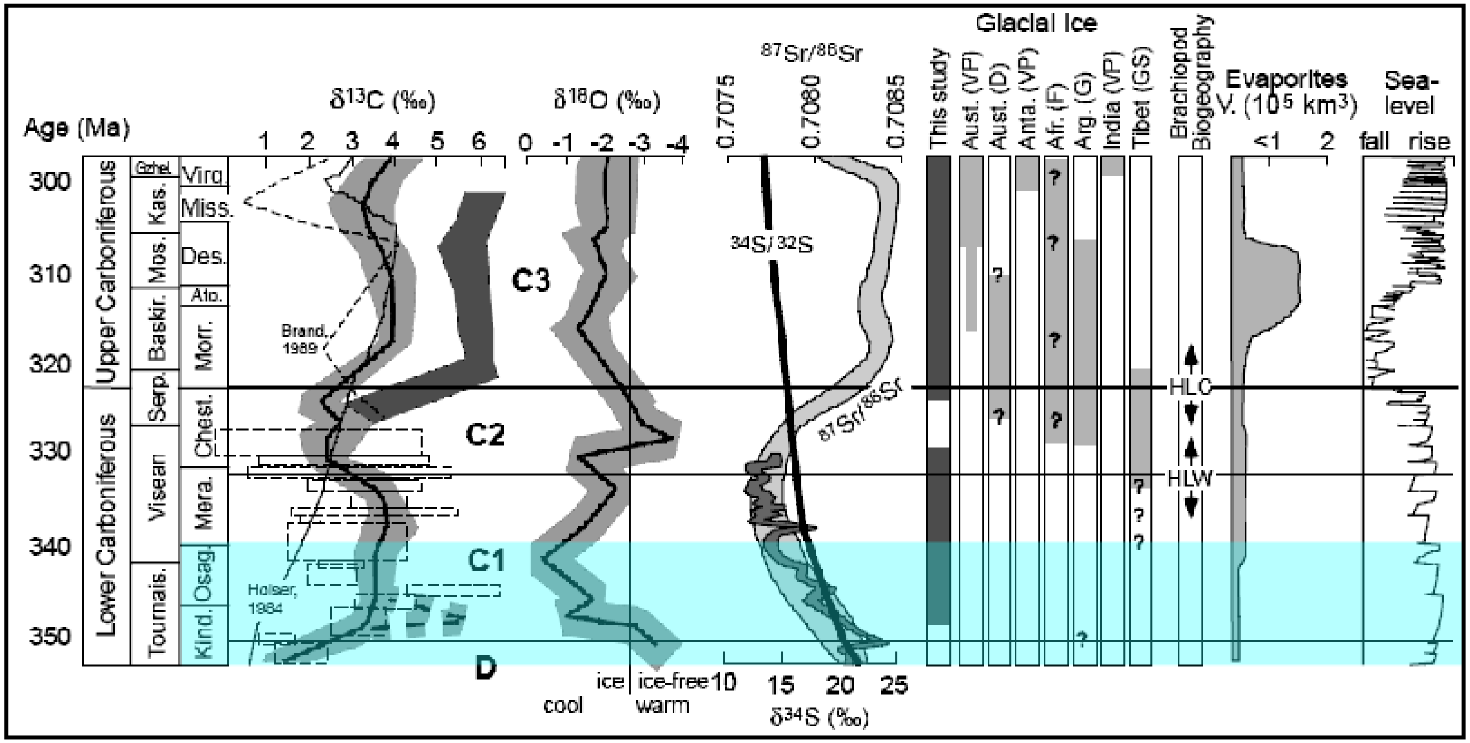



Figure 3.2 – Comparison of Carboniferous carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope stratigraphy from Mii et al. (1999, broad dark band; Pennsylvanian *Composita*), Brand (1989, fine-dashed line), Holser (1984, solid line), and Bruckschen and Veiser (1997, dashed boxes meaning ±1s), with occurrences of glacial ice (VP, Veevers and Powell, 1987; D, Dickens, 1996; F, Frakes et al., 1992; G, Garzanti and Sciunnach, 1997). Paleoclimate is inferred from isotope-migration patterns (Raymond et al., 1989; HLC = high-latitude cooling, HLW = high-latitude warming), evaporite accumulations (Frakes et al., 1992), and sea-level (Ross and Ross, 1988). Sulfur-isotope data (thick line) are from Claypool et al. (1980), and strontium-isotope data are from Denison et al. (1994, light stipple [as modified from Bruckschen et al., 1995]) and from Bruckschen et al, (1995, dark stipple). Divisions D-C3 represent isotope stages. $\delta^{13}C$ increases to the right; $\delta^{18}O$ increases to the left (from Mii et al., 1999). Light-blue rectangle represents study interval. Please note that there were approximately five sea-level cycles during the study time interval (Kinderhookian-Osagean time).

## 3.2 Eustatic Framework

Tectonic loading during fairly continuous craton-margin orogenies, flexural subsidence and uplift, and basement-structure reactivation have always had a major influence in defining sedimentation patterns and sea-level changes in the Appalachian foreland and adjacent basins (Ettensohn, 1985a, 1985b, 1994, 2004, 2005). In foreland-basin sequences, small-scale fifth- to sixth-order ($10^4$-$10^5$ years), high-frequency glacio-eustatic cycle signatures commonly are concealed by the larger scale second-to fourth-order ($10^6$-$10^8$ years) tectonic cycles (Dickinson et al., 1994). Small-scale local cycles could also be caused by the movement of individual structures in a basin.

The Mississippi Valley and Illinois Basin type (Keokuk) section on the North American craton show five transgressive-regressive, eustatic sea-level cycles during Kinderhookian—Osagean time (Fig. 3.3) (Ross and Ross, 1998). Results from this study correspond (Ross and Ross, 1998) well with the global eustatic sea-level curves proposed by Haq and Schutter (2008), where five to six cycles can be identified in Tournaisian to lower Visean (Kinderhookian–Osagean) time (Fig. 3.4). In the Appalachian Basin from the study area, two tectonic loading and relaxation transgressive-regressive cycles were noted by Ettensohn et al. (2004, Fig. 13) for the same time interval. The global and local regressive-transgressive sea-level curves (Ross and Ross, 1988; Haq and Schutter, 2008; Ettensohn et al., 2004) correlate well with glacio-eustatic cycles defined by positive shifts in $\delta^{18}O$ and $\delta^{13}C$ during Kinderhookian–Osagean time (Popp et al., 1986; Mii et al., 1999, 2001). Long periods of regression in these eustatic curves suggest cooler conditions and initiation of Gondwana glaciation during Kinderhookian–Osagean time (Mii et al., 1999).

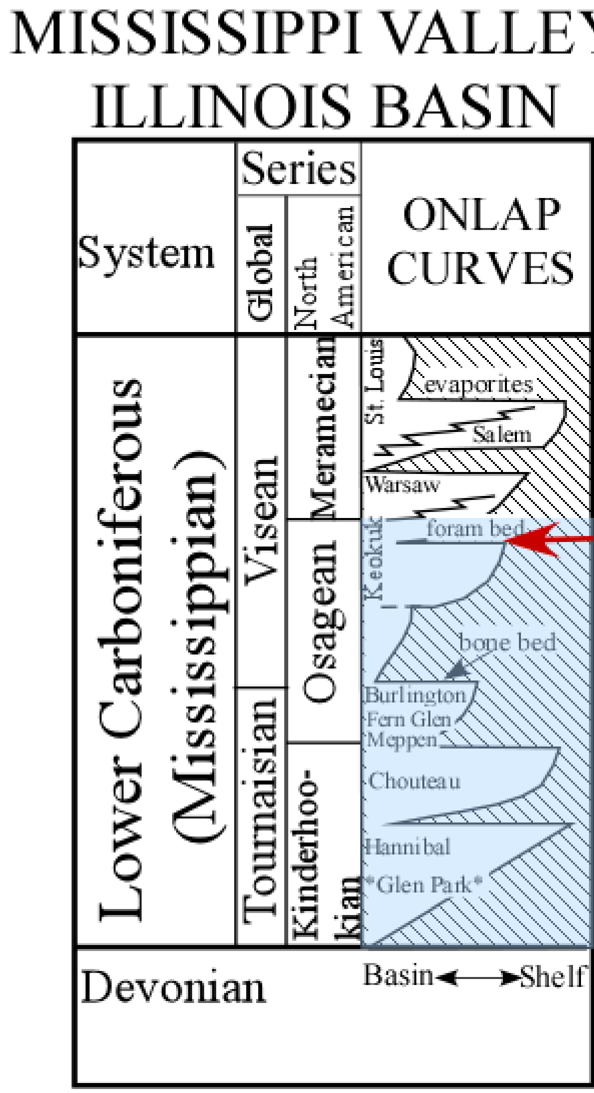



Figure 3.3 –Relative coastal onlap curve for the Mississippi Valley/Illinois Basin type (Keokuk) section (from Ross and Ross, 1988). Blue rectangle represents the study interval in the Appalachian and Illinois basins of Kentucky and adjacent states. Red arrow represents the period of onlap/offlap for the Floyds Knob interval in the Borden and Fort Payne formations. Five episodes of onlap can be seen during Kinderhookian–Osagean time on the North American craton.

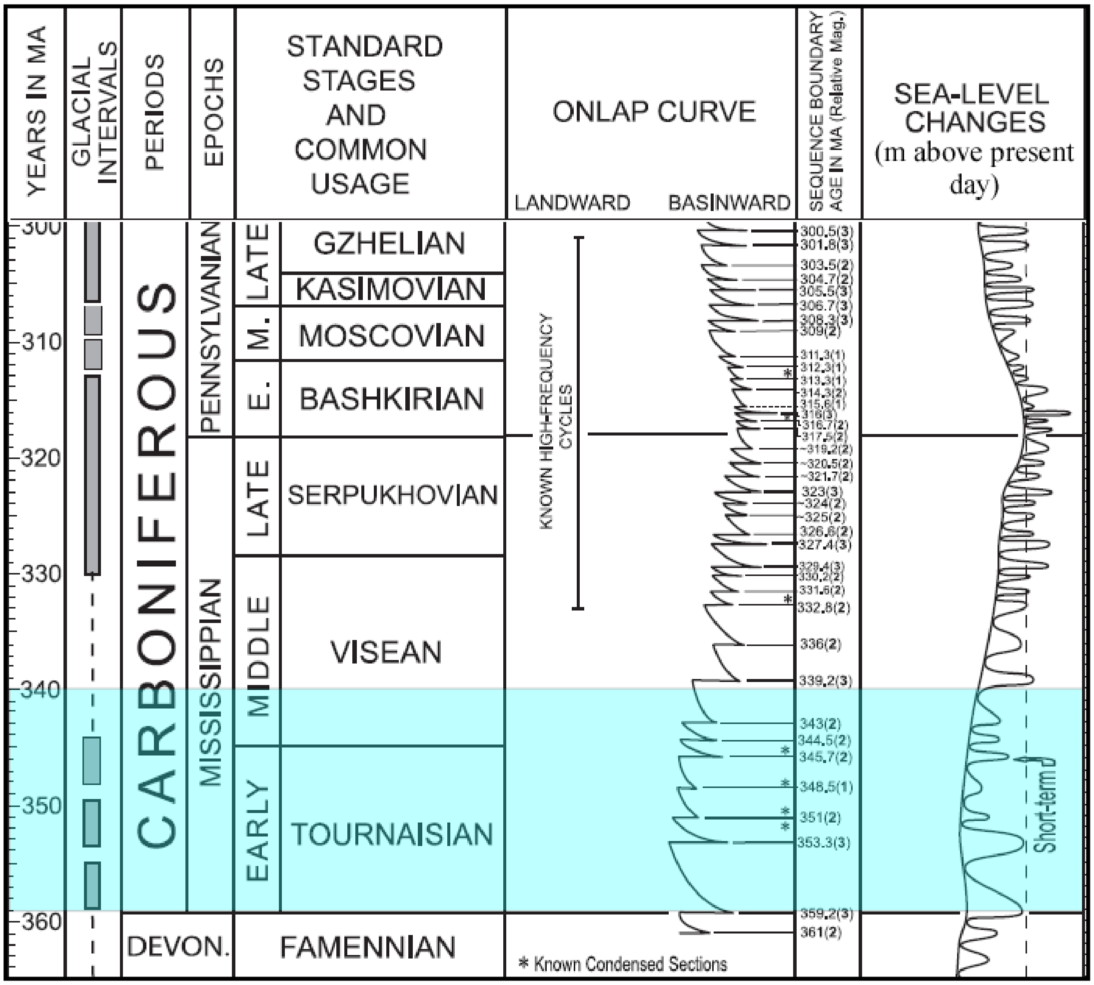



Figure 3.4 – Global sea-level onlap curves for the study interval (Lower-Middle Mississippian) (from Haq and Schutter, 2008). Blue rectangle represents the study interval.

# CHAPTER 4: TECTONIC SETTING

## 4.1 Proterozoic Basement Faults in Kentucky

In sedimentary basins, evidence for recurrent movement of bounding and interior faults that result in depositional thickening of sediments on the downthrown sides, as well as uplift and erosion of deposits on the upthrown sides, is common throughout the geologic record (McKenzie, 1978; Jarvis, 1983; Artyushkov, 1987; McClay, 1990; Stewart et al., 1997; Gawthorpe and Leeder, 2000). In fact, throughout many foreland basins, sediment-distribution patterns reflect an interaction between the rate at which accommodation is generated by fault-controlled subsidence and sea-level controls, and the rate of sediment input (Schlische, 1991; Gawthorpe et al., 1994; Contreras et al., 1997). Basement fault systems usually comprise an array of overlapping and under-lapping fault segments (Drahovzal et al., 1992; Schlische, 1992; Gawthorpe and Hurst, 1993; Peacock and Sanderson, 1994; Trudgill and Cartwright, 1994; Childs et al., 1995), and it is likely that there would be an interaction between growing fault segments that cause changes in faulting and sedimentation patterns through time.

In the Appalachian and Illinois basins of the study area, patterns of depositional thickening and erosional thinning of Lower-Middle Mississippian sediments correlate with known basement structures and are very likely related to movement along faults associated with the East Continent Rift Basin, the Grenville Front Tectonic Zone, and the Rome Trough (Woodward, 1961; MacGill, 1973; Ettensohn, 1977, 1992; Dever, 1990, 1995, 1999; Drahovzal et al., 1992; Lierman et al., 1992; Drahovzal and Noger, 1995; Harris and Drahovzal, 1996; Dever and Moody, 2002; Greb and Dever, 2002; Wilhelm, 2008). Reactivation of bounding and interior faults of the Rome Trough and the East Continent Rift Basin, uplift along the Cincinnati and Waverly arches, renewed movement along the Grenville Front and the Iapetus Rift Margin during Mississippian tectonic activity resulted in both uplift and erosion, as well as depositional thickening and thinning of Lower-Middle Mississippian units in the study area (Dever, 1995; Ettensohn, 1977; MacQuown and Pear, 1983; Drahovzal et al., 1992). Each of these structures will be discussed briefly below.

### 4.1.1 Rome Trough

The Rome Trough is a major intracratonic graben that mainly formed during late-stage Iapetan rifting (Thomas, 1991; Goodman, 1992). The Rome Trough is present in the western Appalachian Basin, east-central Kentucky, and some have considered it to be related to the East Continental Rift Complex (ECRC) (McGuire and Howell, 1963; Stark, 1997) (Fig. 4.1). The trough is a linear graben-like structure in the subsurface bounded on the north by the Kentucky River Fault System and on the west by the Lexington Fault System (Ammerman and Keller, 1979; Webb, 1980; Drahovzal and Noger, 1995). The southern border fault system (Rockcastle River-Warfield Fault Zone) is defined by the margins of basement prominences and subtle arches, rather than by a coherent fault system (Drahovzal and Noger, 1995; Stark, 1997).

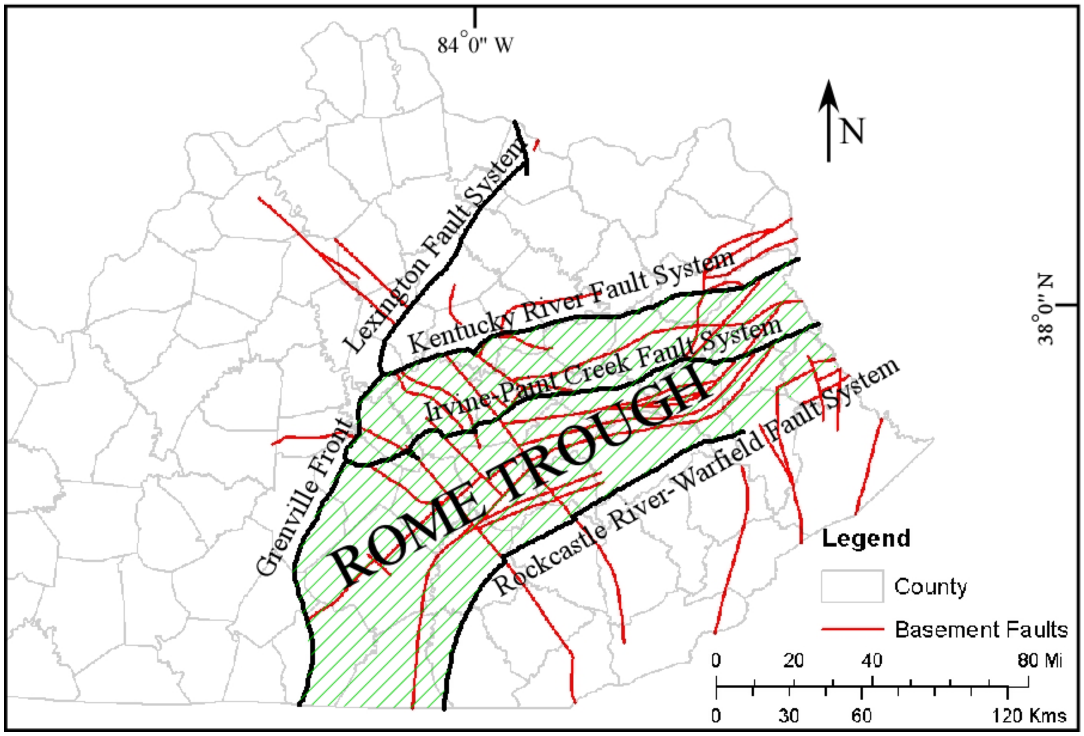



Figure 4.1 – Subsurface extent of the Rome Trough graben in eastern Kentucky. The graben is bound by three fault systems and includes one interior fault system. The Kentucky River Fault System is the northern boundary. The Lexington Fault System/Grenville Front is the western boundary of the Rome trough. The Rockcastle River-Warfield Fault System is the southern boundary. The Irvine-Paint Creek Fault System is located within the Rome Trough and is exposed at the surface in eastern Kentucky. Modified from Drahovzal and Noger (1995).

The Rome Trough is a major negative element in western Appalachian Basin that represents a continental rift zone, formed mainly by Late Precambrian–Early Cambrian faulting during Iapetan rifting. It has been interpreted to be a major rift system, extending from Grenville Front in the west northeastward across Kentucky, West Virginia, and Pennsylvania into south-central New York (Harris, 1978; Webb, 1980; Shumaker, 1986, Black, 1986; Thomas, 1991). In the Rome Trough, greatest subsidence occurred during Cambrian time, and major thickening of Cambrian sediments is present along the downthrown side of the northern border fault systems, and syn-rift sedimentation is associated with growth faulting within the trough (Thomas, 1960; Webb, 1969, 1980). The thickening of Cambrian sediments in the Rome Trough has been interpreted as a response to the activation of growth faults due to the relaxation of steeply ramped thrust faults generated during the Grenville contraction (Ammerman and Keller, 1979). The southern boundary structures include the Rockcastle River uplift, the Pike County High, and the Perry County High (Black, 1986). Differential thicknesses of Cambrian sediments onlapping these features reflect paleo-topographic highs during Cambrian extension (Black, 1986). The interior, intra-rift Irvine-Paint Creek Fault System (Fig. 4.1) and other fault systems within the Rome Trough exhibit down-to-south displacement and trend parallel to the northern border-fault system. The fault systems in the Rome Trough that extend down into the Precambrian basement have experienced periodic movement since Cambrian time with periodic reactivation throughout Paleozoic time (Woodward, 1961; McGuire and Howell, 1963; Webb, 1980; Thomas, 1991; Ettensohn and Pashin, 1992). Cambrian extension of the Rome Trough in east-central Kentucky created a set of half-grabens of alternating polarity and variable displacement

(Walker et al., 1991, 1992). The half-grabens within the trough are bounded in the dip direction by continuous west-southwest oriented faults. Along strike, the half-grabens are laterally segmented by north-south-oriented faults, suggesting significant strike-slip displacement (Drahovzal and Noger, 1995).

Post-Cambrian growth faulting of varied magnitude within the Rome Trough has occurred intermittently along bounding and interior faults during Ordovician, Silurian, Devonian, Mississippian, and Pennsylvanian times, resulting in the thickening of Paleozoic sediments on the downthrown sides (Dever, 1990, 1999). Paleozoic episodes of uplift accompanied by erosional and depositional thinning also occurred along bounding and interior faults of the trough (Dever, 1990, 1999). During Mississippian time, growth-faulting, thickening of the units, and episodic uplift accompanied by erosional and depositional thinning of the units occurred along the bounding and interior faults of the Rome Trough (Dever, 1990, 1999; Ettensohn, 1992, 2004; Ettensohn and Peppers, 1979). In addition, probable seismites, or seismically induced deformation of carbonate bodies in Middle Mississippian units in east-central Kentucky, may reflect seismic, gravity-induced -sliding during fault reactivation (Woodward, 1983; Greb and Dever, 2002). Differential thinning and thickening of Lower to Upper Mississippian rocks of the Borden and Slade formations along the upthrown and downthrown blocks of the Kentucky River and Irvine Paint-Creek fault systems also suggest growth-fault reactivation accompanying tectonic activity (Dever, 1995; Dever and Moody, 2002; Wilhelm, 2008).

### 4.1.2 Grenville Front

The Grenville Front is the western boundary of metamorphism and deformation associated with the Grenville Orogeny, a collisional event along the eastern margin of the Laurentian continent that appears to have emplaced an allochthon of metamorphic strata above the East Continent Rift Basin sediments (Drahovzal et al., 1992; Stark, 1997). The front separates 0.8–1.1 Ga old, high-grade metamorphic rocks of the Grenville province to the east from the 1.2–1.4 Ga anorogenic, calc-alkaline rocks of the eastern Granite–Rhyolite province to the west. The Grenville Front extends from southern Canada southward through south-central Kentucky. In fact, the Lexington Fault System, a late normal fault which may coincide with the older crystalline thrust complex in north-central Kentucky (Fig. 4.2) (Lidiak and Zietz, 1976; Keller et al., 1982; Drahovzal et al., 1992), may be a surface manifestation of the Grenville Front. The Grenville Front marks the western limit of the Grenville Front tectonic zone (Green et al., 1988; Pratt et al., 1989). This 40–50-km wide zone is characterized by prominent, southeast-dipping reflectors interpreted to be mylonitic layering (Pratt et al., 1989). This fabric is interpreted to be the result of imbricate thrusting during the 1.0 Ga old Grenville Orogeny during which the Grenville province was sutured to the Granite–Rhyolite province.

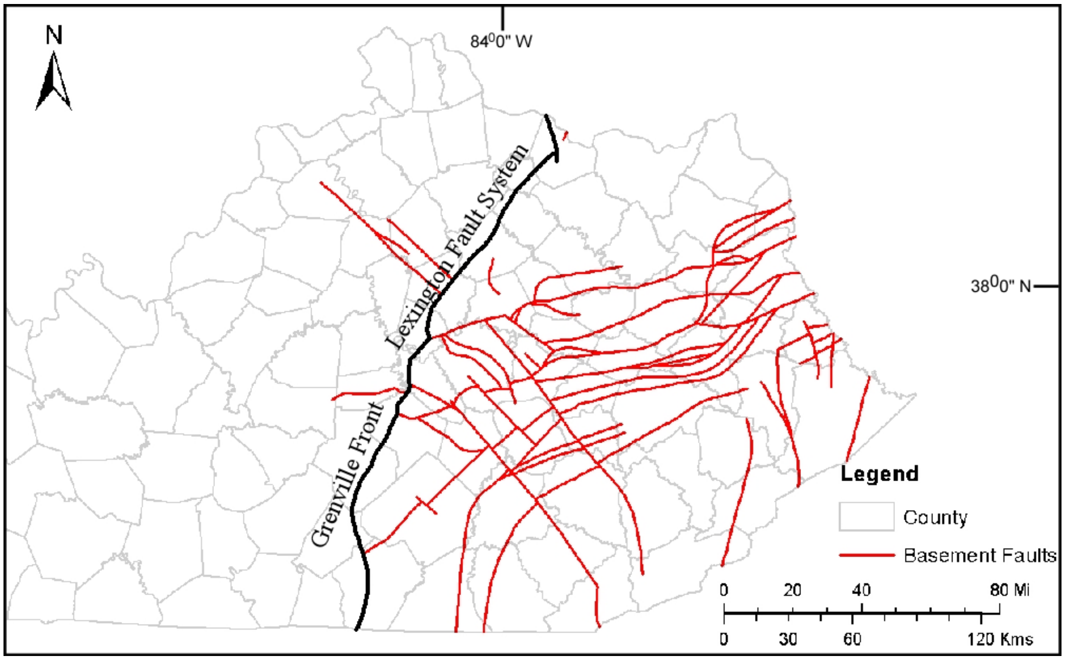



Figure 4.2 – Location and extent of Grenville Front in central and south-central Kentucky (modified from Drahovzal and Noger, 1995). The Grenville Front is concealed in the subsurface in central and south-central Kentucky, whereas the Lexington Fault System may coincide with the Grenville Front in north-central Kentucky.

On the basis of age determinations from limited deep core samples of the local unaltered basement mafic rocks associated with the East Continent Gravity High in central Kentucky, the Grenville Front metamorphism is interpreted to be about 1.0 Ga old (Keller et al., 1981, 1982).

### 4.1.3 East Continent Rift Basin (ECRB) in Illinois Basin

The East Continent Rift Basin (ECRB) is a major negative element situated largely in basement rocks of the Illinois Basin, west of the Grenville Front. It encompasses much of west-central Kentucky, southwestern Ohio, and southeastern Indiana. The ECRB is one of the many rift segments that define the East Continent Rift Complex (ECRC) (Stark, 1997), which has been interpreted to be an extension of the middle Proterozoic (Keweenawan) Midcontinent Rift System (1.05 to 1.3 Ga). The ECRB was first described after the discovery of the thick Precambrian Middle Run Formation below the Cambrian Mount Simon Sandstone in Warren County, Ohio (Shrake, 1991). It is an elongated, north-south-trending Precambrian rift basin that stretches from northern Tennessee through west-central Kentucky, Ohio, and Indiana to southern Michigan. It is bounded by the Grenville Front to the east and by normal fault blocks to the west (Drahovzal et al., 1992; Fig. 4.3).

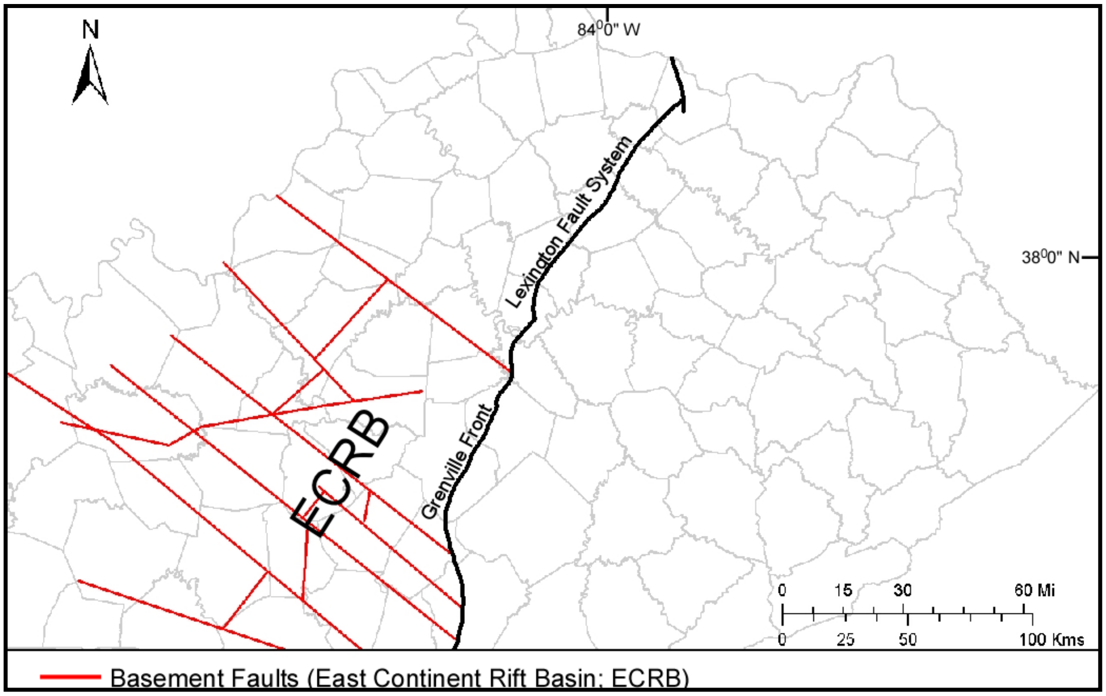



Figure 4.3 – Subsurface extent of the concealed East Continent Rift Basin (ECRB) basement-fault system in south-central and west-central Kentucky (modified from Drahovzal et al., 1992, Drahovzal and Noger, 1995, and Stark, 1997). The Grenville Front is younger than ECRB so, it may not be the true eastern boundary of ECRB.

The ECRB is infilled by a lower succession of interbedded extrusive flows and clastic sediments and an upper succession of apparently alluvial red beds. From gravity, magnetic, and seismic data, it is interpreted that the ECRB is composed of several sub-basins, some of which are as deep as 27,000-feet below sea level and filled with sediments as thick as 22,500 feet (Drahovzal et al., 1992). The basin is older than the Grenville Orogeny (1 Ga) and was overridden by allochthonous Grenville rocks. The subsequent Grenville compressional event resulted in folding and faulting of the rift-fill sequence. It has also been suggested that post-Grenville erosion, Paleozoic orogenic events, and structural inversion caused the present configuration of the basin (Drahovzal et al., 1992). The structures associated with the ECRB (Fig. 4.3) must have been reactivated during later Paleozoic orogenies and may have influenced Paleozoic structures, stratigraphy, diagenesis, as well as hydrocarbon migration and entrapment (Drahovzal et al., 1992).

### 4.1.4 Cincinnati Arch

The Cincinnati Arch is a broad, north-to-south-oriented, regional anticlinal structure, separating the Appalachian Basin on the east from the Illinois Basin, on the west (Fig. 4.4). Rast and Goodman (1994) have suggested that the arch may have resulted from structural inversion of parts of the ECRB that underlies it. Bulge migration may have reactivated the structures associated with ECRB during each successive orogeny. The arch extends from Tennessee through the Nashville Dome northward into Kentucky through the Jessamine Dome toward Cincinnati, Ohio. Major structural elements associated with this arch include the Nashville and Jessamine Domes on the crest, and border faults of the Rome Trough and East Continent Rift Basin on the eastern

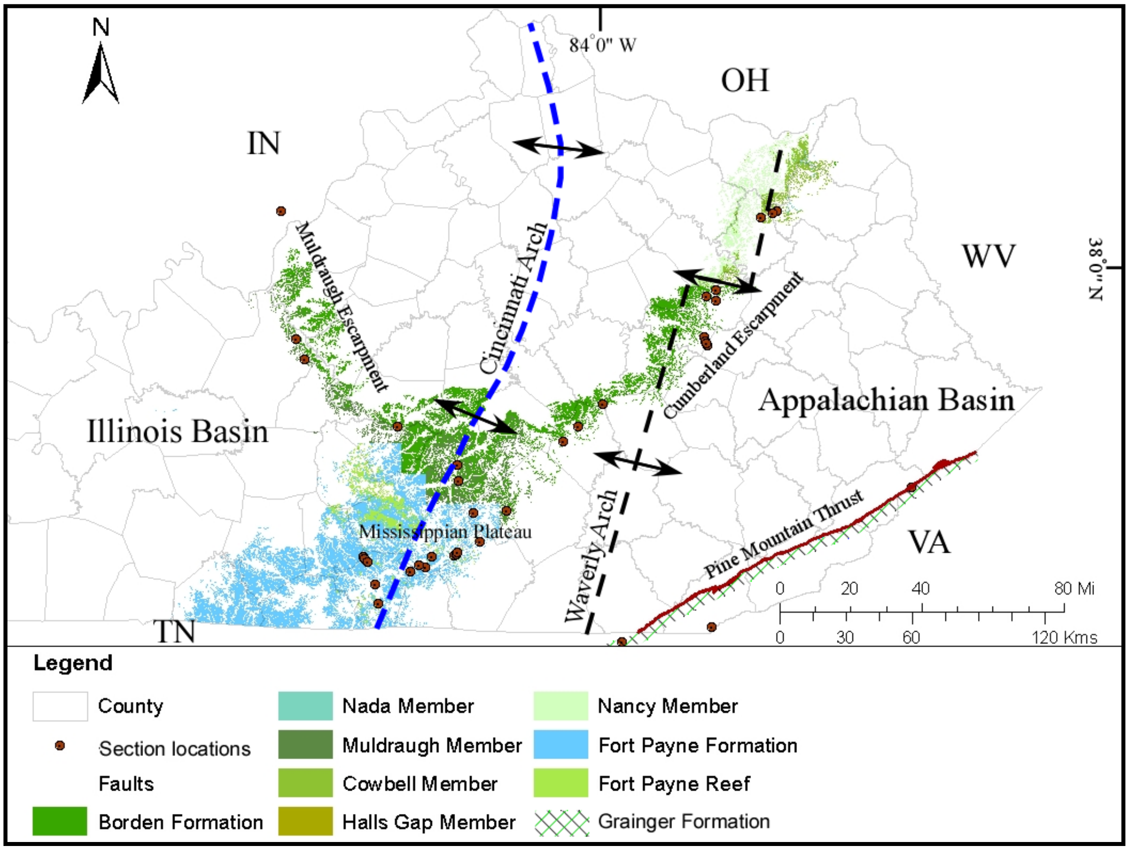



Figure 4.4 – Location of the Cincinnati and Waverly arches in Kentucky. The north-to-south-oriented Cincinnati Arch extends from Tennessee through central Kentucky towards Cincinnati, Ohio, separating the Appalachian and Illinois Basins. The Waverly Arch of northeastern Kentucky is generally oriented north-to-south extending northward into southern Ohio.

and western sides, respectively (Borella and Osborne, 1978; Weir et al., 1984; Drahovzal et al., 1992; Drahovzal and Noger, 1995; Kolata et al., 2001). The Cincinnati Arch is inferred to have been a relatively fixed, positive structural element throughout much of Phanerozoic time, possibly beginning as early as Cambrian–Early Ordovician time (Rodgers, 1971; Read, 1989; Drake et al., 1989).

Thickness and facies variations in Early, Middle, and Late Ordovician shallow-water deposits in central and south-central Kentucky suggest that the arch was mainly an elevated feature in and around the Jessamine Dome (McGuire and Howell, 1963; Borella and Osbourne, 1978; Grossnickle, 1985; Ettensohn et al., 1986; Anderson, 1991; Ettensohn 1992). Features such as seismites, syn-tectonic faulting, and differential subsidence also indicate that the Cincinnati Arch was subjected to seismic activity during Late Ordovician time (Ettensohn et al., 2002; Jewell and Ettensohn, 2004; MacLaughlin and Brett, 2004).

Thickness variations in the Lower Silurian Brassfield Formation as well as restricted westward movement of detrital sediment in Middle and Late Silurian time suggest a restricted open-marine circulation due to the presence of an emergent arch during the Salinic Orogeny (Currie, 1981; Gordon and Ettensohn, 1984; Ettensohn, 1994; Andrews, 1997).

Lower, Middle, and Upper Devonian carbonate rocks and black shales deposited in south-central and central Kentucky show depositional thinning and onlap over older eroded Ordovician and Silurian strata towards the axis of the arch (McFarlan, 1943; Freeman, 1951; Kepferle, 1986). Moreover, depositional thinning of Devonian Chattanooga and equivalent black shales toward the axis of the arch indicate that the arch was a submerged, positive structural element during Late Devonian time (Dillman, 1980; Ettensohn et al., 1988). During this time, however, uplift of the Cincinnati Arch and related subsidence in the Appalachian Basin were apparently related to migratory lithospheric flexure in response to Acadian tectonism (Ettensohn et al., 1988, Ettensohn, 1992).

Depositional and facies architecture of Lower–Middle Mississippian Borden and Fort Payne formations in Kentucky do not show any evidence of an elevated Cincinnati Arch. However, depositional thinning of Sunbury black shale from east to west towards the arch suggests a slightly positive, but submerged structural feature by Early Kinderhookian time (Tournaisian) (Ettensohn and Elam, 1985). Thickness variations and direction of progradation of the Borden and Fort Payne formations do not suggest any evidence of an elevated arch (Whitehead, 1976; Sable and Dever, 1990). However, the Meramecian (Visean) Warsaw Limestone, St. Louis Limestone, and Ste. Genevieve Limestone in the Eastern Interior basin of western Kentucky thin eastward, suggesting that the Cincinnati Arch was a positive feature (Sable, 1979; Sable and Dever, 1990). Evaporites deposited during early parts of St. Louis deposition probably reflect restriction generated by uplift of the Cincinnati Arch and other positive structures, combined with sea-level decline (Craig and Varnes, 1979; De Witt et al., 1979). Paleocurrent patterns in upper Meramecian (Visean) and lower Chesterian limestones in the northern Appalachian basin reflect the presence of a narrow, elongate embayment that was probably constricted on the west by subaerial exposure of the arch in Ohio and north-central Kentucky (Woodward, 1983). By Late Mississippian time, however, depositional thinning and erosion of Upper Mississippian units in northeastern Kentucky, in part, reflect uplift on the Cincinnati Arch (Ettensohn, 1975).

#### 4.1.5 Waverly Arch

The Waverly Arch is a broad, low, concealed, north-to-south-oriented, positive feature, parallel to the Cincinnati Arch, extending from north-central Ohio southward into eastern Kentucky (Fig. 4.4). The arch is probably related to the basement fault systems in the Rome Trough at depth (Pashin and Ettensohn, 1987; Ettensohn, 1992). The arch was first noted in the work of Woodward (1961), who reported depositional and erosional thinning of early Paleozoic formations across the structure. Subsequent investigations of Mississippian and Pennsylvanian formations in eastern and north-eastern Kentucky by Ettensohn (1975, 1980, 1981) and Englund et al., (1981) noted different axial positions of the structure. However, multiple studies suggest the Waverly Arch was a prominent feature during much of mid-Cambrian through Pennsylvanian time.

Thickness variations in the Lower Mississippian Henley Bed of the Farmers Member of the Borden Formation (Kearby, 1971) have been interpreted to reflect syn-depositional uplift on the Waverly Arch (Woodward, 1961; Mason and Lierman, 1992). After deposition of the Henley Bed, the eastern margin of subsequent fan-shaped deposits of the Farmers Member of the Borden Formation was apparently affected by recurrent movement along the Waverly Arch (Woodward, 1961; Lierman et al., 1992). Movement along the Rome Trough basement fault systems and Waverly Arch (Woodward, 1961; Drahovzal and Noger, 1995; Harris and Drahovzal, 1996) was suggested to have been a dominant factor during deposition of the Lower–Middle Mississippian Borden Formation in eastern and northeastern Kentucky.

### 4.2 Lithospheric Flexural Models

The depositional architecture and sedimentation patterns in many foreland basins indicate that the stratigraphy in these basins commonly reflects a complex interplay among sediment supply, eustasy, flexural loading from thrust sheet emplacement, and possibly long-wavelength dynamic loading (Quinlan and Beaumont, 1984; Beaumont et al., 1988). Newly emplaced loads at the orogenic front along cratonic margins not only influence sedimentation in foreland basins by creating new sources of sediment, but also influence development and distribution of major unconformities, basins, areas of regional uplift, and modes of sedimentation in cratonic basins far away from the orogenic front (Beaumont, 1981; Karnmer and Watts, 1983; Quinlan and Beaumont, 1984; Beaumont et al., 1988; Ettensohn, 1993, 1994).

The eastern continental margin of Laurussia experienced parts of two major orogenies during the Carboniferous period: the Acadian Orogeny which began during Devonian time and continued into the Mississippian time, and the Alleghanian Orogeny, which largely occurred during the Pennsylvanian and Permian periods, but emplacement of Mauch Chunk clastic wedges suggests that the Alleghanian Orogeny started during late Mississippian time (Thomas, 1977; Ettensohn, 1994, 2008). Also by Middle Mississippian time, the Ouachita Orogeny had begun on the southern margin of Laurussia (e.g., Arbenz, 1989). Newly emplaced loads along the southern and eastern continental margins of Laurussia caused deformation along the edge of the plate and the coeval cratonward migration of foreland basins and uplifted peripheral bulges on the distal margins of these basins. Some of the basins no doubt impinged upon the study area in east-central and south-central Kentucky.

Lithospheric flexure in foreland basins occurs during orogeny in order to maintain isostatic equilibrium in response to the deformational loading of migrating fold-thrust belts during plate collision. The deformational loading at the craton margin creates a retro-arc foreland basin and associated peripheral bulge (Dickinson, 1974; Quinlan and Beaumont, 1984; Beaumont et al., 1988). As orogeny proceeds and thrust loads shift cratonward, the foreland basin and peripheral bulge also migrate cratonward away from the load.  Moreover, the migrating bulge produces a regional unconformity which is overlapped by foreland-basin sediments.  With increased thrusting, loading, and folding at the orogenic front, the foreland basin subsides to the point that an under-filled foreland basin with a stratified water column develops (e.g., Early Mississippian Sunbury Shale; Ettensohn et al., 2004) (Fig. 4.5). As the deformed load is eroded, however, the basin begins to fill with turbidites, debris flows, deltas, tempestites, and flysch-like sediments (Fig. 4.5). Once the orogeny halts and cratonward movement of deformation ceases, the static load then subsides, forcing the foreland basin to subside more while the bulge gets uplifted and migrates back toward the load. At this time in proximal parts of the basin near to the bulge, the bulge my block the further westward migration of deltaic sediments, such that deltaic sedimentation gives away to shallow open-marine and peritidal sediments on and near the uplifted bulge(e.g., Maccrady Formation; Ettensohn et al., 2004). However, because the uplifted bulge blocks cratonward movement of sediment, distal parts of the foreland basin experience sediment starvation and relative sea-level rise, permitting the deposition of glaucony, phosphate rich-shales and siltstones, as well as chloritic clays (e.g.,  Nada Member and associated Floyds Knob glauconite horizons of Borden Formation (Ettensohn et al., 2004). In the absence of clastic sediments from far distal areas of the foreland basin, deeper water, cherty carbonates may come to dominate (Fig. 4.5).

### 4.2.1 Neoacadian Tectophase

Lower–Middle Mississippian rocks in the study area of the western Appalachian and distal Illinois Basins reflect parts of a tectonic event called the fourth tectophase of the Acadian Orogeny or the Neoacadian tectophase (Ettensohn, 1994, 2004, 2008). This tectophase or orogenic event has been interpreted to represent a unique time of dextral shearing and transpression between the Carolina terrane and Laurussia (Merschat and Hatcher, 2007; Ettensohn, 2008) (Fig. 4.5).

## 4.3 Pine Mountain Thrust

In parts of eastern Kentucky (Pound Gap), western Virginia (Cumberland Gap tunnel), and northeastern Tennessee (Jellico Mountain), a complete section of Mississippian rocks is exposed along the northwestern face of the Pine Mountain thrust sheet (Fig. 4.1). The rocks were thrusted northwestward 3–22 km from deeper parts of the central Appalachian basin during the Alleghanian Orogeny (Coskren, 1981; Mitra, 1988). The Mississippian rocks are exposed along the truncated limbs of the Middlesboro Syncline and the Powell Valley Anticline.

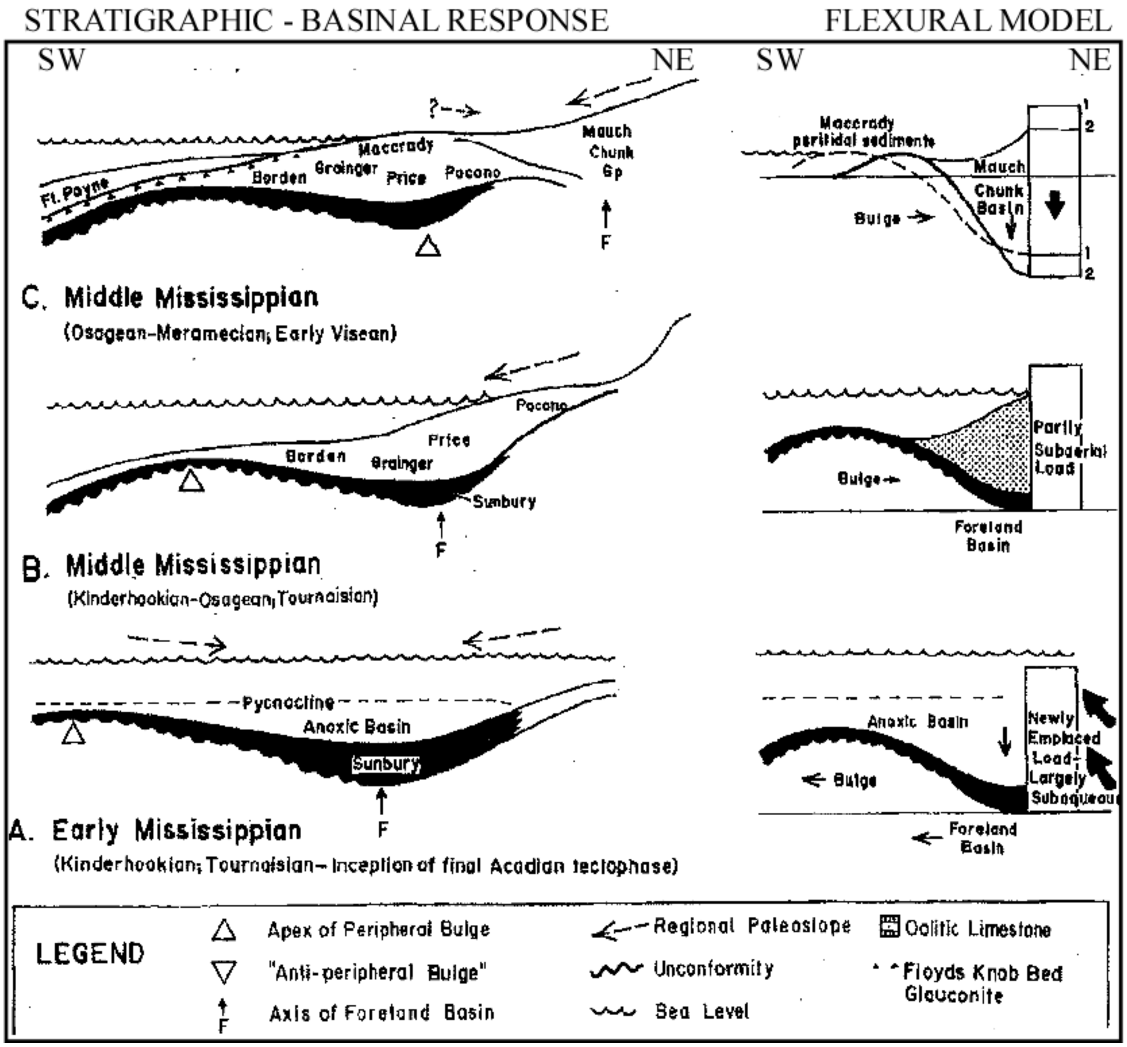



Figure 4.5 – Schematic southwest-northeast cross-section across the central Appalachian Basin showing Mississippian units and lithologies with respect to the flexural events of the Early–Middle Mississippian Neoacadian tectophase of the Acadian Orogeny (adapted from Ettensohn et al., 2004).

# CHAPTER 5: STRATIGRAPHIC FRAMEWORK

## 5.1 Price-Pocono-Grainger-Borden Delta Complex and Fort Payne Formation

The Price-Pocono-Grainger-Borden delta complex represents an Early-Middle Mississippian (Kinderhookian-Osagean) clastic succession deposited in the central and western Appalachian Basin during the loading-type-relaxation phase at the end of the Neoacadian tectophase of the Acadian Orogeny (Ettensohn, 1994, 2001, 2008; Ettensohn et al., 2002). In the western parts of the basin, the delta complex immediately rests unconformably over basinal, black-shale deposits of Devonian and Mississippian age. The Price-Pocono part, which is composed of non-marine, delta-plain sediments, reflects proximal, subaerial parts of the delta complex in eastern parts of the Appalachian Basin near source areas (Bartlett, 1974; Arkle et al., 1979), whereas the Borden-Grainger parts are composed of marine, prodelta, and delta-front sediments that represent more distal, subaqueous part of the wedge (Hasson, 1972). The subaqueous part of the delta lobes in the western Appalachian Basin extends cratonward for 600 km, crossing the Cincinnati Arch into the Illinois Basin (Swan et al., 1965; Lineback, 1966).

The paleoslope of the delta complex was dominantly to the west, but in the Illinois Basin across the Cincinnati Arch, a southern paleoslope was present (Kepferle, 1971; Whitehead, 1978). In the distal parts of the delta complex in eastern Kentucky, the thickness of the Borden and Grainger formations reaches 240 m, and 200 m in the Illinois Basin in southern Indiana and north-central Kentucky, respectively, whereas in the proximal parts (Price-Pocono) in the central part of the basin, the thickness reaches 500 m (Meckel, 1970; Patchen et al., 1985).

The Borden Formation and the correlative Grainger Formation in Kentucky are dominated by terrigenous detrital sediments, especially deep-water prodelta clays and coarsening-upward delta-front silts (Peterson and Kepferle, 1970; Kearby, 1971). In Kentucky, the delta lobes of Borden and Grainger formations (Fig. 5.1) thin progressively westward and southwestward along a paleoslope in central and southeastern parts of Kentucky into the starved-basin conditions of the Fort Payne Formation to the southwest in south-central Kentucky (Peterson and Kepferle, 1970; Kepferle, 1971; Sedimentation Seminar, 1972; Lewis and Potter, 1978; Whitehead, 1984; Sable and Dever, 1990).

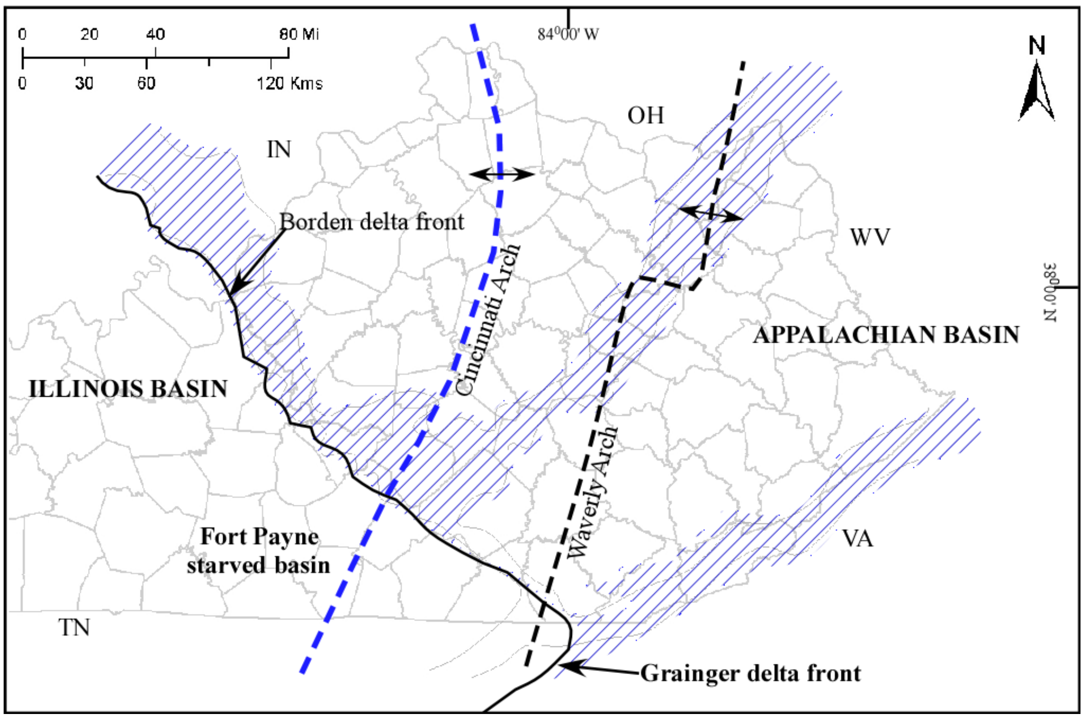



Figure 5.1 – Map showing regional setting of Appalachian and Illinois basins in Kentucky (modified from Lewis and Potter, 1978). Map shows position of the exposed Borden-Grainger delta complex (stippled) in western Appalachian and eastern Illinois basins with respect to the Fort Payne starved basin in south-central Kentucky during Early Mississippian time. The Fort Payne starved basin lies southwest of the Borden-Grainger delta front.

## 5.2 Stratigraphic Relationship and Descriptions

The major stratigraphic units of this study are the Borden Formation, the Fort Payne Formation, the Maccrady Formation, and the Grainger Formation. Other important units like the Maury Shale and Rockford Limestone in Kentucky are commonly subsumed by the Fort Payne and Borden formations, respectively. The lithostratigraphic and chronostratigraphic relationships between correlative units observed in the study area of southeastern Kentucky and northeastern Tennessee, west-central Kentucky and southern Indiana, south-central, east-central, and northeastern Kentucky are presented in Figures 5.2 and 5.3 and described below.

### 5.2.1 Maury Shale

The Maury Shale (Figs. 5.2 and 5.3), or the New Providence Member of earlier workers (Early Mississippian; Kinderhookian), is a green, glauconitic, shale unit with abundant conodonts, fossil fragments, fish remains, and phosphate nodules at its base; it is considered to be the base of the Fort Payne Formation in south-central Kentucky. Other accessory minerals such as pyrite, gypsum, and iron-oxide are found in the unit. The Maury Shale is equivalent to the Maury Formation of Tennessee and unconformably overlies the Upper Devonian and Lower Mississippian Chattanooga or New Albany shales (MacQuown and Perkins, 1982; Lewis and Potter, 1978; Ausich and Meyer, 1990; Leslie et al., 1996; Krause et al., 2002). The Maury Shale unconformably overlies Devonian-Mississippian shales below, and in places, may be unconformably overlain by shales in the Fort Payne and Borden formations.

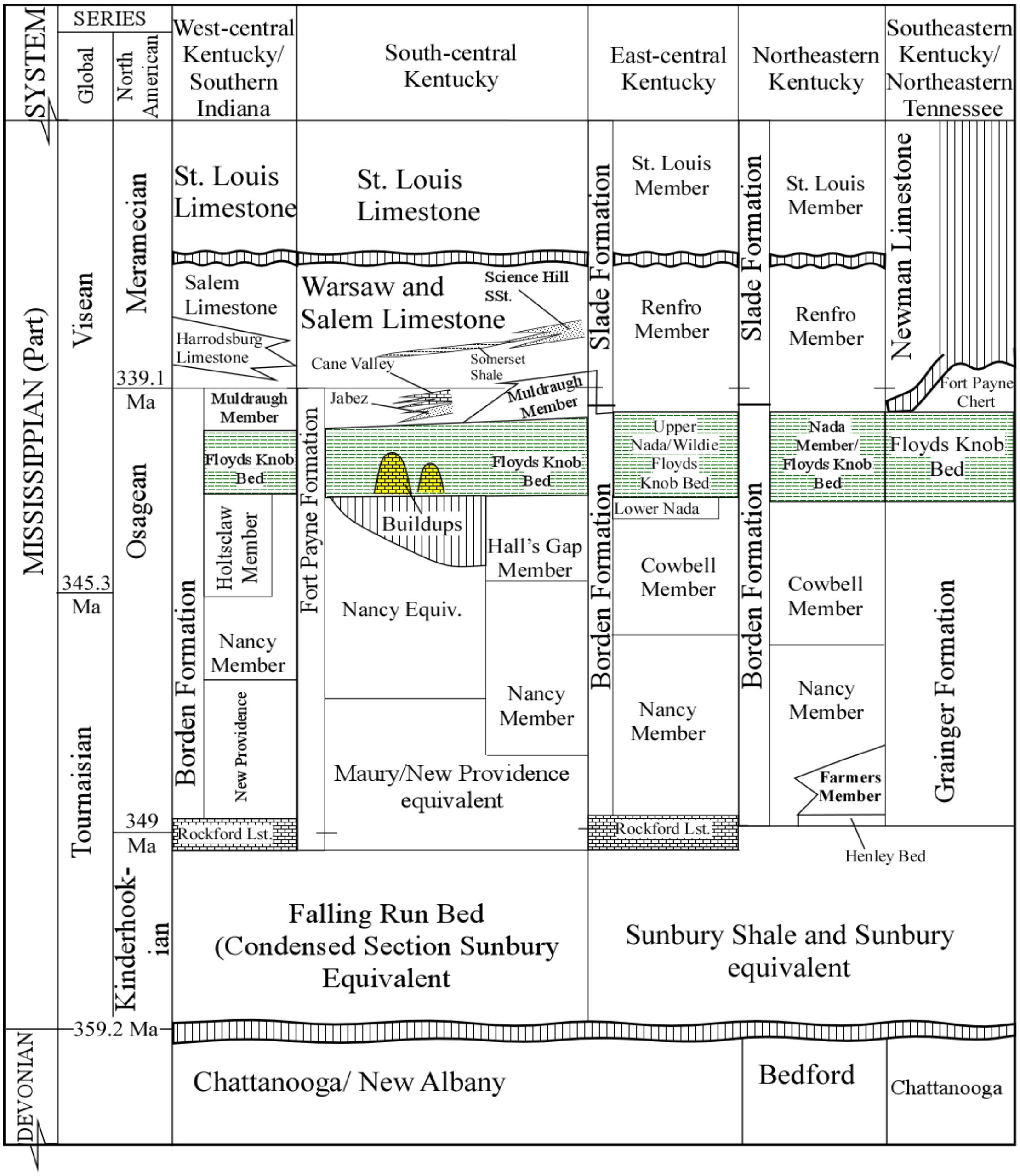



Figure 5.2 – Chronostratigraphic framework showing Early–Middle Mississippian (Kinderhookian–Osagean) Borden, Grainger, and Fort Payne study interval (modified after Sedimentation Seminar, 1972;  Ausich and Meyer, 1990; Sable and Dever, 1990; Khetani and Read, 2002; Lierman and Mason, 2004).

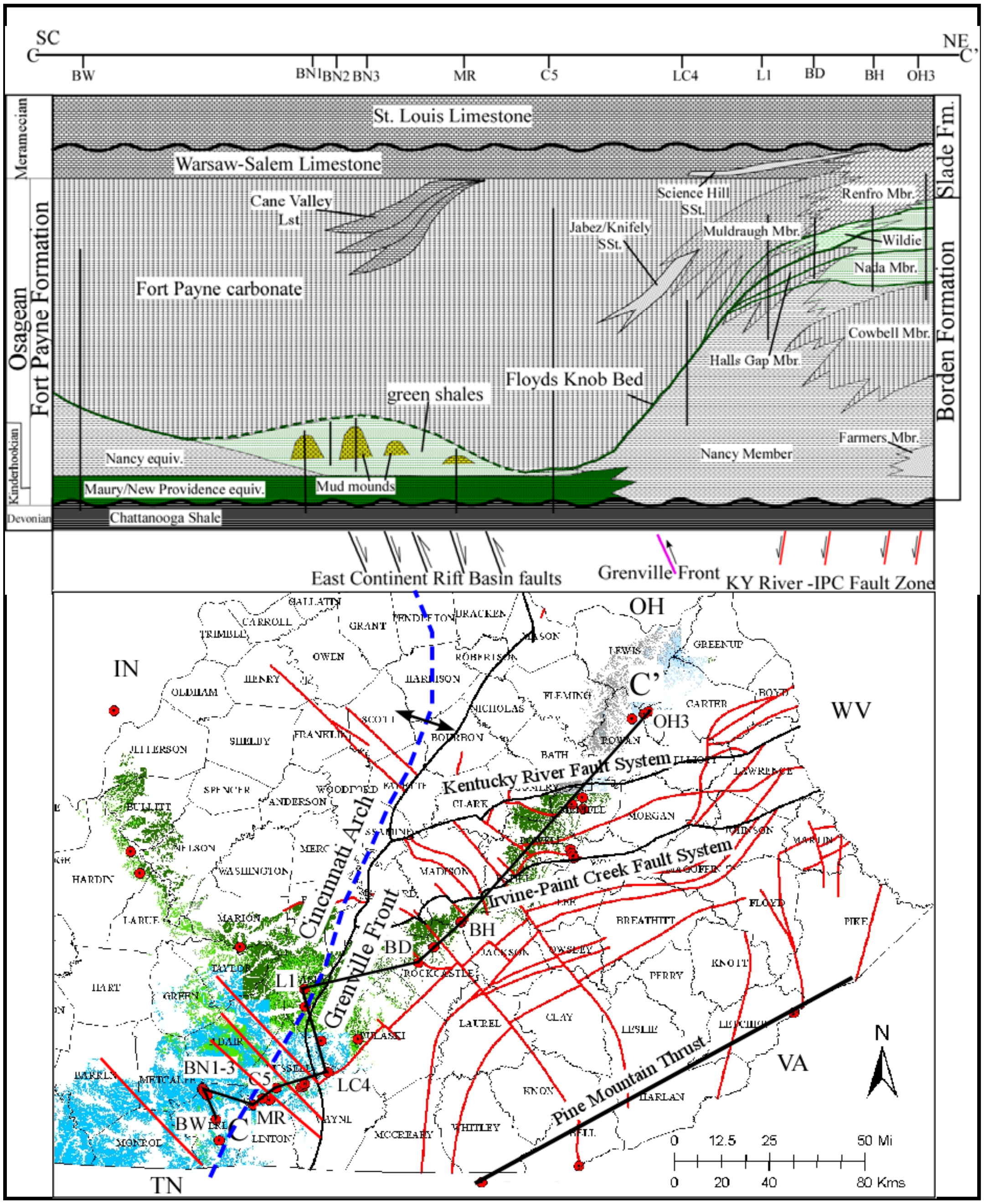



Figure 5.3 – Lithostratigraphic framework showing Lower–Middle Mississippian (Kinderhookian–Osagean) Borden and Fort Payne study interval.

Biostratigraphic studies of extracted conodonts have suggested that the Maury Shale may represent sedimentation during parts of the Kinderhookian and Osagean stages, a period of apparently 17 million years (Conant and Swanson, 1961; Sable and Dever, 1990; Leslie et al., 1996; Krause et al., 2002; Davydov et al., 2004). This shale or its equivalents in the New Providence generally reflects the beginning of the buildup interval in the lower part of the Fort Payne Formation.

Maury lithologic equivalents in the western Appalachian and eastern Illinois basins typically contain mixed conodont assemblages of Devonian, Kinderhookian, and Osagean ages, and are interpreted to represent a lag concentrate at an erosional hiatus, which probably extended through Kinderhookian and early Osagean times (Rexroad and Scott, 1964; Sable and Dever, 1990) (Figs. 5.2 and 5.3). With this interpretation, the depositional environment for the Maury Shale and associated fossiliferous green shales is interpreted to represent very slow clastic influx in a starved marine basin far removed from source areas. Abundant phosphate nodules and fine glauconite clay in the Maury also support a low-energy, sediment-starved environment of precipitation (Conant and Swanson, 1961; Sable and Dever, 1990).

### 5.2.2 Rockford Limestone

The Rockford Limestone is a thin, widespread calcareous unit of Early Mississippian (late Kinderhookian-early Osagean) age present in southern Indiana, and west-central Kentucky (Sable and Dever, 1990) (Fig. 5.2).The Rockford Limestone has also been reported from east-central Kentucky at the Big Hill exposure near Berea (Lierman and Mason, 2004). The Rockford Limestone was named after the Rockford Goniatite Bed in southern Indiana and is a gray to greenish-gray, micritic, phosphatic, glauconitic limestone or dolostone (Sable and Dever, 1990; Lierman and Mason, 2004). It is reported to contain both Kinderhookian and Osagean conodont elements in Indiana, as well as Kinderhookian foraminiferal elements in west-central Kentucky and southern Indiana (Sable and Dever, 1990). Kinderhookian conodont elements have also been reported from the underlying Jacobs Chapel Shale at the Big Hill exposure near Berea, Kentucky (Sandberg et al., 2002; Lierman and Mason, 2004). The Rockford Limestone of west-central Kentucky and Indiana seems to be coeval with parts of the Maury Shale in south-central Kentucky (Sable and Dever, 1990).

The Rockford Limestone is as much as 3 feet (~ 1 m) thick in west-central Kentucky near the Ohio River in Louisville, and rests directly on the Devonian New Albany Shale. This unit has also been reported from the Big Hill exposure in east-central Kentucky, where it is very thin-bedded (5-10 cm), greenish-gray, calcareous, and highly bioturbated; it occurs with the very thin, underlying the Jacobs Chapel Shale Bed (Lierman and Mason, 2004). The Rockford Limestone along with the Jacobs Chapel Shale Bed typically occurs just above an erosional contact with the underlying Devonian–Mississippian New Albany Shale; it has a gradational contact with the overlying Nancy Member of the Borden Formation (Lierman and Mason, 2004).

Previous studies suggest that the Rockford Limestone in Indiana and parts of northern Kentucky were deposited in a low-energy environment on a seafloor with little relief and low clastic influx, in a deeper area behind the Cincinnati Arch (Sable and Dever, 1990). The depositional environment has been interpreted to represent a starved-shelf or basin environment (Sable and Dever, 1990). The Rockford Limestone unit at the Big Hill exposure is devoid of any primary sedimentary structures due to intense bioturbation, and has been interpreted to represent an isolated, distal part of a carbonate turbidite flow in dysaerobic conditions (Lierman and Mason, 2004).

### 5.2.3 Borden Formation

The Borden Group (or Borden Formation) was formally designated by Cumings (1922) for the Lower-Middle Mississippian shales and siltstones exposed near Borden in Clark County, Indiana (Weir et al., 1966). Stockdale (1931, 1939) proposed the use of the Borden Group (or Formation) in Kentucky. The Borden Formation unconformably overlies Upper Devonian and/or Lower Mississippian black shales, and is generally a coarsening-upward, west-to-southwest-thinning- and -fining, clastic sequence that is common in west-central, east-central, south-central, and northeastern parts of Kentucky (Fig. 5.2). The generalized depositional environment is interpreted to have been a subaqueous marine delta, in which the delta prograded westerly from the east and northeast onto a stable cratonic shelf (Peterson and Kepferle, 1970; Lane and Dubar, 1983). In the Borden delta, environments range from pro-delta to delta front.

The following members and one bed of the Borden Formation are described below: Nancy Member, Cowbell Member, Halls Gap Member, Floyds Knob Bed, Wildie Member, Nada Member, and Muldraugh Member.

#### 5.2.3.1 Nancy Member

The Nancy Member is of Osagean age (Figs. 5.2 and 5.3) and is widespread and persistent throughout northeastern, east-central, west-central, and south-central parts Kentucky. The Nancy Member represents distal foreset and bottomset strata of the

Borden delta and was named by Weir et al (1966) for exposures of basal part of Borden Formation in Pulaski County, Kentucky (Kepferle, 1971).

The Nancy Member is composed of non-resistant, gray- to greenish-gray, fossiliferous, bioturbated mudstones, shales, and silty shales with local crinodal packstone lenses, as well as siderite and calcareous concretions. The common fossils include brachiopods, crinoids, cephalopods, gastropods, pelecypods, and bryozoans (Weir et al., 1966; Kepferle, 1971; Warne, 1990). The Nancy Member contains the Gum Sulfur Bed, a lentil of resistant siltstone that emphasizes the clastic-wedge character of the lower Borden (Sable and Dever, 1990). Nancy shales and silty shales lack any sedimentary structures due to extensive bioturbation. The sediments were deposited below normal wave base, on a basin-floor, pro-delta, or delta-slope environment (Kepferle, 1977; Chaplin, 1980, 1985; Kammer and Cox, 1985). Trace fossils reported in the Nancy Member are included in the deeper water *Zoophycus-Nereites* ichnofacies assemblages (Chaplin, 1980, 1985). Lower Nancy and upper Nancy contain *Zoophycus-Nereites*, and *Zoophycus* assemblages, respectively, indicating distal turbidite (*Nereites*) to quiet, deep-water (*Zoophycus*) depositional environments (Chaplin, 1980, 1985; Frey and Seilacher, 1980; Warne, 1990).

In northeastern and east-central Kentucky, the Nancy Member unconformably overlies Devonian and Mississippian black shales, and is unconformably overlain by the Cowbell, Halls Gap or Holtsclaw members of the Borden Formation. In west-central Kentucky in Jefferson and Bullitt counties, however, the Nancy Member is conformably overlain by the Muldraugh Member across a thin glauconitic siltstone unit (Floyds Knob

Bed), locally associated with an oolitic limestone (Kepferle, 1971; Sable and Dever, 1990).

### 5.2.3.2 Cowbell Member

The Cowbell Member (Figs. 5.2 and 5.3) is of Osagean age and is widespread and persistent throughout northeastern and east-central parts of Kentucky. The Cowbell Member represents distal delta-front strata of the Borden delta and was named by Weir et al. (1966) for siltstones exposed near the head of a minor tributary of Cowbell Creek west of Big Hill, Kentucky. The Cowbell Member is as much as 380-feet (115.8-m) thick in northeastern and east-central Kentucky.

The Cowbell Member is composed of bluish-gray to gray, thick, fossiliferous, bioturbated, resistant siltstones separated by thin discontinuous, grey shales. The calcareous, sub-graywacke-type siltstones commonly weather to platy fragments, which commonly obscure original bedding due to extensive bioturbation. The Cowbell Member contains siderite nodules, calcite nodules, and ironstone layers (Warne, 1990). Common fossils include brachiopods, crinoids, pelecypods, gastropods, and bryozoans; ammonoids are sparse to common (Kearby, 1971).

The Cowbell Member conformably overlies the Nancy Member and conformably underlies the Nada Member across a thin glauconitic siltstone layer in northeastern and east-central Kentucky, although in places the glauconite layer is absent (e.g., at Big Hill, near Berea in Kentucky). The Cowbell Member was deposited on the Borden delta-front as a migrating distal bar in a delta-front setting (Kearby, 1971). Trace-fossil associations in the Cowbell Member include the *Cruziana* ichnofacies in the lower portion and *Cruziana-Skolithos* ichnofacies in the uppermost portion, indicating subtidal deposition

(Kearby, 1971; Chaplin, 1980, 1985). Based on sedimentary structures and trace-fossil assemblages, the Cowbell Member was deposited in a high pro-delta and delta-front environment, deposited as a result of constant distributary-channel migration and switching (Kearby, 1971; Chaplin, 1980, 1985).

**5.2.3.3 Halls Gap Member**

The Halls Gap Member is of Osagean age (Figs. 5.2 and 5.3), and named after a calcareous-to-dolomitic siltstone unit that is present in west-central, south-central, and east-central Kentucky. The unit is composed of resistant, greenish-gray to medium-gray limy siltstone with minor clayey siltstones and silty limestones (Weir et al., 1966). The unit weathers to a brownish orange-gray color and generally thickens to the southwest. The bedding usually displays planar laminae, ripple cross-laminae, and small-scale hummocky cross-stratification. Locally, the bedding displays a fining-upward texture into bioturbated, friable siltstones. The unit thickens to the southwest where it measures almost 100 feet (30.5 m) thick southeast of Halls Gap, Kentucky.

The Halls Gap Member exhibits foreset beds dipping west and southwest at angles of generally less than 5°, and thins or grades to extinction southwestward into the Fort Payne Formation (Sable and Dever, 1990). The unit is truncated in places by the overlying Wildie Member (or Nada Member) and grades laterally into siltstones and shaley siltstones of the Nancy Member (Weir et al., 1966). The Muldraugh Member conformably overlies the Halls Gap Member across the glauconitic siltstones represented by the Floyds Knob Bed. Siliceous geodes and concretions occur throughout the unit, and lenses of limestone become more persistent in its upper parts.

#### 5.2.3.4 Floyds Knob Bed

The widespread, Late Osagean Floyds Knob Bed (Figs. 5.2 and 5.3) was first described as the Floyds Knob Formation by Stockdale (1931, 1939) for the fossiliferous glauconitic limestones and siltstones exposed near Floyds Knob Post Office, Floyd County, Indiana.  The Floyds Knob Bed was described by Stockdale (1939) as an important ‘marker’ horizon in the Appalachian and Illinois basins that has been used in tracing facies from strata, both above and below, and in establishing correlations across the region. Whitehead (1978) formally designated the unit as the Floyds Knob Bed of the Borden Formation after Weir et al. (1966) suggested that the Floyds Knob Formation of Stockdale (1939) is too thin, too discontinuous, and could be easily confused with other glauconite horizons that commonly occur in the upper Borden Formation.

The Floyds Knob Bed is generally composed of an upper bioturbated, peloidal glauconite and a lower limestone or dolostone bed. In places, only the glauconite is present in Kentucky; where the carbonate is present, it is generally composed of glauconitic, crinoidal, mudstones, wackestones, or packstones which are fossiliferous and locally dolomitic (Stockdale, 1931; Kepferle, 1971; Whitehead, 1978, Sable and Dever, 1990). The Floyds Knob Bed is extensively burrowed and bioturbated, and glauconite pellets are mostly concentrated in burrows and trails. The unit is abundantly fossiliferous, including gastropods, foraminifera, brachiopods, corals, echinoderms, pelecypods, bryozoans, and crinoids (Whitehead, 1976, 1978). Abundant pyrite, chertified fossils, ferroan dolomitic mud, and secondary calcite deposits are recognized in association with the Floyds Knob Bed in Kentucky. Phosphorite nodules and phosphatic fossil remains are also common in the Floyds Knob Bed throughout the study area, but they are more abundant in southern parts of its distribution. Nodules range in diameter from 0.25 inches to about 2 inches (0.6 to 5 cm), are rounded and elongate in shape, locally contain fossils like cephalopods, and have divots and distinctive markings that are the result of boring by invertebrate species. Lierman and Mason (2004) reported phosphatic fossil remains including fish teeth, scales, small fragmented bones, internal molds of gastropods and brachiopods, and crinoidal debris.

The unit is distributed widely and has been reported in southern Indiana in the basal part of the Edwardsville Limestone (Whitehead, 1978) and to the east at Newman Ridge, Tennessee, in the basal part of the Maccrady Formation (Hasson, 1986). In west-central Kentucky, the Floyds Knob Bed overlies the Halls Gap Member and underlies the Muldraugh Member south of Lebanon (Kentucky Highway 208) in Marion County. It is conformably underlain by the Nancy Member and overlain by the Muldraugh Member at the Fort Knox and Bluegrass Parkway exposures in Hardin County. In south-central Kentucky, the Floyds Knob Bed conformably overlies the Halls Gap Member and underlies the Muldraugh Member west of Somerset (Cumberland Parkway) in Pulaski County and south of Liberty (US 127S) in Casey County. In Cumberland, Wayne, Clinton, and Russell counties, the Floyds Knob Bed overlies unnamed dark-grey silty shales of the Fort Payne Formation and underlies Fort Payne calcisiltites and dolosiltites. In northeastern Kentucky, the Floyds Knob Bed conformably overlies the Cowbell Member and occurs within the Nada Member near Morehead (Interstate 64) in Rowan and Carter counties. In east-central Kentucky, the Floyds Knob Bed overlies the Cowbell Member and occurs within Nada Member near Slade (Natural Bridge area, Kentucky Highway 11) in Powell County, near Frenchburg in Menifee County (US 460), and near

Brodhead (Kentucky Highway 70) in Rockcastle County. The Floyds Knob Bed also occurs within the Nada Member at the Big Hill exposure in Madison County and at the Interstate 75 exposure near Mt. Vernon in Rockcastle County. The Floyds Knob Bed is conformably underlain by the Grainger Formation and overlain by the Fort Payne Formation in the Jellico Mountain area, Campbell County, Tennessee. At Pound Gap in Letcher County, Kentucky though glauconite is absent, the Floyds Knob Bed is represented by a concentrated interval of medium-gray to greenish gray mudstones and siltstones that occur at the contact between the Grainger Formation below and the Newman Limestone above. At Cumberland Gap, Virginia, the Floyds Knob Bed has been assigned to an interval of medium-gray to greenish-gray mudstones and siltstones that occur at the contact between the Grainger Formation below and the Fort Payne Formation above (Vanover et al., 1989).

**5.2.3.5 Nada Member**

The Nada Member (Figs. 5.2 and 5.3) of the Borden Formation is composed of nonresistant, greenish-blue to bluish-green gray, dark-red, and greenish-purple clay shales and silty shales with minor siltstones, packstones, grainstones, dolomicrites, and glauconites. Dark-green glauconite grains of the Floyds Knob Bed are scattered throughout, but are commonly concentrated in 1–2-inch (2.5–5-cm) thick laminae, which are generally phosphatic (Stockdale, 1931; Weir et al., 1966; Chaplin, 1980). Four to five glauconite horizons, including the Floyds Knob Bed, occur in the Nada Member. The thickness of the Nada Member ranges from 0 to about 75 feet (22.8 m), reaching the maximum in east-central Kentucky; it thins to the northeast, east of Morehead, Kentucky (Chaplin, 1980).

The Nada Member (Figs. 5.2 and 5.3) is the uppermost deposit across the Borden delta and represents an open-marine, shelf-margin, delta-destruction facies on the Borden delta platform (Ettensohn, 1979, 1980, 1981; Chaplin, 1980; Ettensohn et al., 2004) on top of the delta-front silts and sands of the Cowbell Member. The Nada Member is generally conformable with the underlying Cowbell Member and the overlying Renfro Member of the Slade Formation. In places, however an apparently erosional contact between the Renfro and the Nada may indicate an unconformity. The glauconite-rich Floyds Knob Bed is located within the Nada Member and is continuous throughout the region (Stockdale, 1931; Kepferle, 1971; Whitehead, 1978, Sable and Dever, 1990).

The high concentration of glauconite and phosphorite nodules in the upper part of the Nada Member is not typical of delta-platform, siliciclastic deposition. Both minerals suggest that the rate of sedimentation was greatly reduced in comparison to lower members of the Borden Formation. Ettensohn et al. (2004) suggested that the bluish-green coloration of the siltstones and shales of the Nada Member represents a unique example of chlorite-rich verdine-facies development with attributes similar to the glauconite facies reported by Odin and Letolle (1980), Odin and Matter (1981), Odin and Fullager (1988), and Thamban and Rao (2000).

Conodont and ammonoid species (Work and Mason, 2003), and crinoids (Lee et al., 2005) found in northeastern Kentucky at the Hilltop Church Section and along Interstate 64 between Morehead and Olive Hill, Kentucky, suggest that the upper Nada is late middle Osagean (late Tournaisian to earliest Visean) in age. Crinoids sampled at many exposures in northeastern Kentucky suggest that the Nada is of late early Osagean age (Lane and Dubar, 1983; Kammer, 1984; Matchen and Kammer, 1994). Conodonts and foraminifera in the overlying Renfro Member, in contrast, suggest that the Renfro is largely Meramecian (Visean) in age (Weir, 1970). Therefore, an unconformity may exist between the two members where evidence for late Osagean rocks in northeastern Kentucky is absent (Lee et al., 2005).

The Nada Member is remarkably different in northeastern Kentucky compared to occurrences in east-central Kentucky along the Cumberland Escarpment. In northeastern Kentucky, the Nada Member includes many carbonate-buildup horizons, characterized by abundant brachiopods, bryozoans, cephalopods, gastropods, pelecypods, pelmetazoans, and rugose corals (Chaplin, 1980). The diverse fauna suggests that open-marine conditions existed during deposition of the Nada in northeastern Kentucky. Chaplin (1980) interpreted the buildups as a series of crinoid-bryozoan shoals that grew on top of abandoned delta lobes. However, to the southwest in east-central Kentucky, the Nada Member is composed mostly of shales and silty shales, suggesting that clastic deposition was more active and probably occurred in deeper conditions there than to the northeast. Bryozoans, brachiopods, and crinoids are common along with phosphorite nodules, and phosphorite has replaced much of the skeletal material in the lower and middle parts of the member. Hence, the abundance and diversity of fossil material suggests that sedimentation rates must have been slow enough to allow these quiet-bottom communities to develop on the muddy substrate (Ettensohn et al., 2004). Water depths were likely above storm wave-base because of the presence of hummocky cross-beds and debris-filled scours in some beds, which are infilled with the disarticulated invertebrate remains (Lierman and Mason, 2004; Ettensohn et al., 2004). The siltstone beds within the Nada Member typically are tabular and massive (bioturbated) and exhibit planar and hummocky cross-bedding; ripple-bedding is common, as are erosional scours (flute casts, tool marks) and/or loadcasts along the lower contacts. Trace fossils are evident in the lower and upper parts of individual beds, and trace fossils from the *Zoophycus* and *Cruziana* ichnofacies are common (Chapman, 1980). Siltstone beds are commonly separated by thin shale partings (Chapman, 1980). Overall, deposition in the Nada Member is interpreted to have occurred on a shallow-subtidal delta platform with local carbonate banks and interdeltaic lagoons in waters less than 200-feet (60-m) deep (Ettensohn et al., 2004).

#### 5.2.3.6 Wildie Member

The Wildie Member or upper Nada Member of Lierman and Mason (2004) of the Borden Formation (Figs. 5.2 and 5.3) is composed of two principal lithologies: olive-gray siltstones or fine-grained sandstones, and dark olive-gray mudstones that are more common in the upper part of the unit. The unit is exposed in the vicinity of northern Rockcastle County and southern Madison County as an elongate, lobe-shaped body. The unit dips and pinches out towards the southwest and is bound at the lower and upper contacts by glauconitic siltstone beds (Weir et al., 1966). It has sharp, erosional contacts with both the underlying Nada Member and overlying Renfro Member across erosional surfaces characterized by silty glauconite beds.

The siltstone beds of the Wildie Member are primarily composed of moderately sorted, angular, detrital quartz and feldspar within beds that range from 0.2 to 7.0 feet (0.06 to 2.0 m) in thickness (Gauthier, 1988). The thickest beds are found in outcrop exposures between the towns of Wildie and Hummel in northern Rockcastle County (Gauthier, 1988). The siltstone beds typically are tabular and massive (bioturbated) and exhibit planar and hummocky cross-bedding; ripple-bedding is common, as are erosional scours (flute casts, tool marks) and/or loadcasts along the lower contacts. Trace fossils are evident in the lower and upper parts of individual beds, and fossils from the *Zoophycus* and *Cruziana* ichnofacies are common (Gauthier, 1988). Siltstone beds are often separated by thin shale partings (Gauthier, 1988).

The mudstone beds of the Wildie Member contain glauconite and lesser amounts of iron pyrite. The mudstone beds range from less than one inch thick (several millimeters) to beds that are greater than 13 feet (4 m) thick at the distal margins (Gauthier, 1988). The Wildie Member, overall, is a fining-upward sequence in which mudstone tends to be more abundant in the upper parts of the section. The mudstones are typically bioturbated, thus destroying any bedding and sedimentary structures (Gauthier, 1988).

The Wildie Member of the Borden Formation is interpreted as having been deposited in an upper delta-front and platform setting adjacent to a nearby distributary channel (Weir et al., 1966; Weir, 1970; Gauthier, 1988). Sediments of the Wildie Member were deposited following the regional hiatus and accompanying deposition of the underlying Floyd Knob Bed (Weir et al., 1966). The quartz, feldspar, and glauconitic grains in the Wildie Member are interpreted to have been derived from an easterly source controlled by fluvial and wave-dominated conditions (Weir et al., 1966; Weir, 1970; Gauthier, 1988). Where hummocky cross stratification is present in outcrop, Gauthier (1988) inferred that the beds were deposited by storm-generated waves on parts of an abandoned delta lobe that were scoured and reworked by unidirectional and oscillatory flow regimes. Gauthier (1988) also suggested that the mudstone facies was deposited during fair-weather conditions.

#### 5.2.3.7 Muldraugh Member

On the Borden-delta slope, the hiatus or time of slow deposition represented by the Floyds Knob Bed marks the beginning of carbonate deposition in Middle Mississippian time, which continued throughout much of Late Mississippian time on the platform before the renewal of terrigenous-detrital sedimentation in latest Mississippian time. In south-central, west-central, and central Kentucky, basal deposits of the carbonate sequence are assigned to the Muldraugh Member (Figs. 5.2 and 5.3) of the Borden Formation. The Muldraugh Member is characterized by diverse lithologies, but is primarily composed of resistant cherty dolosiltites, wackestones, silty micrites, and dolomicrites, with packstone-grainstone lenses, calcareous shales, and siliceous geodes. In general, the Muldraugh Member exhibits thin- to- medium, lenticular bedding, such that the bases of the beds are irregular and erosional while the tops show pinch-and-swell structures. Structures include megaripples, cross bedding, and graded bedding, and some beds are bioturbated with *Chondrites* and *Zoophycus* trace fossils.

The Muldraugh is exposed in west-central, central, and south-central Kentucky. The lower contact is the topmost glauconite seam in the Floyds Knob Bed (Weir, 1970), whereas the upper contact is with the overlying Salem-Warsaw Formation to the north and with the equivalent Science Hill Sandstone in south-central Kentucky (Weir, 1970). The Muldraugh Member is subdivided into seven intervals based on biostratigraphic and lithostratigraphic relationships (Kammer et al., 1990; Kammer et al., 2007). On the basis of conodonts (Nicoll and Rexroad, 1975), the Muldraugh is thought to be largely late Osagean (Tournaisian) in age.

The Muldraugh Member was deposited down-dip of the Renfro Member and up-dip of Fort Payne sediments as a carbonate-ramp facies along the outer-delta platform and delta slope of the Borden delta (Peterson and Kepferle, 1970; Sable and Dever, 1990; Ausich and Meyer, 1992). The Muldraugh Member carbonates have been interpreted to represent largely subtidal sediments; much of the carbonate sediment was transported to the platform margin, onto the foreset slope, and into the sediment-starved basin, forming clinoform deposits that built a southwestwardly prograding carbonate platform (Sedimentation Seminar, 1972; Klein, 1974; Hannan, 1975; Benson, 1976). Deposits of the Muldraugh thicken abruptly to the southwest across the Borden Delta front, ranging in thickness from about 36 to 60 feet (11 to 18 m) on the platform to almost 300 feet (90 m) on the slope and basinward (Dever, 1995). In the basin southwest of the delta-front, rocks correlative with the Muldraugh are assigned to the Fort Payne Formation.

### 5.2.4 Grainger Formation

The Grainger Formation (Fig. 5.2) of late Kinderhookian–Osagean (late Tournaisian–early Visean) age in central Appalachian Basin is only exposed at the surface along Pine Mountain in southeastern Kentucky, northeastern Tennessee, and western Virginia, where it attains a thickness of 200–500 feet (60–150 m) (Howell and Mason, 1998; Sable and Dever, 1990; Ettensohn et al., 2002). The Grainger is composed of shelf-edge to basinal, pro-deltaic deposits, equivalent to more proximal delta-front and delta-plain deposits of the more proximal Price and Pocono formations to the northeast (Hasson, 1972, 1986; Rice et al., 1979; Ettensohn et al., 2002). The Grainger Formation is characterized by gray and greenish-gray, silty shales with thin laminae and beds of siltstones, as well as by siderite nodules and lenses similar to those in the Nancy Member of the Borden Formation; however, the upper part of the Grainger is characterized by resistant grey, greenish-gray, and reddish-grey siltstones, shales, and sandstones similar to those in the Nada Member of the Borden Formation (Sable and Dever, 1990). The overall grain size of the Grainger decreases southward into Virginia and Tennessee, where shale is the only lithic component (Englund, 1964).

The Grainger Formation at Pound Gap, Letcher County, in southeastern Kentucky, has a gradational contact with the underlying Kinderhookian Sunbury Shale and an erosional contact with the overlying upper Meramecian–lower Chesterian (middle Visean) Newman Limestone. The middle part of the Grainger is characterized by several stacked sequences of interbedded siltstones and shales, each of which generally thins upward, showing the characteristics of graded (Bouma) sequences. The siltstones represent turbidite-sequence development in an outer-fan environment of deposition (Howell and Mason, 1998). The upper part of the Grainger contains reddish-gray to greenish-gray siltstones and shales with abundant iron-oxide nodules. Abundance of sedimentary structures including hummocky cross-strata and channeling suggest subsequent development of a shallow, storm-dominated shelf environment during the deposition of the upper part (Howell and Mason, 1998; Ettensohn et al., 2002). The red shales and siltstone units at the top have been correlated with the Maccrady Formation to the east (Smith et al., 1967; Ettensohn et al., 2002), a sequence of red peritidal shales and sandstones with evaporites (Warne, 1990).

In the Cumberland Gap area of western Virginia, and the Jellico Mountain area of northeastern Tennessee, the Grainger consist of shales, silty shale, and siltstones with abundant iron-oxide nodules at the top. The color of the sediments changes gradually from dark-gray at the base to greenish-gray and reddish-gray at the top (Dean et al., 1989), indicating conditions of sedimentation changing from anoxic conditions at the base to shallower oxic conditions at the top. The upper contact with the overlying upper Osagean (lower Visean) sequence of interbedded cherts, siliceous dolostones, and shales of the Fort Payne Formation is erosional and sharp, defined by the glauconite-rich Floyds Knob Bed (Dean et al., 1989; Sable and Dever, 1990; Ettensohn et al., 2002). The thickness of Fort Payne Formation increases southward; about 5 m of cherty Fort Payne equivalent occurs at the top of the Grainger in the Cumberland Gap Tunnel, whereas about 23 m of Fort Payne is present in the Jellico Mountain area.

### 5.2.5 Fort Payne Formation

The Lower to Middle Mississippian (Late Kinderhookian–Osagean) Fort Payne Formation (Figs. 5.2 and 5.3) in south-central Kentucky is an extremely heterogeneous mixed clastic-carbonate unit that occurs between the underlying Devonian–Mississippian Chattanooga (New Albany) Shale, Maury Formation equivalent, and the overlying Meramecian Warsaw-Salem Limestone. Deposition of the Fort Payne is intimately associated with the deposition of the Borden delta to northeast, as it is placed stratigraphically in front of the abandoned Borden delta lobes. During middle and late Osagean time, the Borden deltaic wedge migrated into central and south-central Kentucky, after which the focus of major clastic deposition shifted to the north into Indiana, creating a widespread, starved-basin condition that extended from southern

Kentucky southward into Tennessee, Mississippi, and Alabama and was ideal for thick carbonate and silica precipitation (Peterson and Kepferle, 1970; Sedimentation Seminar, 1972; Pryor and Sable, 1974; Lewis and Potter, 1978).

The Fort Payne is the most diverse and lithologically complex unit in the southwestern Appalachian and eastern Illinois basins of Kentucky. The Fort Payne contains dolomitic and calcareous, silty, medium- to light-gray, bioturbated shales with abundant, scattered quartz geodes; argillaceous, medium- to dark-gray, typically thin-bedded, bioturbated dolomites; bedded chert; crinoidal grainstone-packstones; and wackestones. Waulsortian-like mud mounds, as well as bryozoan-crinoidal bioherms that occur in trends that strike parallel to the Borden front, are also present in the Fort Payne Formation (Thaden and Lewis, 1962, 1966; Sedimentation Seminar, 1972). These bioherms and mud mounds are composed chiefly of crinoidal and bryozoan limestones, including mudstone and/or wackestone. They are partly dolomitized with some minor chert and are commonly associated with greenish-gray and dark-grey, fossiliferous shales (Lewis and Potter, 1978; Ausich and Meyer, 1990; Krause and Meyer, 2004). These carbonate-mud mounds are mainly scattered west of the Cincinnati Arch in Kentucky and around the Nashville Dome in central Tennessee. Both occurrences seem to overlain deeply buried parts of the Grenville Front and East Continent Rift Basin structures.

The elongated, northeast-trending, coarsening-upward, very fine-grained, porous, thoroughly bioturbated bodies of the Knifley/Jabez Sandstone Member of the Fort Payne Formation occur on the crest of the Cincinnati Arch (Kepferle and Lewis, 1975; Hannan, 1975; Lewis and Potter, 1978). The Knifley/Jabez Sandstone has been interpreted to be a slope-break shoal deposit (Sedimentation Seminar, 1972). The Cane Valley Limestone

Member of the Fort Payne is a cross-bedded, elongated, bryozoan-crinoidal grainstone body that occurs parallel to the Knifley Sandstone and shows an off-lapping relationship with the underlying Borden Formation (Klein, 1974; Kepferle and Lewis, 1975; Sedimentation Seminar, 1972; Lewis and Potter, 1978). The Cane Valley Limestone has been interpreted to be a slope or platform-edge shoal bank deposit into which fossil debris on the deltaic platform to the east was transported (Sedimentation Seminar, 1972).

Argillaceous, silty, calcareous-to-dolomitic, bioturbated carbonates of the Fort Payne Formation and Muldraugh Member of the Borden occur widely in the Appalachian and Illinois basins between the biohermal facies and the Knifley Sandstone. In fact, carbonate-rich facies between the Knifley Sandstone and the Cane Valley Limestone, as well as above the Cane Valley Limestone up to the Warsaw-Salem Limestone contact, suggest continued sedimentation with a dominance of carbonate mud prograding basinward with increased water depths (Sedimentation Seminar, 1972; Klein, 1974; Lewis and Potter, 1978; Sable and Dever, 1990).

Although the Borden and Fort Payne formations both overlie the Chattanooga Shale, much of the Borden was deposited as westerly prograding prodelta silts, prior to the deposition of the Fort Payne. On the basis of diverse lithology, lateral variability, and the thickness changes of different facies in the Fort Payne, the depositional environment has been interpreted to be a marine, oxic to dysoxic southwestward-dipping ramp in front of the Borden delta front, consisting of the varied facies described in the previous paragraphs. In south-central Kentucky, the Fort Payne Formation varies between 225–300 feet (70–90 m) in thickness (Lewis and Potter, 1978).

### 5.2.6 Maccrady Formation

The Maccrady Formation was named by Stose (1913) for a thin section of red shale and limestone exposed near the town of Maccrady in southwest Virginia. The unit is described as is a fining-upward sequence of red and green clay shales, mudstones, and siltstones with local sandstones, argillaceous micrites, argillaceous dolostones, gypsum, anhydrites, coals, and gray shales. In the type area, the Maccrady Formation contains marine facies with evaporites (Dennison and Wheeler, 1975), and at Caldwell, West Virginia, the Maccrady Formation is more than 220 ft (67 m) thick. It consists of non-marine, crumbly, red mudstones with channel-fill and crevasse-splay sandstones and siltstones and a bedded limestone of apparent non-marine origin near the top (Bjerstedt and Kammer, 1988). In southwest Virginia, marine limestones in the Maccrady contain fossils that indicate an early Meramecian age (Butts, 1940). The Maccrady is interbedded with, and replaced by, the Fort Payne Chert to the southwest along Newman Ridge in northeast Tennessee (Hasson, 1986).

Evaporites in the Maccrady Formation have been documented in the Plasterco-Saltville-Locust Cove, Virginia, area, but gypsum and anhydrite have also been recognized as far south as Brumley Gap, Washington County, Virginia (Bartlett, 1974); as far west as Russell and Tazewell counties, Virginia (Cooper, 1961); and as far north as southern West Virginia (Heller, 1980). Solution breccias in the Maccrady Formation, in Tazewell County, Virginia, have been noted by Warne (1990), and are considered to have formed by telogenetic solution of evaporites.

Iron-rich shales, siltstones, and sandstones occur locally in the Maccrady Formation in southwestern Virginia (Warne, 1990), Newman Ridge, Tennessee (Hasson, 1972;

Kuczynski and Hicks, 1978), and along Pine Mountain in eastern Kentucky (Wilpolt and Marden, 1959; Howell and Mason, 1998). Along Pine Mountain in eastern Kentucky and at Little Stone Gap and Pennington Gap, southwestern Virginia, the uppermost 0.5-2.0 feet (0.15-0.6 m) of the Maccrady Formation are composed of distinctive light greenish-gray, light olive-gray to pale-red, dusky-red streaked, chloritic (identified in thin-section), very fine-grained sandstones, siltstones, and silty mudstones.  This unit is well-indurated and commonly has undulatory, discontinuous chert laminae or nodules, which are hematitic in places. This is considered to be the same bed as that at the top of the Fort Payne Formation at Cumberland Gap, Virginia, and in northeastern Tennessee (Warne, 1990).  It may also be equivalent to the Floyds Knob observed at the top of the Grainger Formation at Jellico Mountain, Cumberland Gap, and Pound Gap. In fact, Wilpolt and Marden (1959) have equated the upper red parts of the Grainger with the Maccrady farther to the east.

# CHAPTER 6: CHARACTERIZATION

## 6.1 Stratigraphy and Correlation of Units Containing the Floyds Knob Interval

In the study area of Kentucky and adjacent states, 39 outcrops and one core containing the Floyds Knob Bed were measured and described (total 40). The measured section locations are shown in Figure 6.1, and the section descriptions are shown in Appendix 1 with assigned outcrop identifiers and a section legend. Outcrop identifiers are also shown in Figure 6.2, and the legend for cross-sections and measured section locations is provided in Figure 6.3. All sections are described, named, and followed by outcrop identifiers in the following text.

All the sections were measured using the Floyds Knob Bed as the datum to show thickness of the units above and below. Special attempts were made to find the Floyds Knob Bed, or its equivalent strata, in all the sections. After compiling results from the measured sections (Figs. 6.1 and 6.2), six cross-sections and one isopach map were made with accompanying thickness profiles to visualize the lateral and vertical extent of the measured units. Two cross-sections were constructed using the Floyds Knob Bed as the datum in south-central Kentucky, and one cross-section was constructed from northeastern to east-central Kentucky using the base of the Renfro Member as the datum. Three cross-sections were constructed using the top of the upper Devonian Chattanooga Shale as the datum. Different data horizons were used to help to visualize potential vertical variation of the Floyds Knob Bed across the Borden Front in the western Appalachian and eastern Illinois basins.

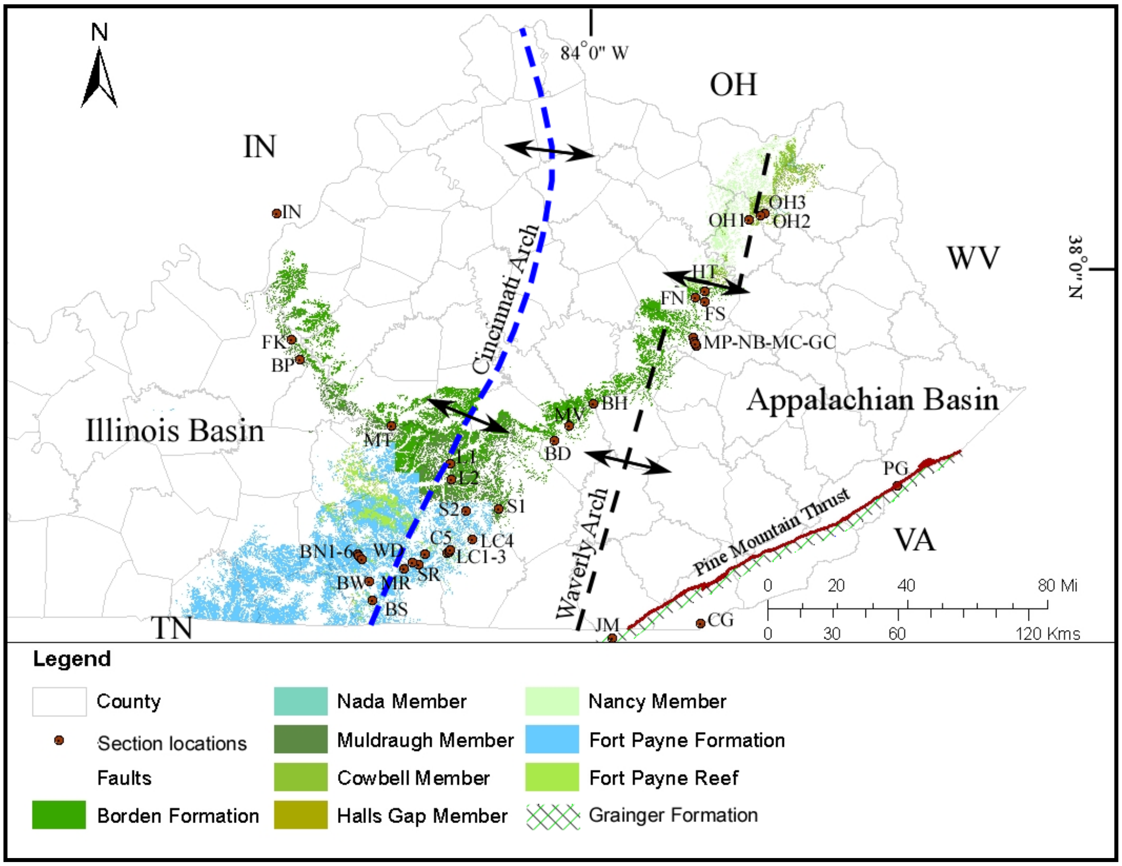



Figure 6.1 – Geologic map of the study area, showing the distribution of Borden Formation members, as well as of the Grainger and Fort Payne formations, and the location of studied sections in Kentucky and adjacent states.

| Section no | Section name | ID | Coordinates | County | Quadrangle |
|---|---|---|---|---|---|
| 1 | I-64, Stop1 | OH1 | 83°22'31.62"W, 38°16'34.2"N | Rowan | Cranston |
| 2 | I-64, Stop2 | OH2 | 83°18'59.28"W, 38°17'32.76"N | Carter | Soldier |
| 3 | I-64, Stop3 | OH3 | 83°17'40.02"W, 38°18'6"N | Carter | Soldier |
| 4 | Mountain Parkway | MP | 83°41'1.32"W; 37°47'34.98"N | Powell | Slade |
| 5 | KY-11S Natural Bridge | NB | 83°40'37.92"W, 37°46'35.22"N | Powell | Slade |
| 6 | KY-11S Lake, Mill Creek Lake | MC | 83°40'22.14"W, 37°45'58.44"N | Wolfe | Slade |
| 7 | KY-11S Glen Caren Fault | GC | 83°40'11.7"W, 37°45'32.34"N | Wolfe | Slade |
| 8 | HillTop Church, KY-36 | HT | 83°37'14.4"W, 37°59'10.74"N | Menifee | Scranton |
| 9 | US-460 N Frenchburg | FN | 83°40'17.34"W, 37°57'35.1"N | Menifee | Frenchburg |
| 10 | US-460 S Frenchburg | FS | 83°37'11.52"W, 37°56'33.18"N | Menifee | Scranton |
| 11 | Bighill, Bighill Road | BH | 84°12'40.98"W; 37°31'43.98"N | Madison | Bighill |
| 12 | I-75S Mt. Vernon | MV | 84°20'30.72"W, 37°26'9.54"N | Rockcastle | Wildie |
| 13 | US 150/KY 70 Broadhead | BD | 84°24'59.28"W, 37°22'42.06"N | Rockcastle | Brodhead |
| 14 | Indiana Floyds Knob type section | IN | 85°54'1.38"W, 38°17'12.9"N | Floyd (Indiana) | |
| 15 | Fort Knox; KY-313 | FK | 85°47'4.2"W, 37°48'9.3"N | Hardin | Colesburg |
| 16 | BlueGrass Pkway | BP | 85°44'18.54"W, 37°43'16.32"N | Hardin | Nelsonville |
| 17 | Muldraugh type section (KY-208) | MT | 85°15'49.8"W, 37°26'38.58"N | Marion | Spurlington |
| 18 | US-127 South Liberty | L1 | 84°57'31.38"W, 37°17'8.4"N | Casey | Liberty |
| 19 | US-127S South Liberty section 2 | L2 | 84°57'25.62"W, 37°13'11.04"N | Casey | Phil |
| 20 | Cumberland Parkway, Somerset section-1 | S1 | 84°42'33.48"W, 37°5'45.12"N | Pulaski | Delmer |
| 21 | Cumberland Parkway, Somerset section-2 | S2 | 84°52'59.34"W, 37°5'22.26"N | Pulaski | Eli |
| 22 | Lake Cumberland, Stop 1 | LC1 | 84°58'43.8"W, 36°55'3.36"N | Russell | Jabez |
| 23 | Lake Cumberland, Stop 2 | LC2 | 84°58'2.28"W, 36°55'18.36"N | Russell | Jabez |
| 24 | Lake Cumberland,Stop 3 | LC3 | 84°57'44.52"W, 36°55'48.66"N | Russell | Jabez |
| 25 | Lake Cumberland, Floyds Knob Section, Stop 4 | LC4 | 84°51'4.08"W, 36°58'21.06"N | Wayne | Mill Springs |
| 26 | Wolf Creek Dam section | WD | 85°7'44.7"W, 36°52'9.36"N | Russell | Cumberland City |
| 27 | South Lake Cumberland; Swanpond Road | SR | 85°9'43.74"W, 36°52'34.44"N | Russell | Wolf Creek Dam |
| 28 | Mantown Road (Mudmound) | MR | 85°12'15.78"W, 36°51'11.16"N | Clinton | Wolf Creek Dam |
| 29 | KY-61N Section 1 | BN1 | 85°25'22.38"W, 36°53'24.36"N | Cumberland | Breeding |
| 30 | KY-61N Section 2 | BN2 | 85°25'41.88"W, 36°53'47.82"N | Cumberland | Breeding |
| 31 | KY-61N Section 3 | BN3 | 85°25'46.74"W, 36°54'0.6"N | Cumberland | Breeding |
| 32 | KY-61N Section 4 | BN4 | 85°25'54.36"W, 36°54'7.02"N | Cumberland | Breeding |
| 33 | KY-61N Section 5 | BN5 | 85°26'16.14"W, 36°54'17.46"N | Cumberland | Breeding |
| 34 | KY-61S | BS | 85°21'59.94"W, 36°43'14.7"N | Cumberland | Frogue |
| 35 | KY-90W Burkesville | BW | 85°22'55.86"W, 36°47'59.04"N | Cumberland | Waterview |
| 36 | KY-61N; Fort Payne Siltstone | BN6 | 85°26'36.3"W, 36°54'53.76"N | Cumberland | Breeding |
| 37 | Core C-505 | C5 | 85°5'48.919"W, 36°54'52.088"N | Russell | Jamestown |
| 38 | Pound Gap | PG | 82°38'37.73"W, 37°9'25.1"N | Letcher | |
| 39 | Cumberland Gap Tunnel | CG | 83°40'36.96"W, 36°36'21.01"N | Claiborne (VA) | |
| 40 | Jellico Mountain TN | JM | 84°8'9.96"W, 36°33'12.25"N | Campbell (TN) | |

Figure 6.2 – Chart showing section locations with outcrop identifiers in Kentucky and adjacent states.

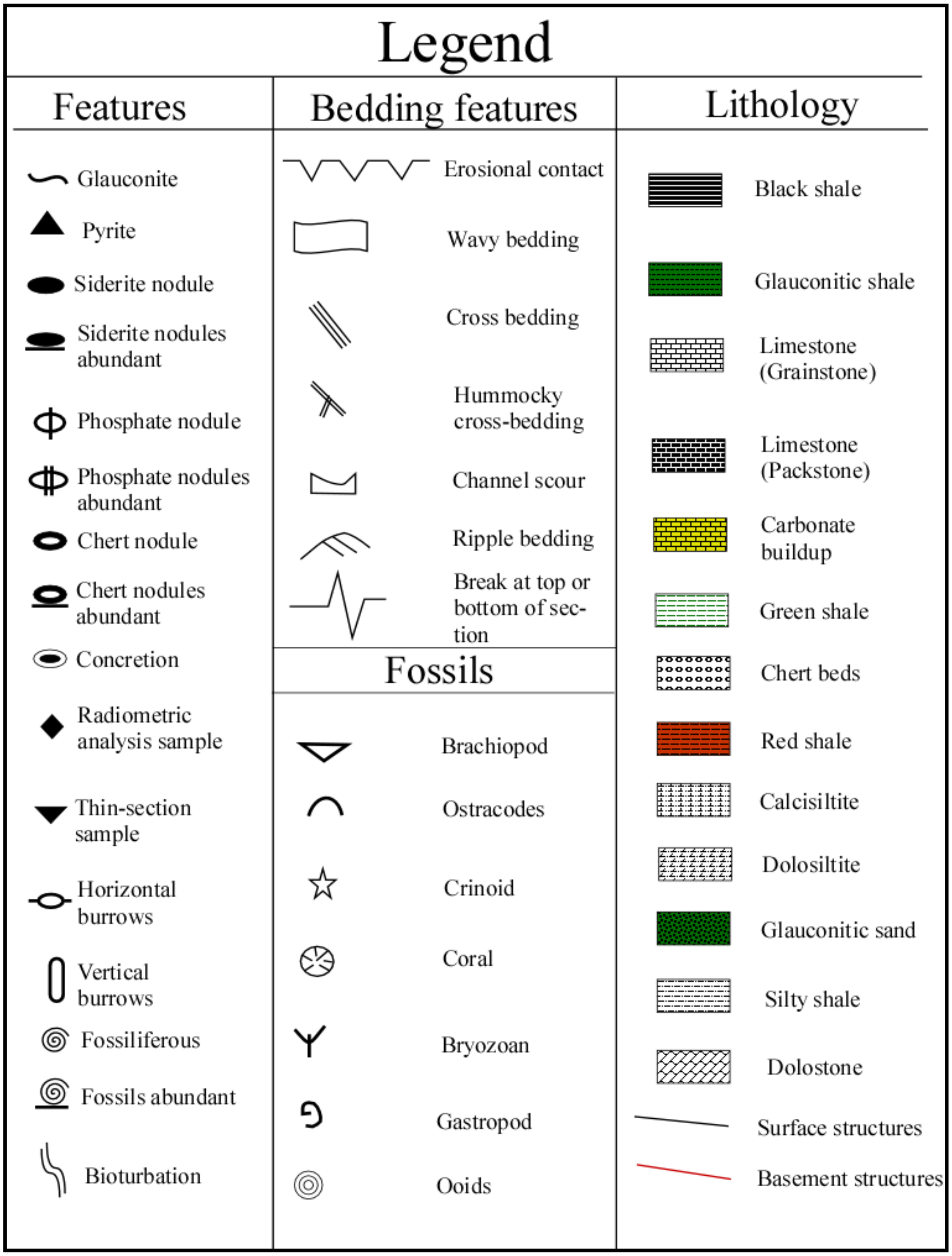
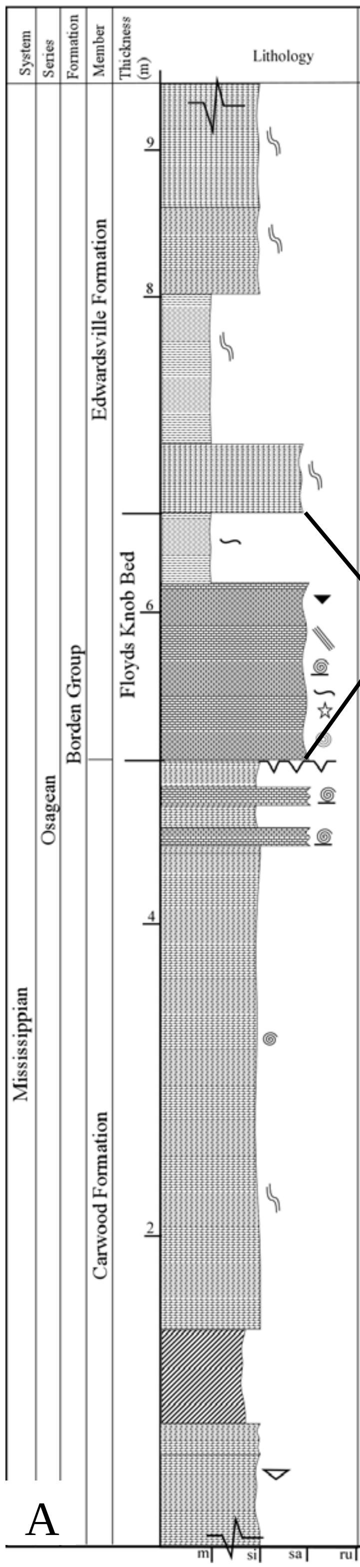



Figure 6.3 – Chart showing legend symbols to be used for identifying different features in measured sections and cross-sections in the following figures of this section.

Glauconite precipitation occurs in suboxic, iron-rich environments where there is low sediment input. The fact that the Floyds Knob interval glauconite is widespread means that similar conditions must have been laterally continuous throughout the western Appalachian and eastern Illinois basins at the end of the loading-type relaxation phase of the Neoacadian tectophase during a global sea-level lowstand (Figs. 3.3 and 4.5), and that the interval is largely synchronous throughout. Therefore, parts of units containing the Floyds Knob Bed and associated glauconite-horizons, green shales, and siltstones (Floyds Knob interval), must be largely equivalent. Hence, in the following sections, parts of every unit containing the Floyds Knob Bed will be described.

### 6.1.1 Floyds Knob Bed/Interval

The widespread, upper Osagean Floyds Knob Bed was first described as the Floyds Knob Formation by Stockdale (1931, 1939) for the fossiliferous, glauconitic limestones and siltstones exposed near the Floyds Knob Post Office, Floyd County, Indiana (Fig. 6.4). The Floyds Knob Bed was described by Stockdale (1939) as an important 'marker' horizon in the Appalachian and Illinois basins that has been subsequently used for tracing related facies, both above and below, and in establishing correlations across the region. Whitehead (1978) formally designated the unit as the Floyds Knob Bed of the Borden Formation after Weir et al. (1966), suggested that the Floyds Knob Formation of Stockdale (1939) is too thin and too discontinuous to be considered a formation rather than a bed. Also, the unit is not distinctive everywhere and could be easily confused with other glauconite horizons that commonly occur in the upper part of the Borden Formation. However, for this study, the Floyds Knob Bed of



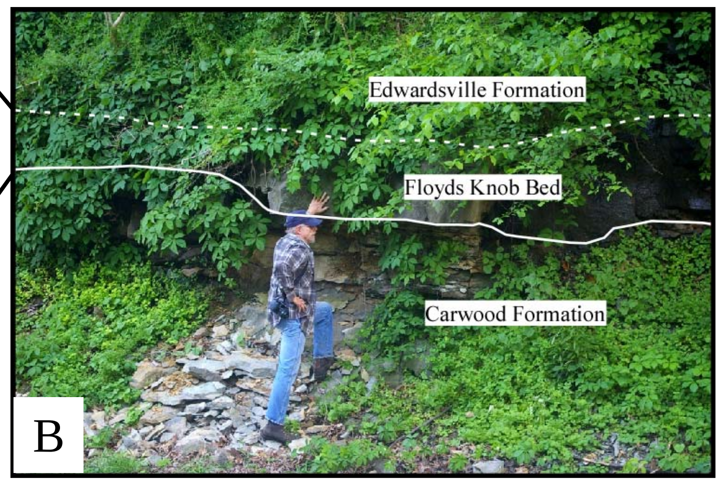




Figure 6.4 – A) Measured stratigraphic section at the Floyds Knob type (IN) section, Indiana. B) Field photograph of the location.

Weir et al. (1966) and Whitehead (1978) and the associated glauconite horizons, green shales, and pelletal glauconite-rich siltstones will be grouped together as the Floyds Knob interval.

The Floyds Knob interval is a glauconitic, phosphatic rich-interval that occurs throughout the study area (Fig. 6.5). In the east-central and northeastern parts of Kentucky, the Floyds Knob interval is associated with the Wildie and Nada members of the Borden Formation. In this part of Kentucky, the Floyds Knob interval is composed of three to four pelletal glauconite horizons, green shales, and siltstones as in the Wildie and Nada members within 10–15 m thick strata (Figs. 6.5 and 6.6).

In the eastern parts of south-central Kentucky in Pulaski and Casey counties, the Floyds Knob interval is comprised of four pelletal glauconite horizons within 15 m thick strata. One occurs at the base of the Muldraugh Member, and is composed of pelletal glauconite grains embedded in dolomitic matrix. Two more prominent glauconite horizons associated with the Floyds Knob Bed occur at the top of the underlying Halls Gap Member (Fig. 6.5), and another horizon occurs within the Muldraugh Member in Casey County, south of Liberty along the US-127 (L1) section. In Wayne County in south-central Kentucky at the Lake Cumberland (LC4) section, the Floyds Knob interval is represented by a single prominent horizon (0.4 m) embedded in dolomitic matrix that sits at the contact between the underlying shales of the Nancy Member of the Borden Formation and the overlying carbonates of the Fort Payne Formation (Fig. 6.5).

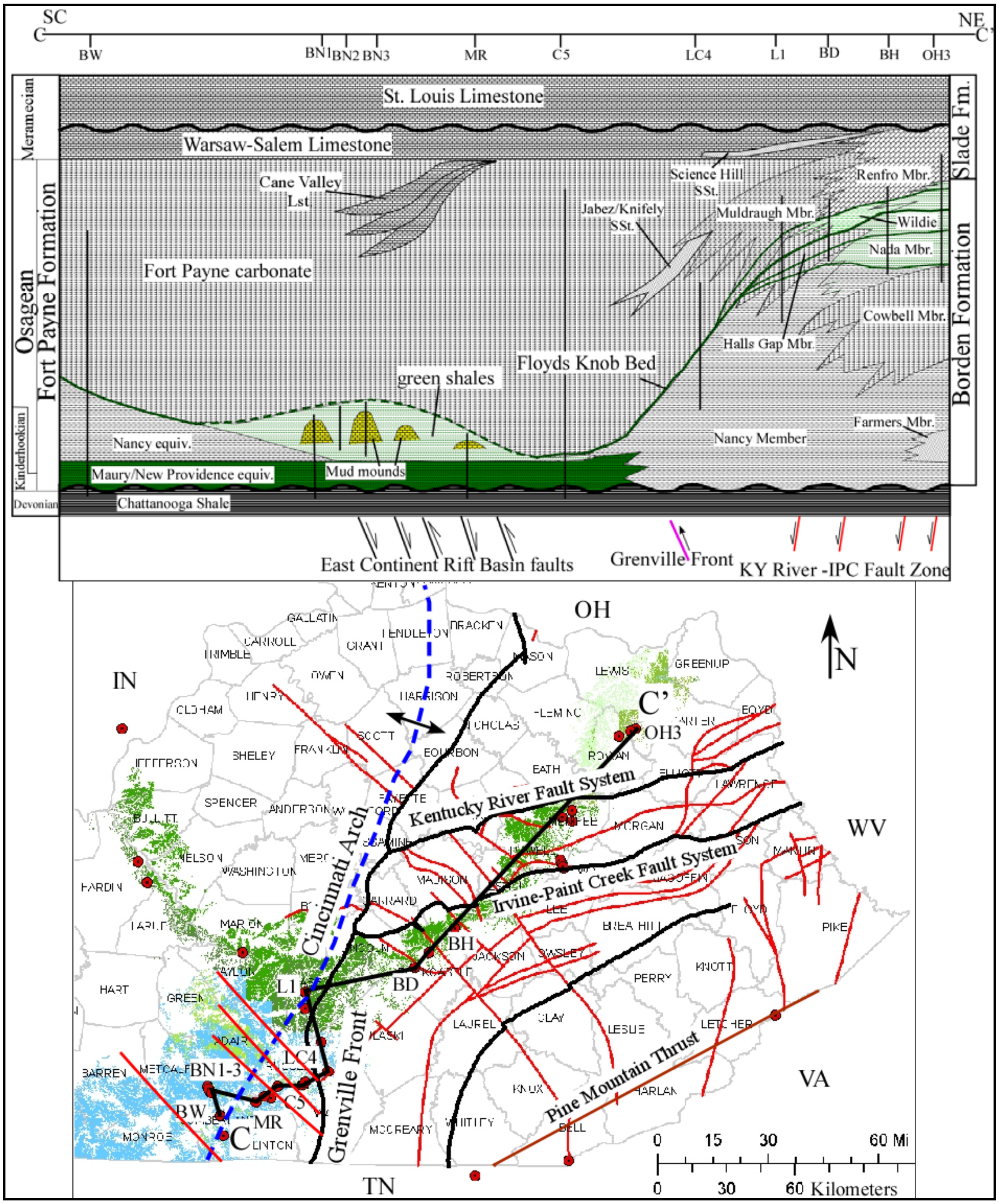



Figure 6.5 – Cross-section C-C' from northeastern to south-central Kentucky through east-central Kentucky, showing the distribution of different units associated with the Floyds Knob Bed/interval in the western Appalachian and eastern Illinois basins. Datum is the top of the Upper Devonian Chattanooga Shale. Index map included below. Data from geological quadrangle maps were used, where study locations are absent. Not to scale.

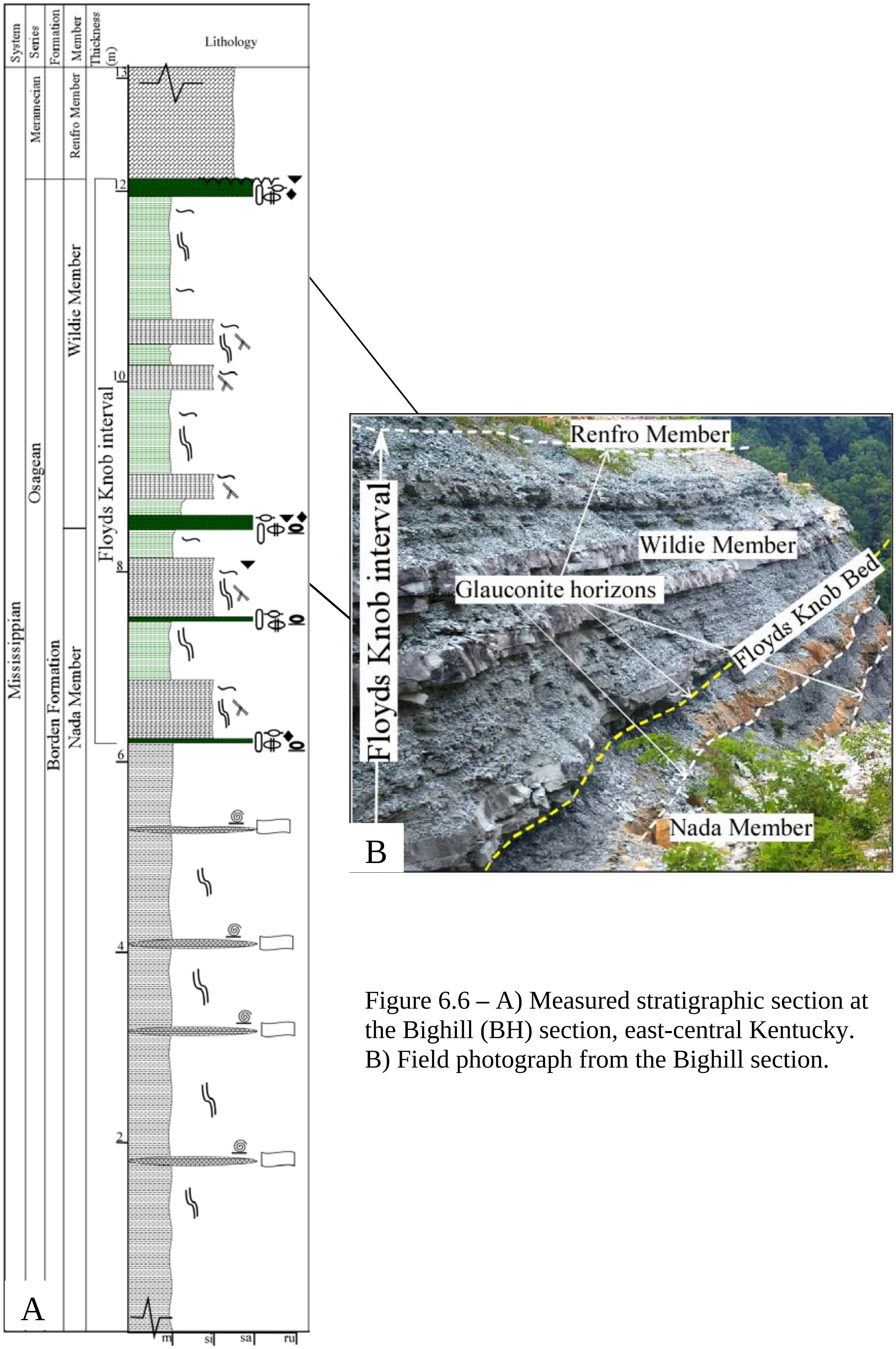
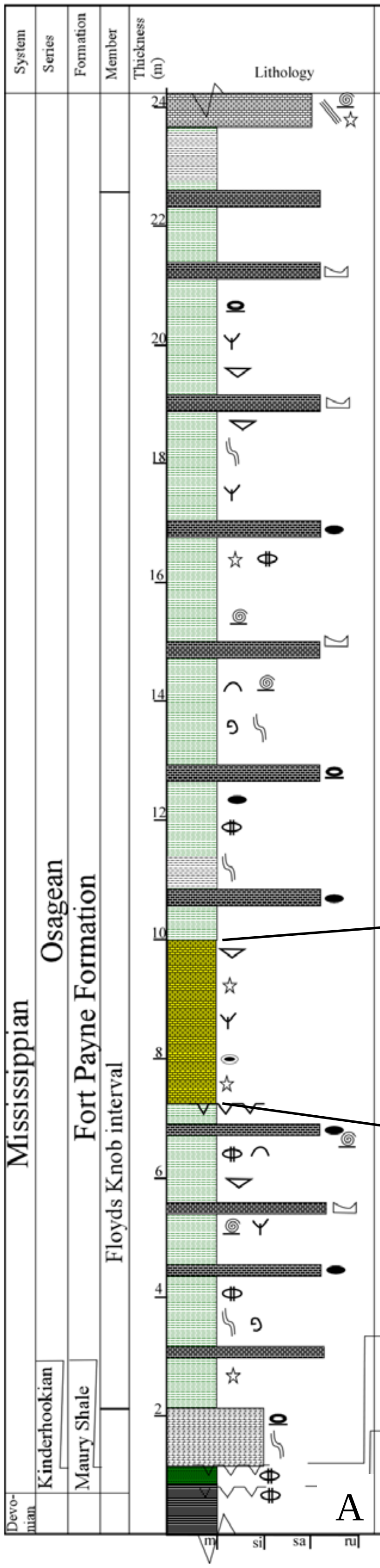



Figure 6.6 – A) Measured stratigraphic section at the Bighill (BH) section, east-central Kentucky. B) Field photograph from the Bighill section.

In south-central Kentucky, however, at the three Lake Cumberland sections (LC1, LC2, and LC3) in Russell County, at the Mantown Road section (MR) in Clinton County, and at three Burkesville north sections (BN1, BN2, and BN3) in Cumberland County, no distinct glauconite horizon has been found. Each of these sections is associated with carbonate-mud mounds that occur at the top of the Maury Shale and/or New Providence equivalent (Figs. 6.5 and 6.7). Instead of pelletal glauconite, however, the Floyds Knob interval at each of these sections comprised of fossiliferous green shales containing limestone lenses that are very similar to those occurring in the Nada and Wildie members in northeastern and east-central Kentucky, respectively.

In southern Indiana, the Floyds Knob interval occurs at the base of the Edwardsville Formation (Fig. 6.8). In Floyd County, southern Indiana, at the Floyds Knob type section (IN), the Floyds Knob interval is represented by a single glauconitic grainstone horizon (1.5 m) that occurs at the contact between the overlying Edwardsville and underlying Carwood formations of the Borden Group (Fig. 6.4). In Hardin County, at the Fort Knox (FK) and Bluegrass Parkway (BP) sections, the Floyds Knob interval occurs within the Muldraugh Member at the contact between the overlying Muldraugh and underlying Nancy members (Figs. 6.9 and 6.10). At the Fort Knox (FK) section, the Floyds Knob interval is represented by a single thick glauconite horizon (1 m) (Fig. 6.9), whereas at the Bluegrass Parkway (BP) section, the Floyds Knob interval (29 m) is represented by three to four pelletal horizons that occur within the Muldraugh Member (Fig. 6.10). At the same section, all of these horizons converge along foresets into a thick Floyds Knob horizon (Fig. 6.10). At the Muldraugh type (MT) section in Marion County



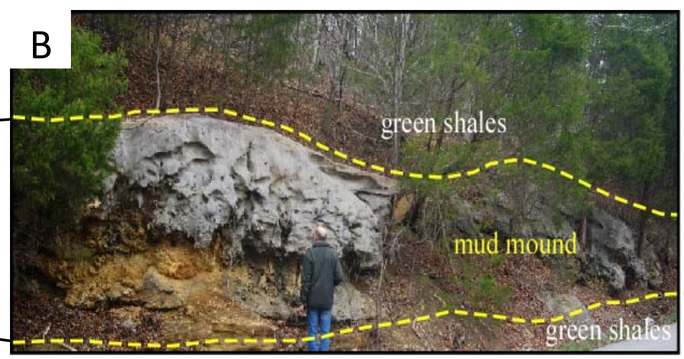
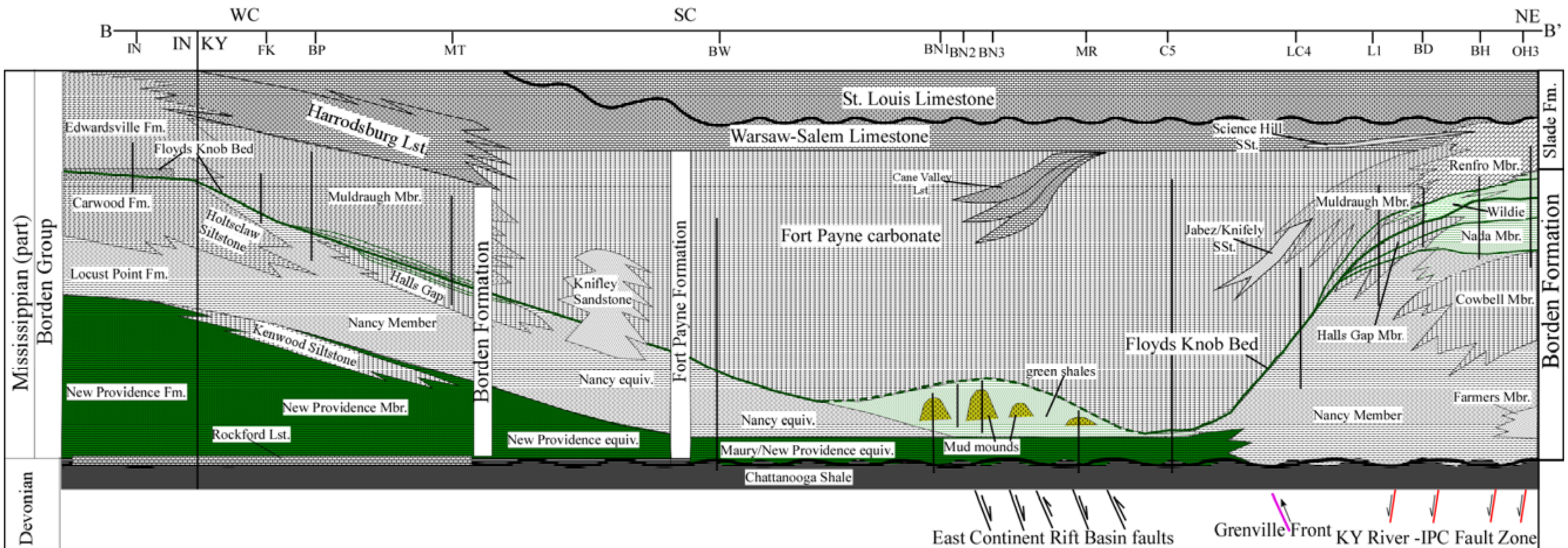



Figure 6.7 – A) Measured stratigraphic section at the Mantown Road (MR) section, Clinton County, south-central Kentucky. B) Field photograph from the Mantown Road section.

along KY Highway208, the Floyds Knob interval (15 m) occurs within the overlying Muldraugh and the underlying Halls Gap members (Fig. 6.11).

In northeastern Tennessee, at the Jellico Mountain (JM) section, the Floyds Knob interval is represented by a single pelletal glauconite horizon (0.35 m) that occurs at the contact between the underlying shales and siltstones of the Grainger Formation and the overlying chertified carbonates of the Fort Payne Formation (Fig. 6.12). At the Pound Gap (PG) and Cumberland Gap (CG) sections in southeastern Kentucky, the Floyds Knob interval is devoid of any glauconite grains, but has been interpreted to be represented by thin green shales and siltstones (1.5–0.5 m) that occur at the contact between the underlying Grainger Formation and the overlying Newman Limestone (Dean and Moshier, 1989) (Fig. 6.12).



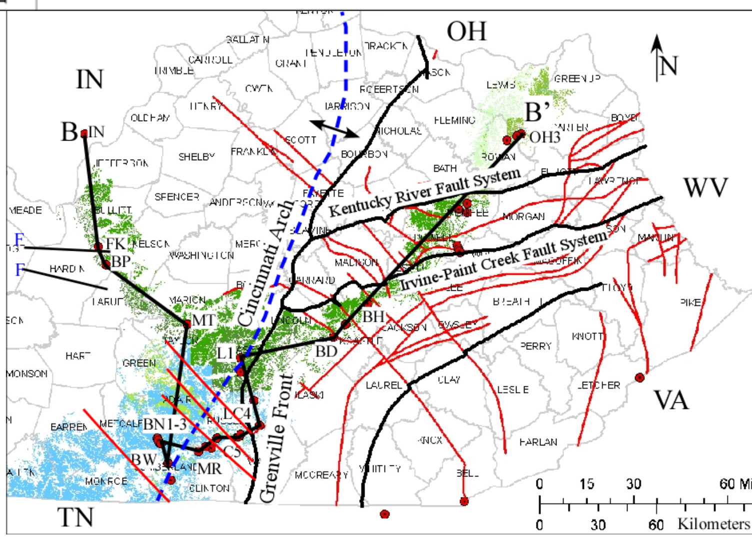




Figure 6.8 – Cross-section B-B' from northeastern Kentucky to southern Indiana through east-central, south-central, and west-central Kentucky, showing the distribution of different units associated with the Floyds Knob Bed/interval in the western Appalachian and eastern Illinois basins. Datum is the top of the Upper Devonian Chattanooga Shale. Index map included at bottom. Data from geological quadrangle maps were used, where study locations are absent. Not to scale.

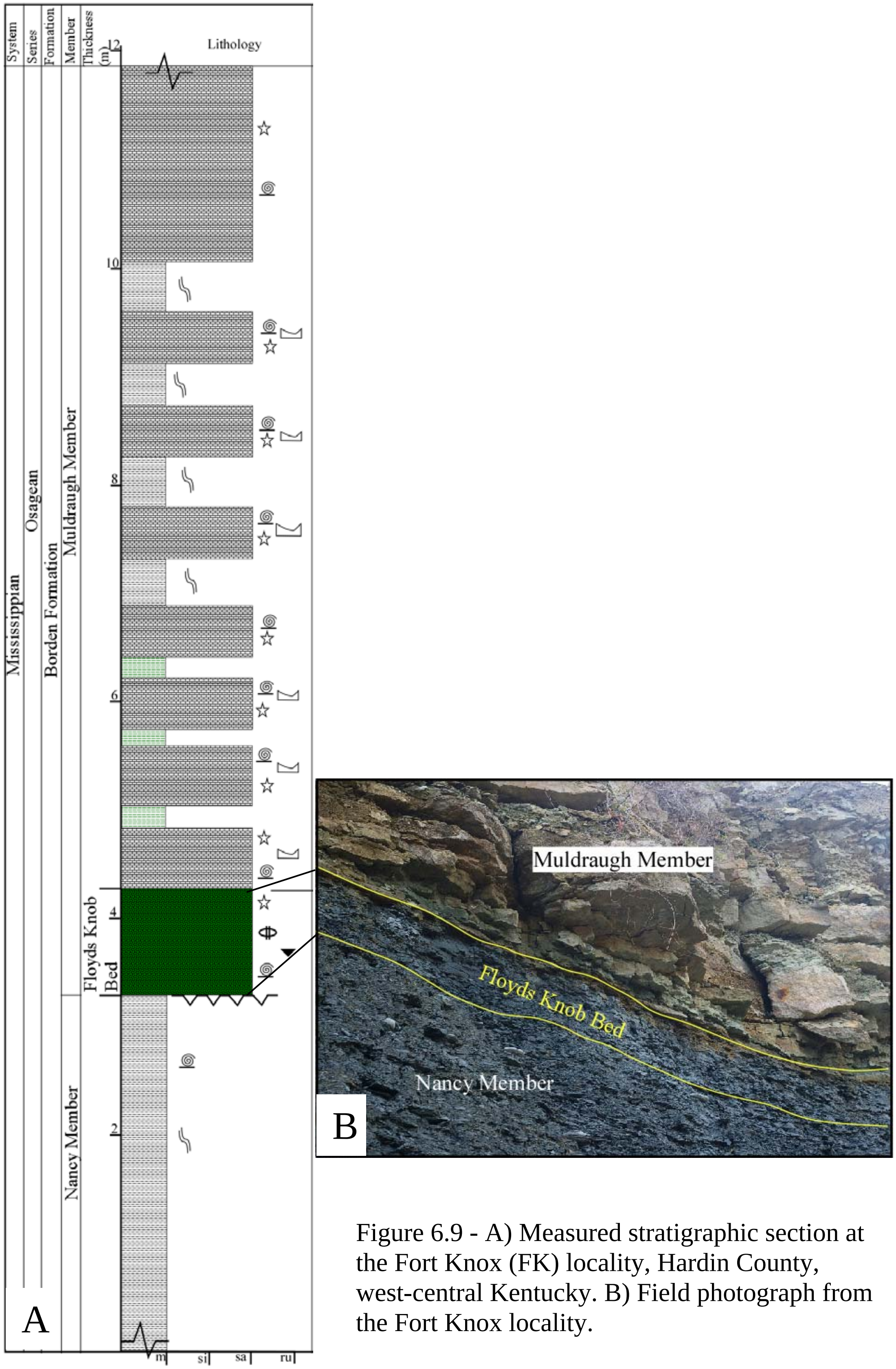
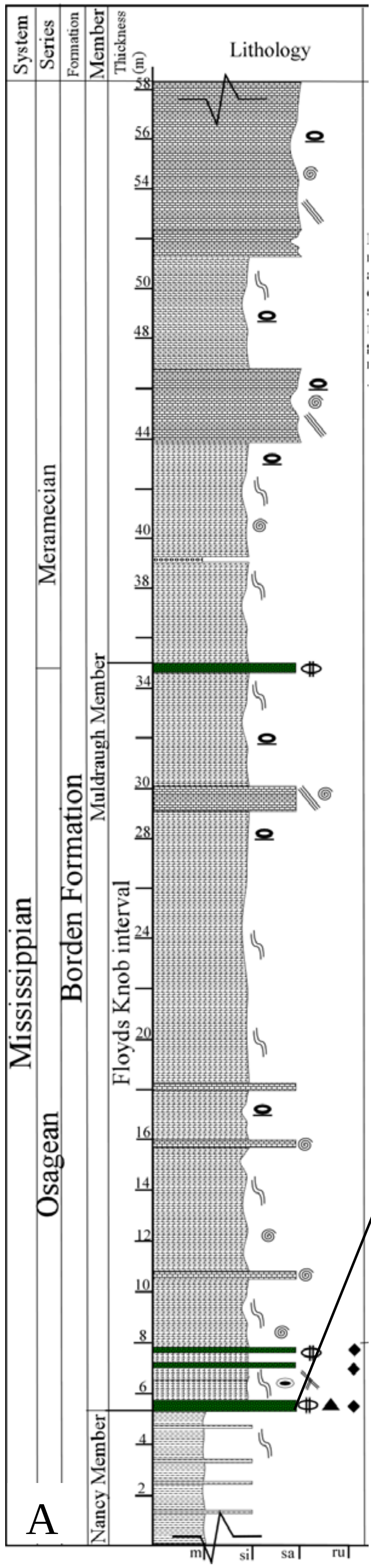



Figure 6.9 - A) Measured stratigraphic section at the Fort Knox (FK) locality, Hardin County, west-central Kentucky. B) Field photograph from the Fort Knox locality.



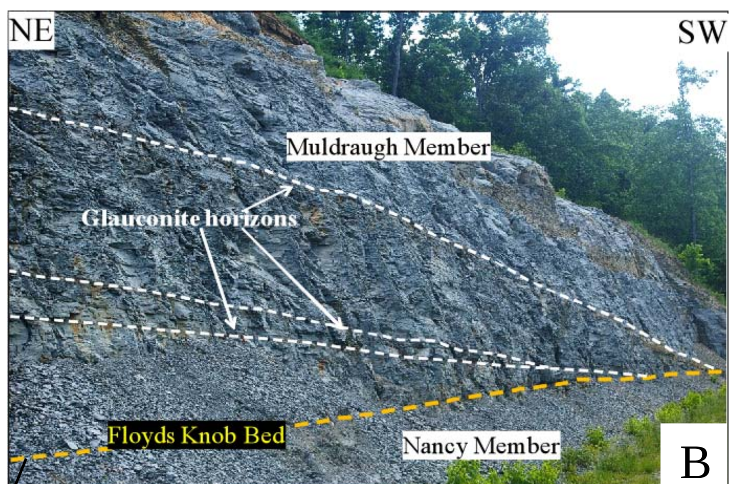




Figure 6.10 - A) Measured stratigraphic section at the Bluegrass Parkway (BP) locality, Hardin County, west-central Kentucky. B) Field photograph from the Bluegrass Parkway locality. Dashed lines represent glauconite horizons that merge to the southwest.

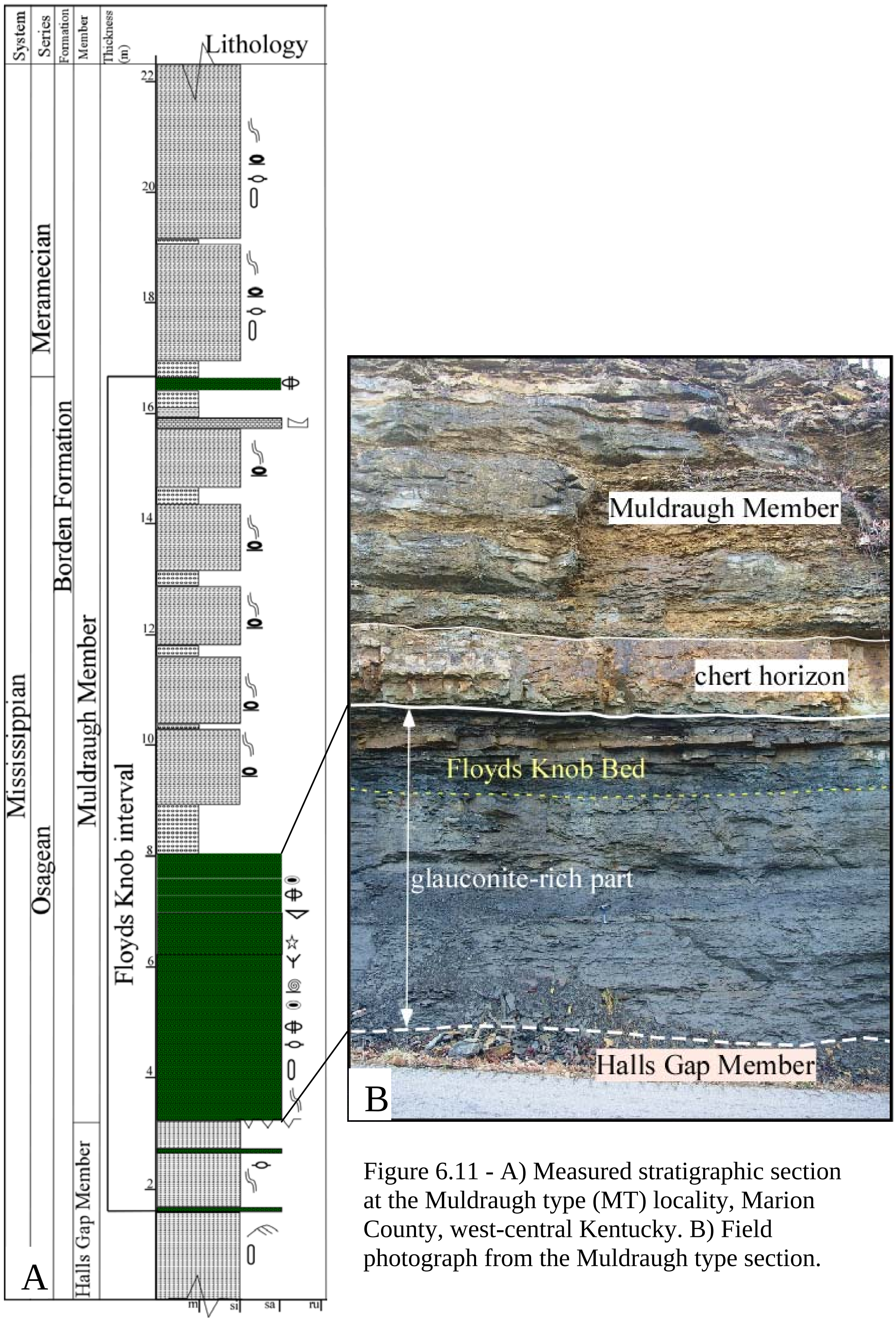



Figure 6.11 - A) Measured stratigraphic section at the Muldraugh type (MT) locality, Marion County, west-central Kentucky. B) Field photograph from the Muldraugh type section.

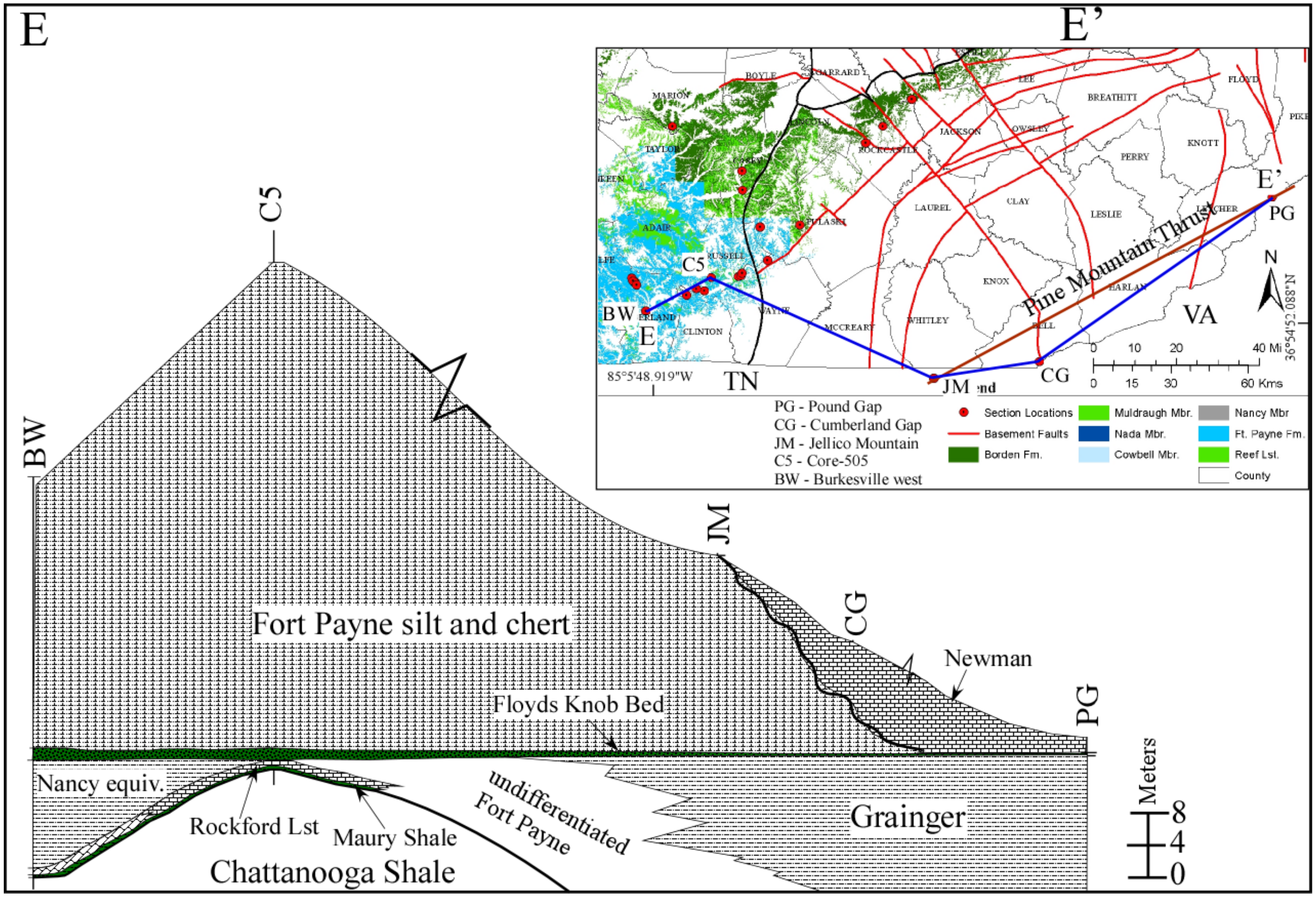



Figure 6.12 – Stratigraphic cross-section E-E’ showing the distribution of the Fort Payne and Grainger formations in Kentucky and adjacent states. Datum is the Floyds Knob Bed/interval. Index map is in the upper right-hand corner.

X-ray diffraction studies of the Floyds Knob interval (pelletal glauconites and associated green shales) from the Nada and Wildie members at the Big Hill section (BH) show that the green shales are composed of fine-grained, clay-size, dispersed glauconite and chloritic-clay-rich verdine facies (Fig. 6.13). Similar studies were done for the green shales associated with the carbonate-mud mounds from the Lake Cumberland region (sections LC1, LC2 and LC3) in south-central Kentucky. The results show that the green shales are composed of very fine-grained, clay-size, dispersed glauconite and chloritic-clay-rich verdine facies (Fig. 6.14).

The Floyds Knob Bed/interval is generally composed of an upper bioturbated, pelletal glauconite and a lower limestone or dolostone bed. In places, only the glauconite is present in Kentucky. Where the carbonate is present, however, it is generally composed of glauconitic and crinoidal mudstones, wackestones, or packstones, which are fossiliferous and locally dolomitic (Stockdale, 1931; Kepferle, 1971; Whitehead, 1978, Sable and Dever, 1990) (Fig. 6.15). In southern Indiana at the type section in Floyd County (IN), the interval is mostly a single glauconitic grainstone facies. In much of west-central and south-central Kentucky, the interval is chiefly composed of pelletal glauconite horizons that occur with phosphates (Fig. 6.15). In south-central Kentucky, in Lake Cumberland region, in Clinton and Cumberland counties, around the well-known carbonate-mud mounds distinctive glauconite horizons are absent. The Floyds Knob interval, however, is indicated by the presence of wackestone-mudstone and green-shale facies (Fig. 6.15). As already indicated, these green shales have a glauconitic component (Fig. 6.14), but any pelletal glauconite is absent.

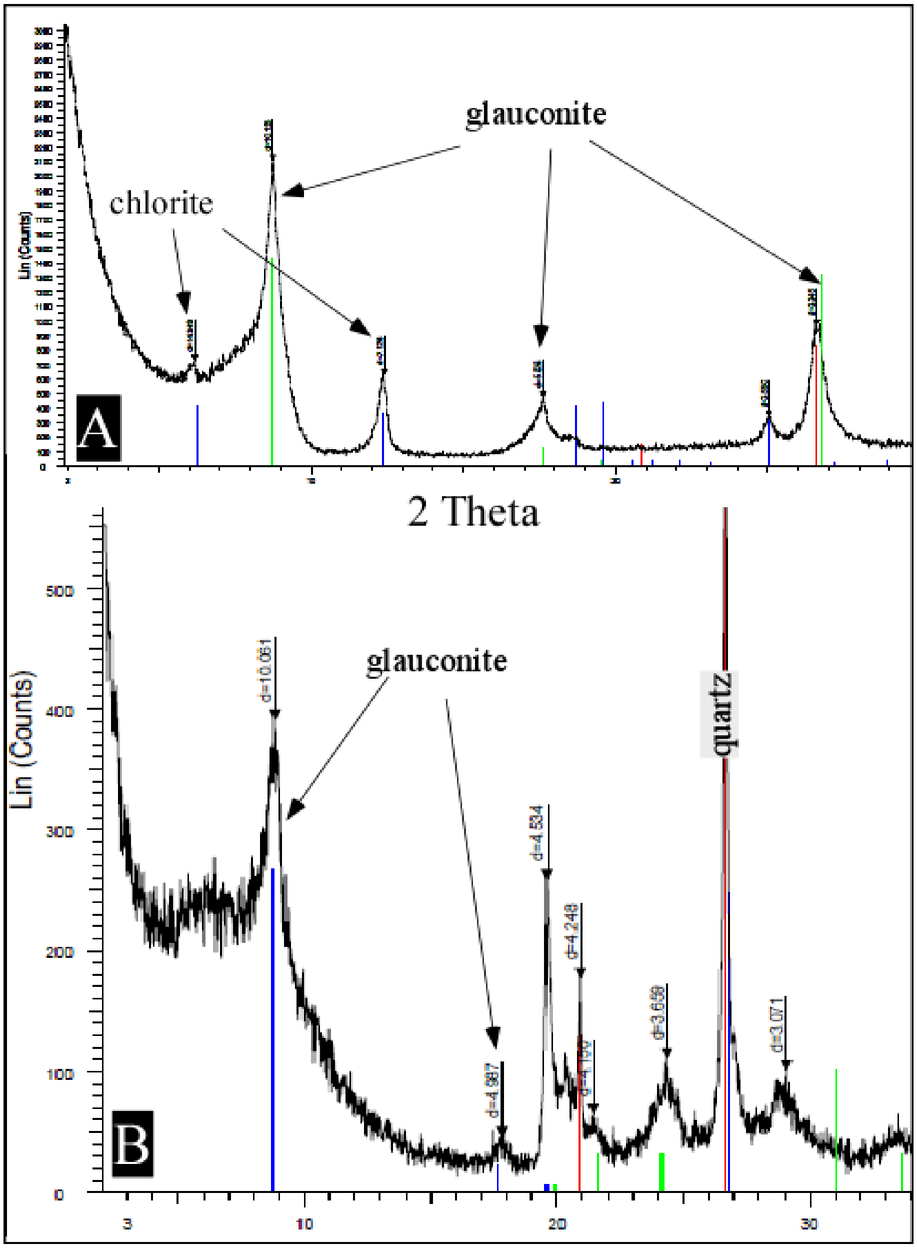



Figure 6.13 – A) X-ray diffractogram of the green shales from the Bighill (BH) exposure. The green shales are chiefly composed of finely disseminated glauconitic and chloritic clay (altered verdine facies). B) X-ray diffractogram of the glauconite grains from the Floyds Knob Bed (granular glauconites) at the Bighill (BH) exposure. The green pelletal grains are chiefly composed of glauconite.

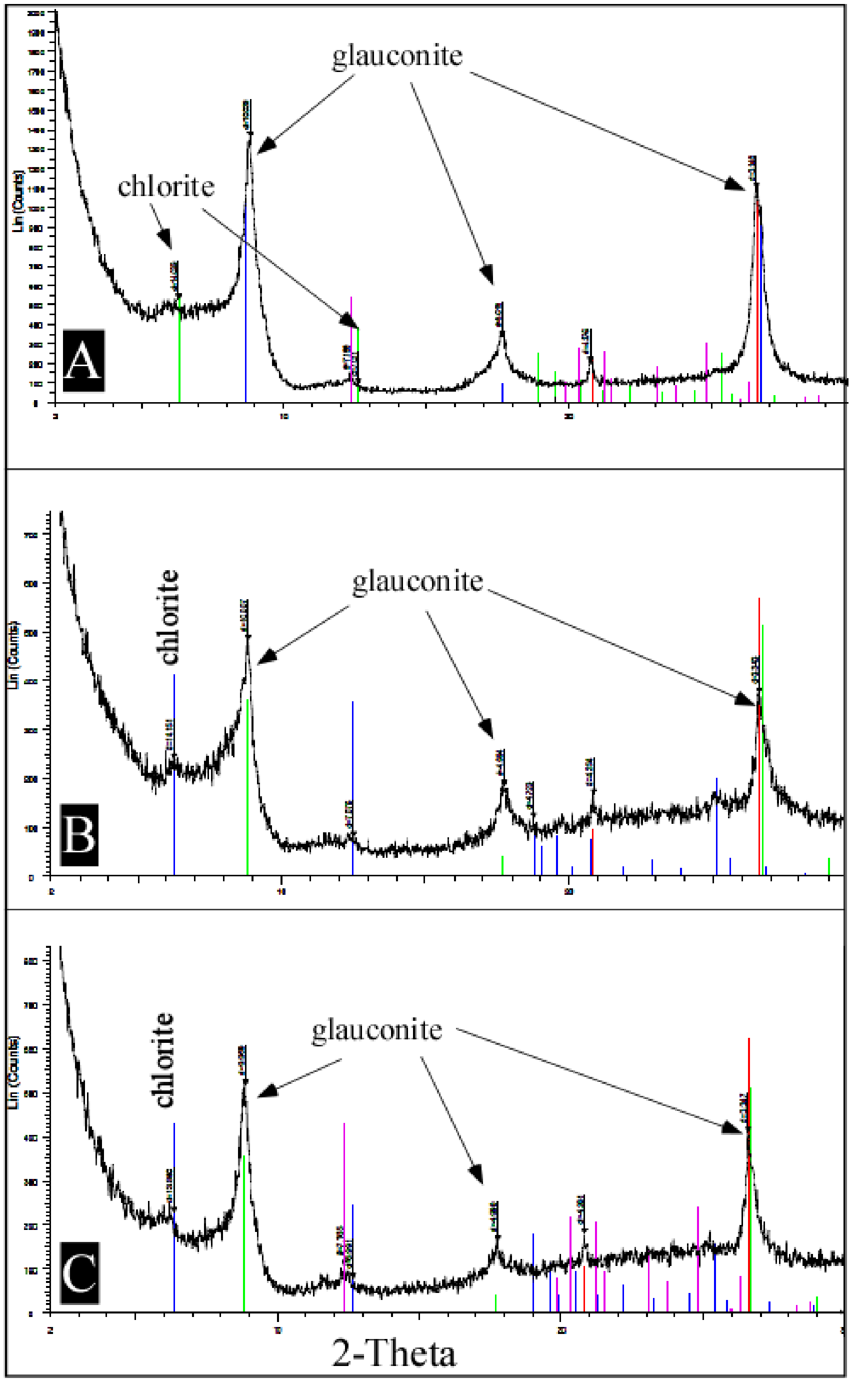



Figure 6.14 – A) X-ray diffractogram of the green shales from below the mud mounds at the Lake Cumberland (LC1) exposure. B) X-ray diffractogram of the green shales from the top of the mud mounds at the Lake Cumberland (LC2) exposure. C) X-ray diffractogram of the green shales from below the mud mounds at the Lake Cumberland (LC3) exposure. The green shales are chiefly composed of finely disseminated glauconitic and chloritic (altered verdine facies) clay.

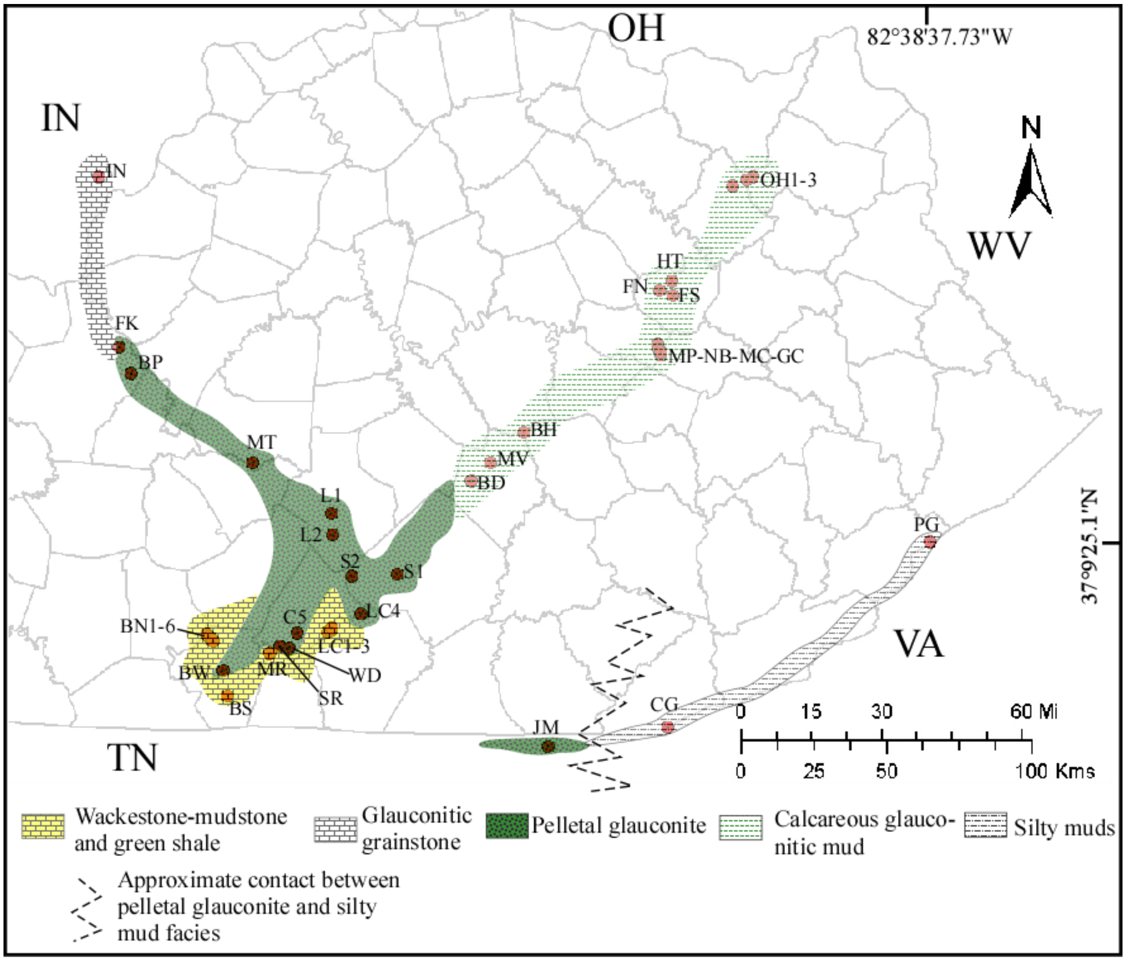



Figure 6.15 – Lithofacies map for the Floyds Knob interval in Kentucky and adjacent states relative to the outcrop belts.

In contrast, in east-central and northeastern Kentucky, the Floyds Knob interval is represented by two to four horizons of glauconite that are present within the green, glauconitic shales and siltstones of the Nada and Wildie members (Figs. 6.5 and 6.6). In as much as the entirety of these units is glauconite, in contrast to bounding units, and individual glauconite horizons merge to the southwest (Fig. 6.8), it seems best to interpret the entirety of the green, calcareous, glauconitic-mud sections (Fig. 6.15) as part of the Floyds Knob interval. In southeastern Kentucky at the Pound Gap (PG) and Cumberland Gap (CG) sections, the Floyds Knob interval is devoid of any glauconite grains, but is represented by a very thin green-shale and siltstone facies (Fig. 6.15) that occur at the contact between the underlying Grainger Formation and overlying Newman Limestone in a section that normally contains dark gray shales and siltstones (Dean and Moshier, 1989). In northeastern Tennessee, at the Jellico Mountain (JM) section, the Floyds Knob interval is represented by a single pelletal glauconite horizon that occurs at the contact between the underlying Grainger Formation and overlying Fort Payne chert (Fig. 6.15).

An isopach map for the Floyds Knob interval is shown in Figure 6.16. It can be seen that there are two sites of major depositional thickening in west-central and northeastern Kentucky. The thickness decreases southeast into south-central Kentucky. In south-central Kentucky, the Floyds Knob interval attains its greatest thicknesses around the mud mounds, but the thickness is irregular because of the presence and absence of the mounds (Fig. 6.16). On the other hand, thicknesses are minimal where the Floyds Knob has been condensed to a single pelletal glauconite horizon in the deepest parts of the Fort Payne starved basin between the mud mounds and Borden delta front to the northeast.

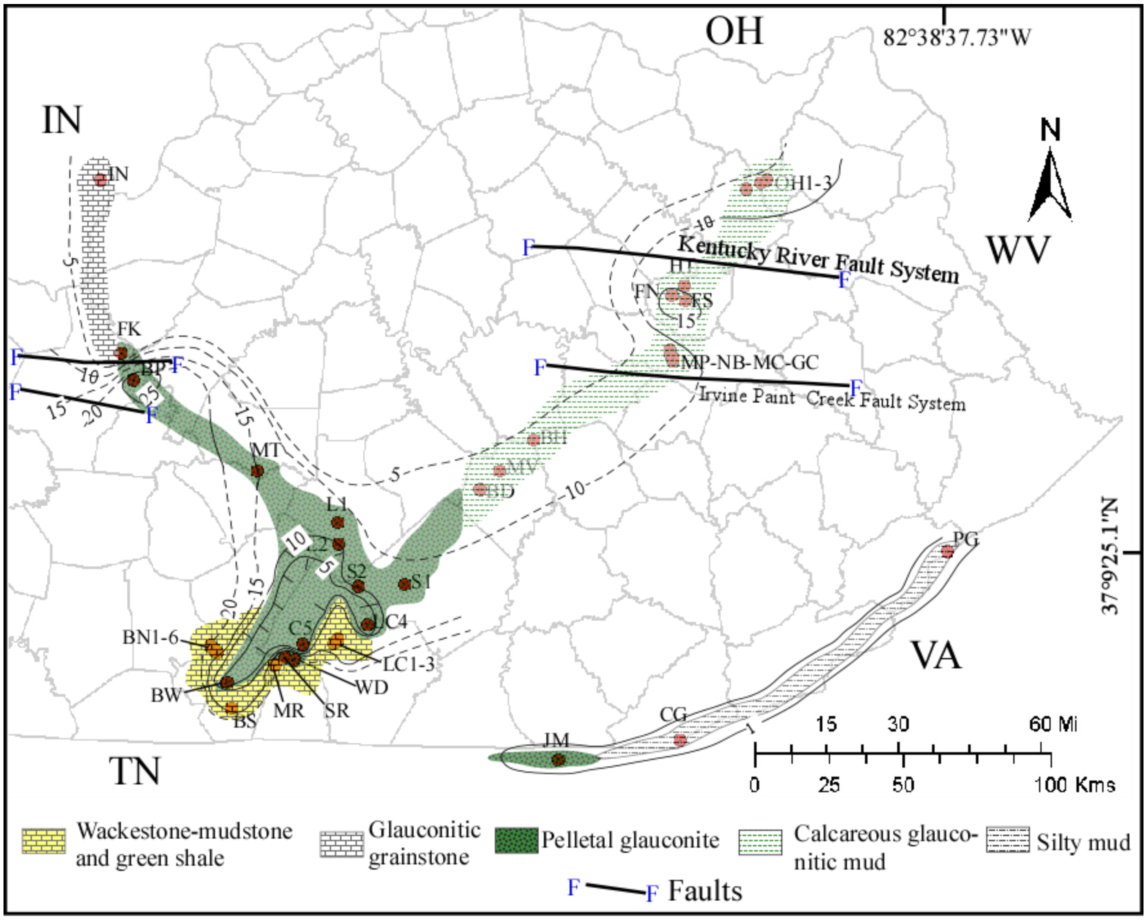



Figure 6.16 - Lithofacies and isopach map for the Floyds Knob interval in Kentucky and adjacent states relative to outcrop belt. Contour interval 5 meters except on the Pine Mountain exposures. Inferred faults were from geological quadrangle maps.

### 6.1.2 Nada Member of the Borden Formation

The distribution of the Nada Member and the equivalent Wildie Member in the study area is shown in Figure 6.17. The southern and western limit of the Nada and Wildie members occurs in Madison and Rockcastle counties in east-central Kentucky at the Big Hill (BH) and Brodhead (BD) sections. The Nada grades downdip (southwestward) into upper parts of the Halls Gap and Nancy members and upward into lower part of the Wildie Member (Fig. 6.18). In the northeastern part of Kentucky, the Nada is present throughout the study area (Fig. 6.17), overlies the Cowbell Member, and grades upward into the Renfro Member north of the Kentucky River fault system near the Waverly Arch at the Olive Hill (OH3) section in Rowan and Carter counties (Fig. 6.18; Appendix 1).

The Nada Member in east-central Kentucky, in general, is a silty to clayey shale, which is laminated to thin-bedded and blue-gray, greenish-blue-gray, and locally dark-reddish-purple in color. The Nada also shows an increase in the amount of silt to the north and east, where silty shale and thin-bedded, shaley siltstone beds become more prominent in outcrop. As silt content increases to the north and east, the thickness of bedding tends to increase as well. The dominant color of the Nada also changes to the north and east as blue-gray siltstones and shales become greener in color. This color change is directly related to an observed increase in amount of glauconite present throughout the Nada within the Floyds Knob interval. In general, the shales observed in measured sections to the north appear to have glauconite dispersed more evenly throughout the section within the Floyds Knob interval. The amount of red mud in the shales also increases to the north, and the red shales may occur within the Floyds Knob

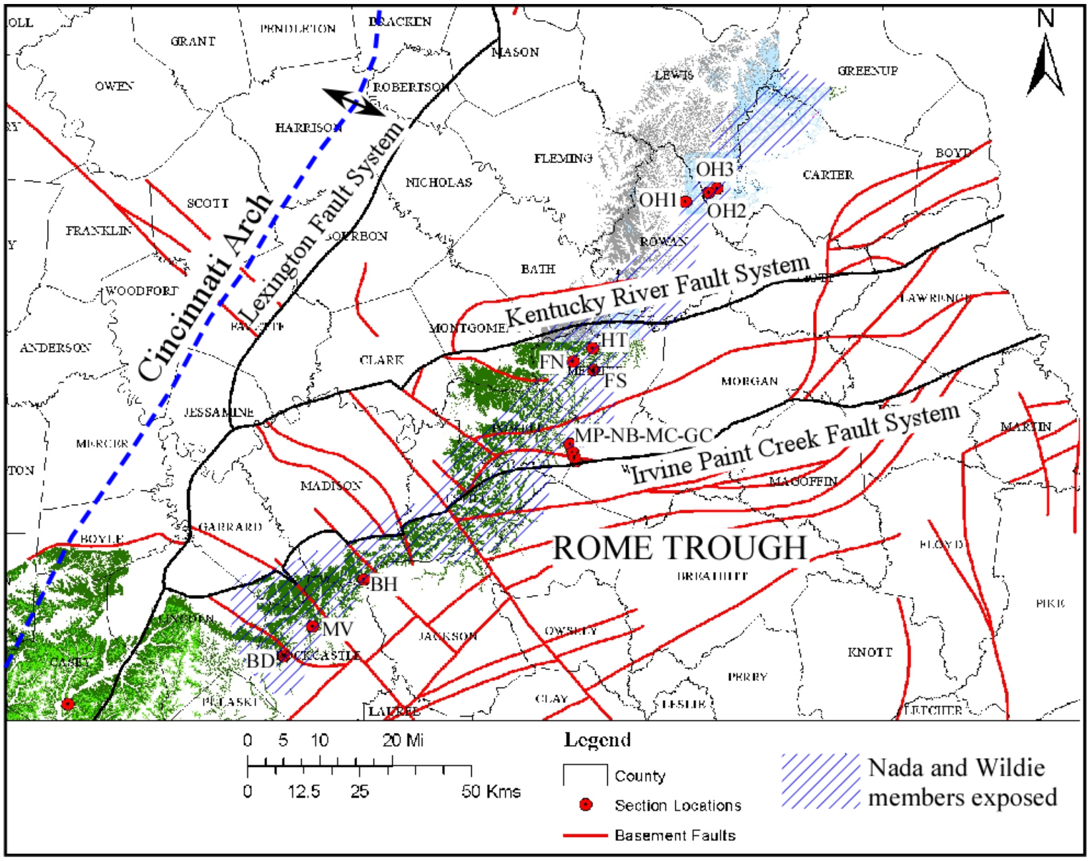



Figure 6.17 – Map showing distribution of the Nada and equivalent Wildie members exposed in northeastern and east-central Kentucky. Blue crosshatching represents the Nada and Wildie members.

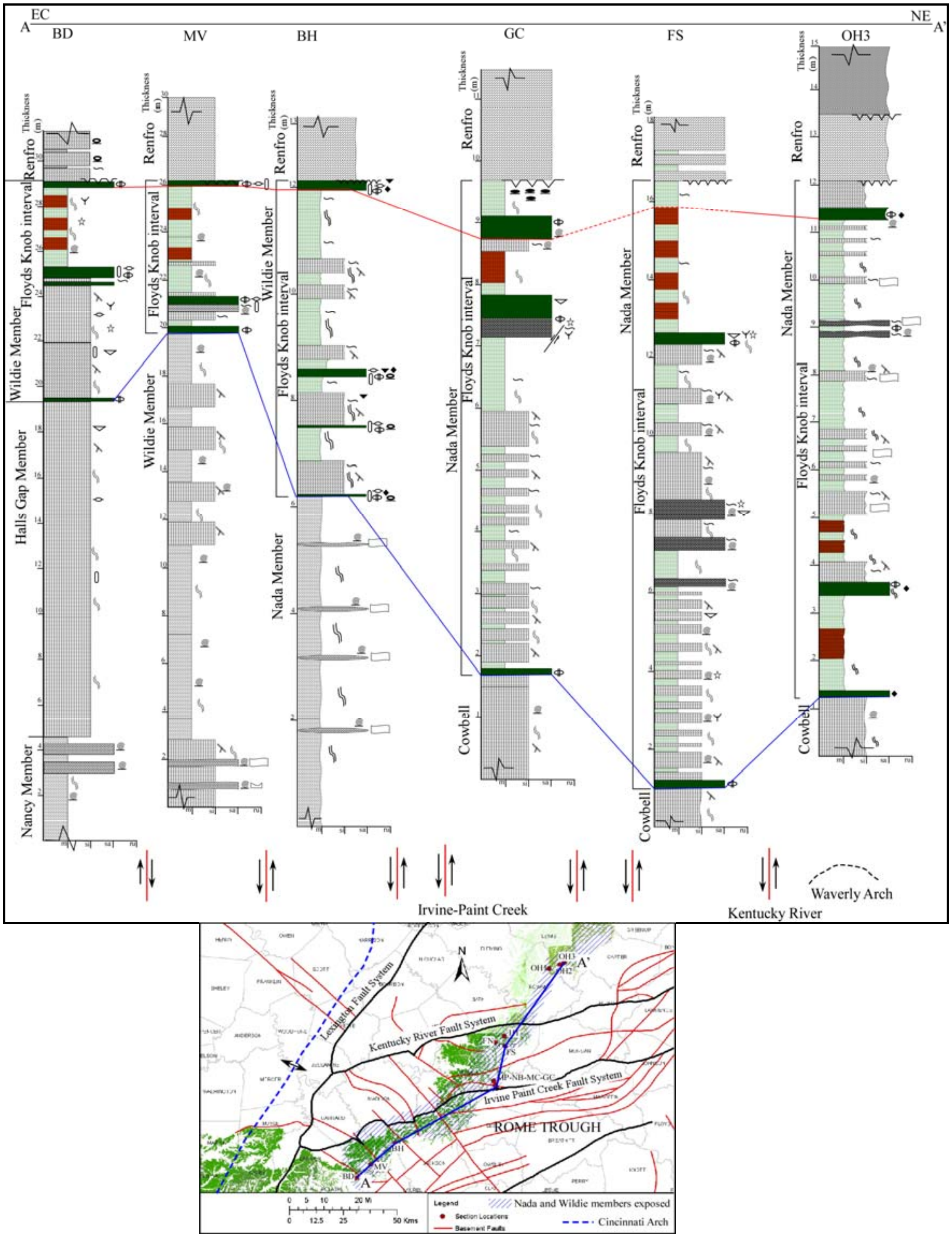



Figure 6.18 – Stratigraphic cross-section (A-A') from northeastern to east-central Kentucky, showing the distribution and intertongueing between the Nada, Wildie, and Halls Gap Members of the Borden Formation and the Renfro Member, all of which are associated with the Floyds Knob interval in the western Appalachian Basin. The datum is the base of the Renfro Member. Index map included at bottom.

interval.  The red shales are typically clayey and do not appear to contain any fossils (Fig 6.18; Appendix 1).

### 6.1.3 Muldraugh Member of the Borden Formation

The distribution of the Muldraugh Member is shown in Figure 6.19. The southern and eastern limits of the Muldraugh Member occur in Casey and Pulaski counties in south-central Kentucky south of the Liberty (L1) and west of the Somerset (S2) sections. The Muldraugh Member represents a highly resistant, bioturbated, olive-gray, cherty dolosiltite with thin shale partings (Fig. 6.20). Chert nodules and concretions are locally common, and the main matrix minerals are silica and carbonate (dolomite and calcite). The Muldraugh grades laterally into the Renfro Member of the Slade Formation toward the east, west of the Brodhead section in Rockcastle County, and into the silty, shaly carbonates of the Fort Payne Formation towards the southeast and southwest near the Liberty (L2) and Somerset (S2) sections (Figs. 6.5 and 6.8In west-central and south-central parts of Kentucky, the Muldraugh overlies the Halls Gap Member in Casey, Marion, and Pulaski counties and the Nancy Member in Hardin County. (Fig. 6.8).

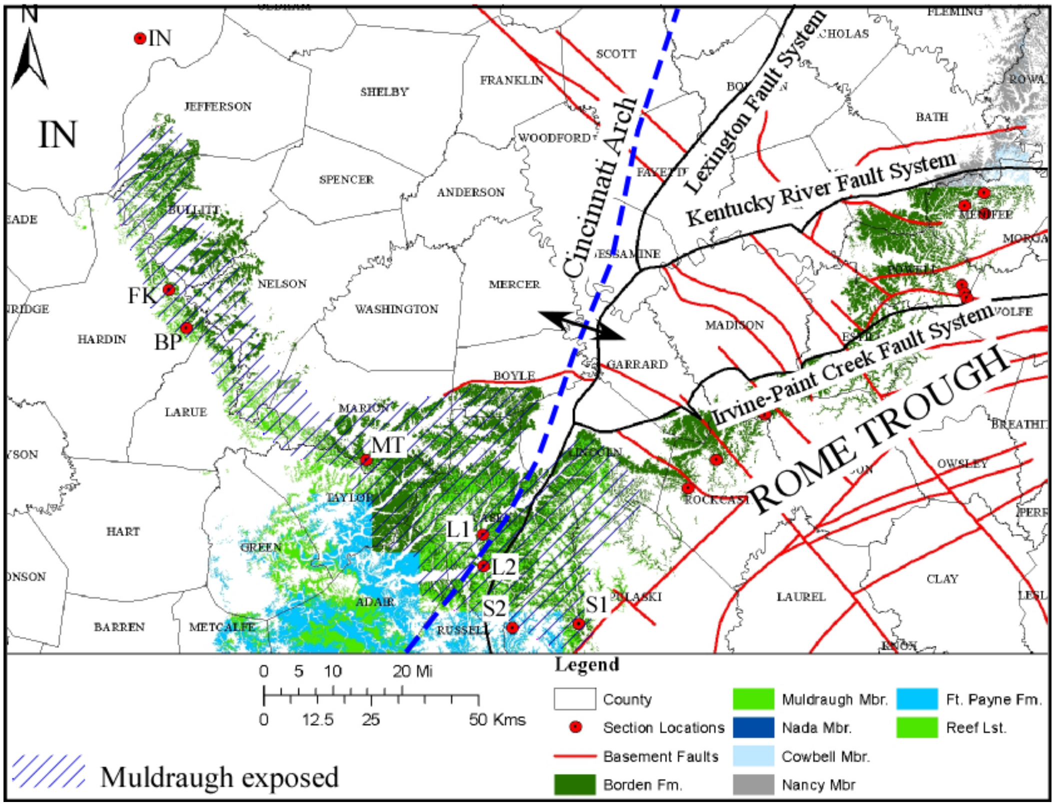


Figure 6.19 - Map showing distribution of the Muldraugh Member in southern Indiana, west-central, and south-central Kentucky. Blue crosshatching represents the distribution of the Muldraugh Member.

Figure 6.20 – General lithology of the Muldraugh Member. Olive-gray, bioturbated, cherty, dolosiltite with abundant chert nodules. Photograph from the south Liberty section 1 (L1).

### 6.1.4 Halls Gap Member of the Borden Formation

The Halls Gap Member is a calcareous-to-dolomitic siltstone unit that is present in west-central, south-central, and east-central Kentucky. The unit is composed of resistant, greenish-gray to medium-gray limy siltstone with minor clayey siltstones, and silty limestones (Weir et al., 1966). The southern and eastern limits of the Halls Gap Member occur in Pulaski and Rockcastle counties, respectively, in east-central Kentucky at the Brodhead (BD) section and west of the Somerset (S2) section. The Halls Gap grades laterally into the Nada and Wildie members toward the east near the Brodhead section (BD) in Rockcastle County, and into the Nancy Member toward the southwest near the Liberty (L2) and Somerset (S2) sections (Figs. 6.5 and 6.8). In west-central and south-central parts of Kentucky, the Halls Gap Member in the study area underlies the Muldraugh Member and overlies the Nancy Member in Casey, Marion, Pulaski, and Rockcastle counties.

### 6.1.6 Fort Payne Formation

The distribution of the Fort Payne Formation is shown in Figure 6.21. The northern and eastern limits of the Fort Payne Formation are in Taylor, Casey, Russell and Pulaski counties, in south-central Kentucky west of the Somerset (S2) and east of the Lake Cumberland (LC4) sections. The Fort Payne Formation extends south and southwest all the way to Georgia, Alabama, and Mississippi through Tennessee. The Fort Payne grades into the Muldraugh Member of the Borden Formation toward the east and north, west of the Somerset (S1) and east of the Lake Cumberland (LC4) sections in Pulaski and Russell counties, respectively (Figs. 6.5 and 6.21). In south-central part of Kentucky at the Lake Cumberland (LC4) section in Russell County, the Fort Payne overlies the Nancy Member separated by the Floyds Knob interval (Fig. 6.22). In most of south-central and west-central Kentucky, Maury and Nancy equivalents are included in the Fort Payne Formation, so that the Fort Payne Formation widely overlies the Devonian/Mississippian Chattanooga or New Albany Shales unconformably (Figs. 6.5, 6.8, and 6.12). It can be seen that the Floyds Knob interval in south-central Kentucky is represented by a single, thick, glauconite-horizon in the Fort Payne starved basin in front of the Borden delta (section LC4), in contrast to the multiple glauconite horizons within the Borden deltaic sequence (section S1) (Fig. 6.22). This change in the manifestation of the Floyds Knob interval could be interpreted to represent the absence of sediment influx in to the Fort Payne starved basin across the Borden delta-front, whereas within the Borden deltaic sequence, multiple glauconite-horizons may be the result of continuous sedimentation disturbing the glauconite precipitation.

The Fort Payne is the most diverse and lithologically complex unit that occurs in the southwestern Appalachian and Illinois basins of Kentucky. The Fort Payne contains dolomitic and calcareous, silty, medium- to light-gray, bioturbated shales with abundant, scattered quartz geodes; argillaceous, medium- to dark-gray, typically thin-bedded, bioturbated dolomites; bedded chert; crinoidal grainstone-packstones; and wackestones. Waulsortian-like mud mounds, as well as bryozoan-crinoidal bioherms in trends that strike parallel to the Borden front, are also present in the Fort Payne Formation (Thaden and Lewis, 1962, 1966; Sedimentation Seminar, 1972). These bioherms and mud mounds are composed chiefly of crinoidal and bryozoan limestones, including mudstone and/or wackestone. They are partly dolomitized with some minor chert and are

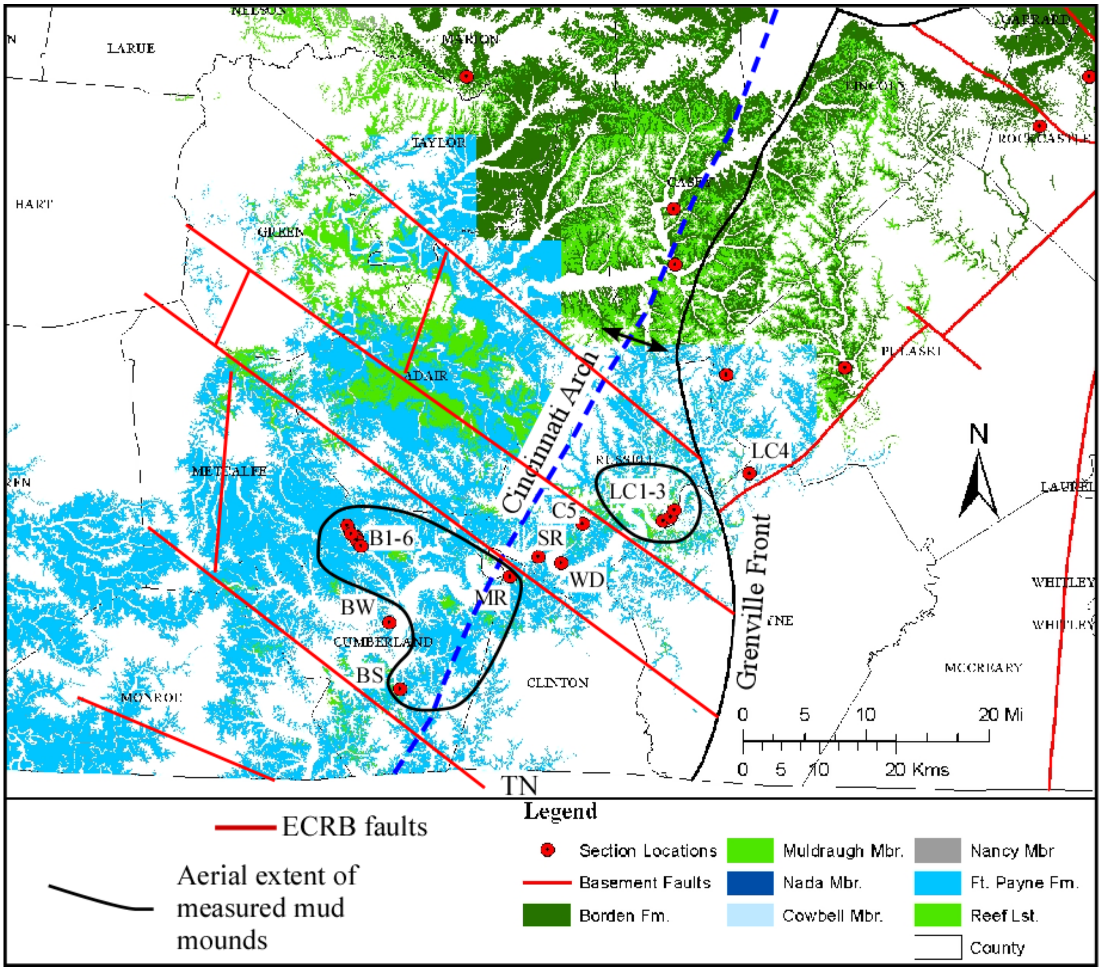



Figure 6.21 – Map showing distribution of the Fort Payne Formation in south-central Kentucky. ECRB faults adapted from Drahovzal et al. (1992) and Stark (1997).

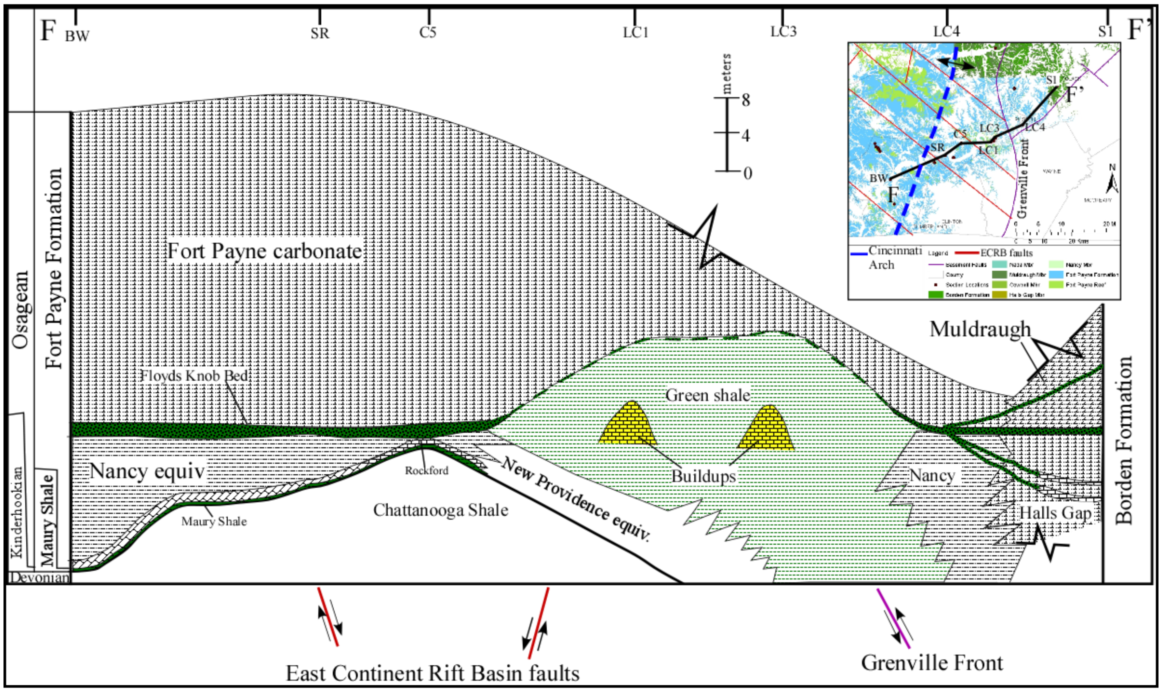



Figure 6.22 – Stratigraphic cross-section F-F' showing distribution of the Fort Payne mud mounds in the Lake Cumberland region with respect to the Floyds Knob interval and the Muldraugh Member of the Borden Formation in south-central Kentucky across the western Appalachian and eastern Illinois basins. Datum is the Floyds Knob Bed. Index map is in the upper right-hand corner. ECRB faults adapted from Drahovzal et al. (1992) and Stark (1997).

commonly associated with greenish-gray and dark-grey, fossiliferous shales (Lewis and Potter, 1978; Ausich and Meyer, 1990; Krause and Meyer, 2004) (Fig. 6.23). These carbonate reef-like structures are mainly scattered along the Cincinnati Arch in Kentucky and around the Nashville Dome in central Tennessee. Both occurrences seem to overlap deeply buried parts of the Grenville Front, faults associated with the East Continent Rift Basin (ECRB), and the Cincinnati Arch (Figs.6.21 and 6.22).

The Fort Payne Formation also contains argillaceous, silty, calcareous-to-dolomitic, bioturbated carbonates that occur widely in the Appalachian and Illinois basins between the biohermal facies. These lithologies overlie Nancy-equivalent dark-gray shales across a glauconite horizon, which is interpreted to be the Floyds Knob Bed/interval in the Fort Payne Formation (Figs. 6.24 and 6.25). This is the first report of the Floyds Knob Bed/interval in the Fort Payne Formation. The glauconite-rich Maury Shale of the Fort Payne Formation in south-central Kentucky is clearly different from the Floyds Knob interval, separated by Nancy-equivalent dark shales (Figs. 6.24 and 6.25). The Maury Shale is a very fine-grained glauconitic clay-rich horizon, whereas the Floyds Knob interval is defined by pelletal glauconite horizons.

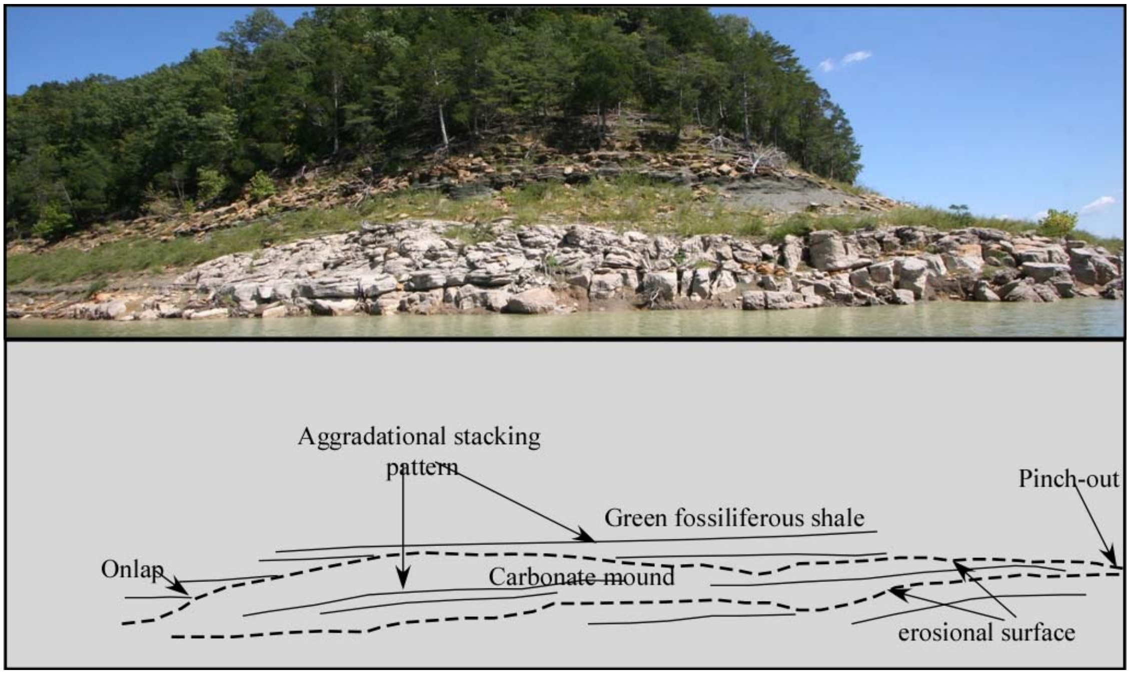



Figure 6.23 – Photograph showing mud mounds and associated green shales from Lake Cumberland section 1 (LC1).

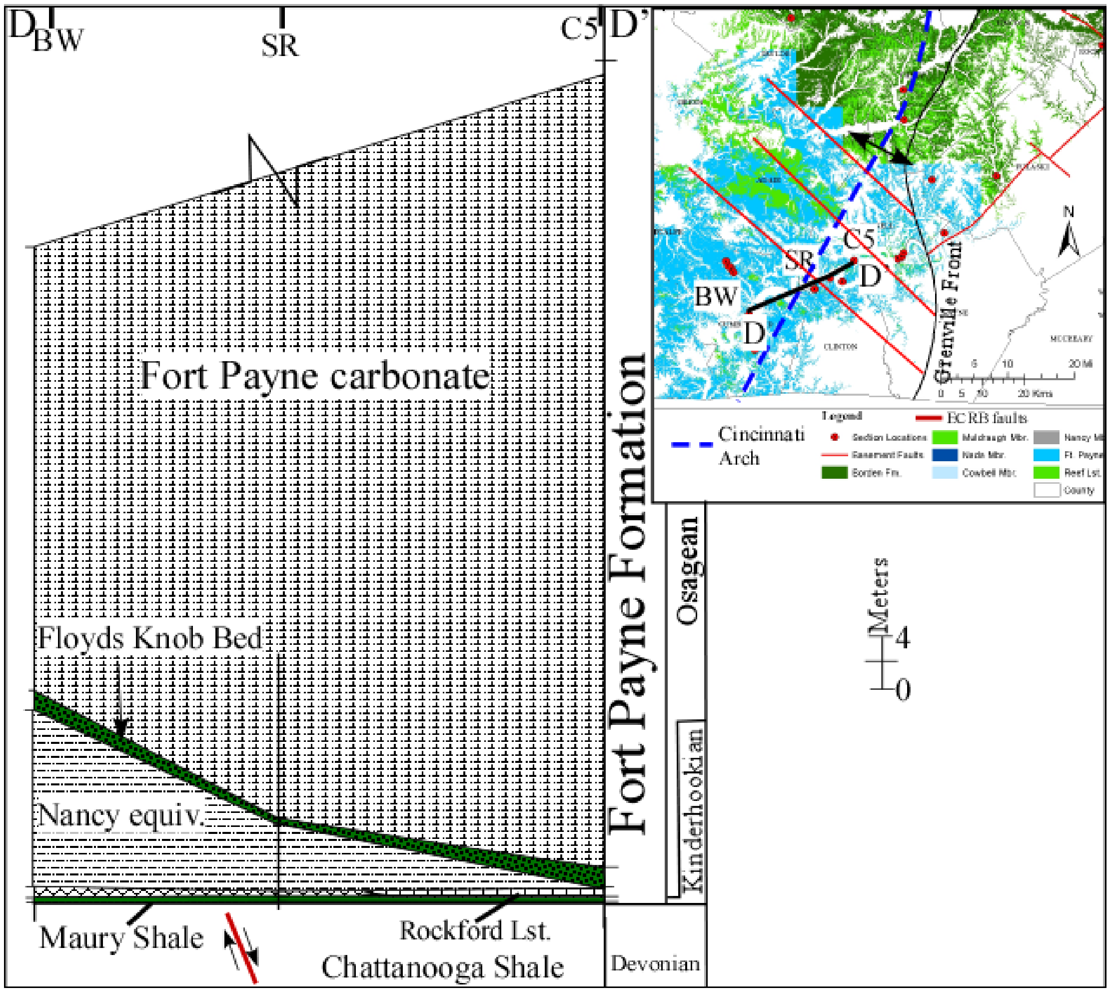



Figure 6.24 – Stratigraphic cross-section D-D' showing the distribution, nature, and vertical extent of the Floyds Knob interval in the Fort Payne Formation in south-central Kentucky across the western Appalachian and eastern Illinois basins. The datum is the top of the Upper Devonian Chattanooga Shale. Index map is in the upper right-hand corner. ECRB faults adapted from Drahovzal et al. (1992) and Stark (1997).

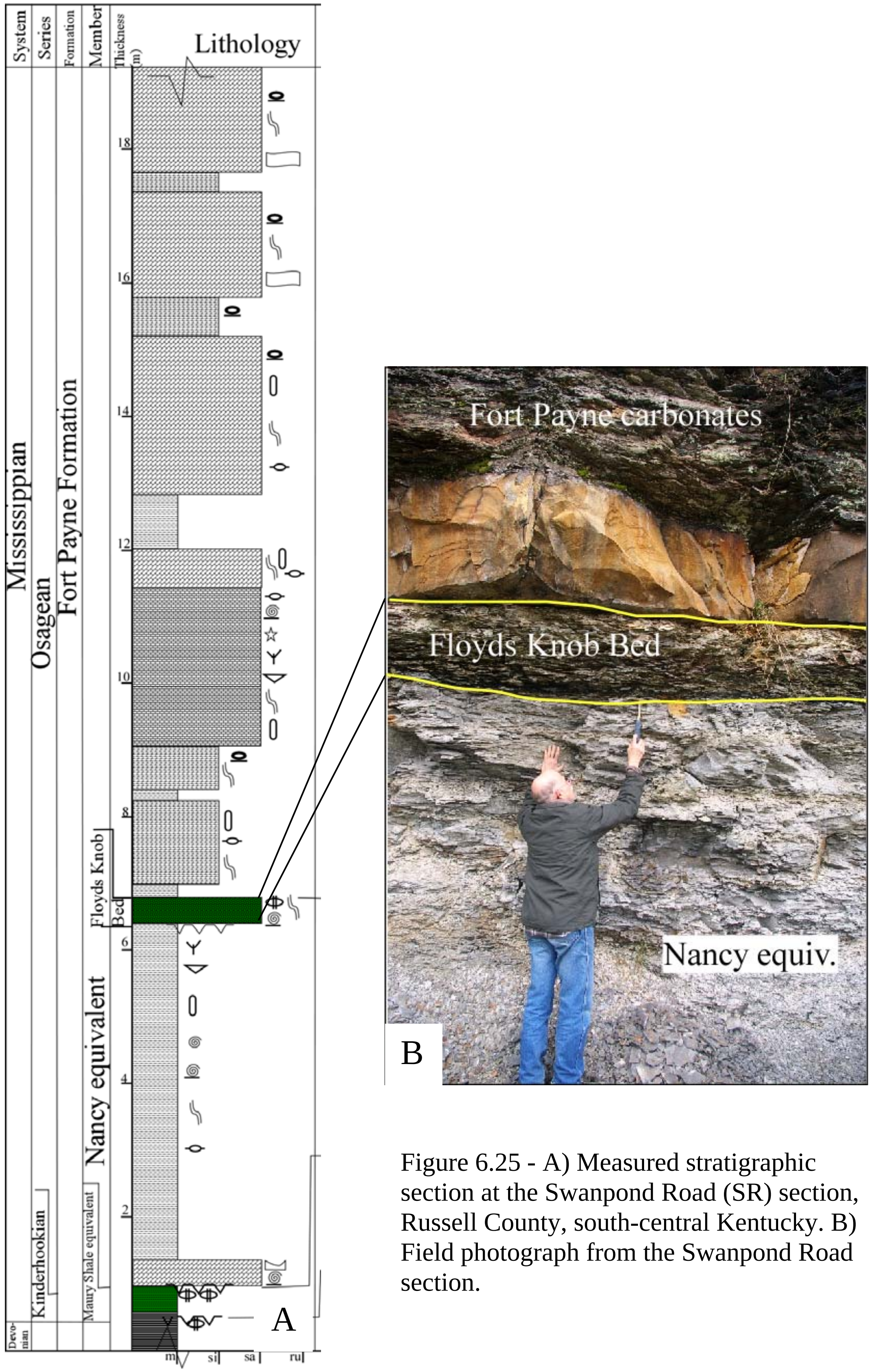



Figure 6.25 - A) Measured stratigraphic section at the Swanpond Road (SR) section, Russell County, south-central Kentucky. B) Field photograph from the Swanpond Road section.

### 6.1.7 Grainger Formation

The distribution of the late Kinderhookian–Osagean (late Tournaisian–early Visean) age Grainger Formation is shown in Figure 6.1. The Grainger Formation in the central Appalachian Basin is exposed at the surface along the Pine Mountain Thrust in southeastern Kentucky, northeastern Tennessee, and western Virginia. The Grainger Formation is characterized by gray and greenish-gray, silty shales with thin laminae and beds of siltstones, as well as by siderite nodules and lenses similar to those in the Nancy Member of the Borden Formation; however, the upper part of the Grainger is characterized by resistant gray, greenish-gray, and reddish-gray siltstones, shales, and sandstones similar to those in the Nada Member of the Borden Formation (Sable and Dever, 1990).

In northeastern Tennessee, at the Jellico Mountain (JM) section, the Grainger Formation is overlain by the chertified carbonates of the Fort Payne Formation across the Floyds Knob Bed (Figs. 6.12 and 6.26). At the Pound Gap (PG) and Cumberland Gap (CG) sections in eastern and southeastern Kentucky, the Grainger Formation is overlain by the Newman Limestone across thin green shales and siltstones devoid of any pelletal glauconite, which has been interpreted as the Floyds Knob Bed (Fig. 6.12) (Dean and Moshier, 1989). Red beds containing mud-cracks, and salt casts just below these green shales and silts have been interpreted to represent Maccrady equivalents in upper parts of the Grainger Formation (Wilpolt and Marden, 1949; Ettensohn, 1998; Ettensohn et al., 2002).

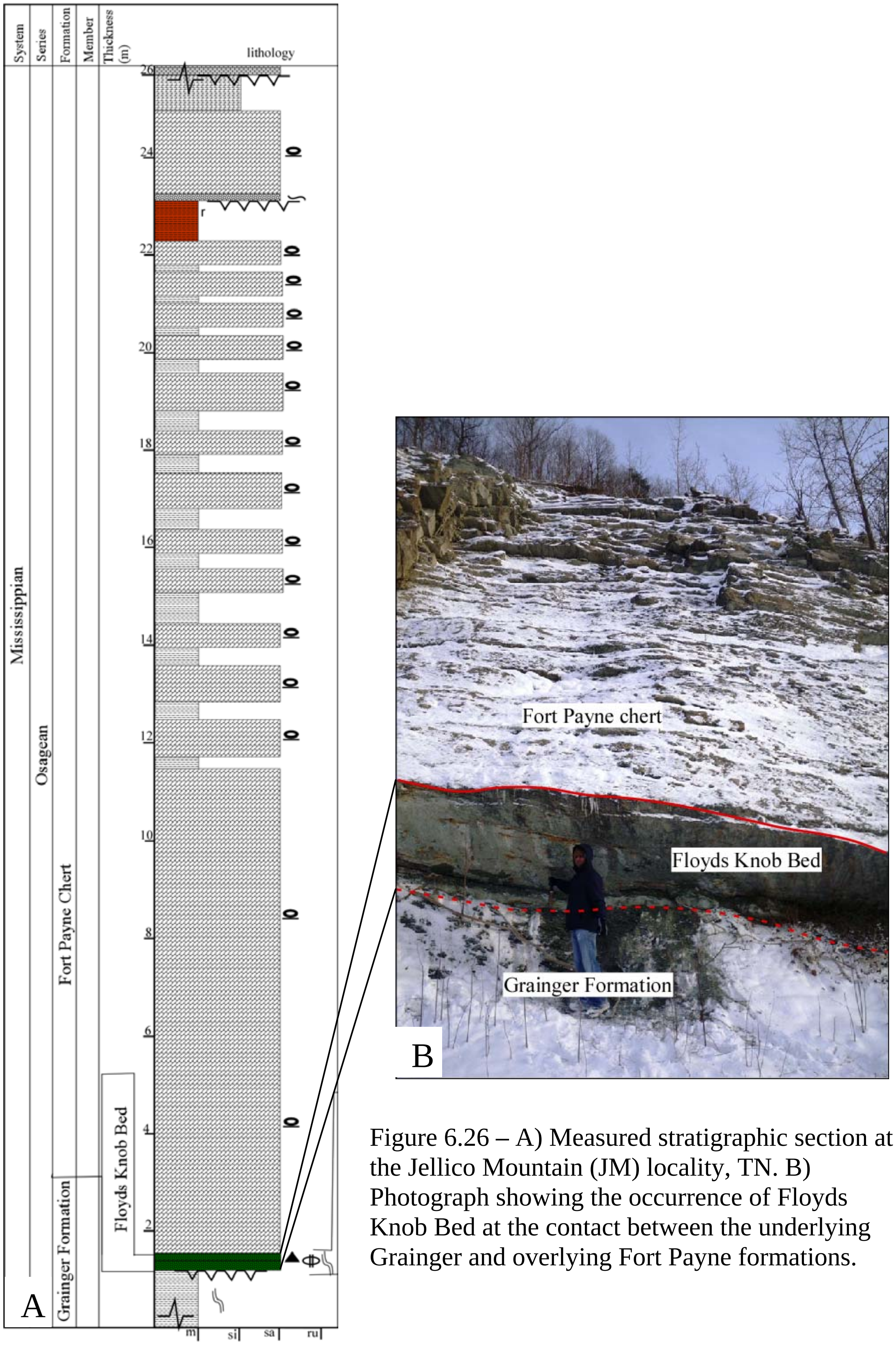



Figure 6.26 – A) Measured stratigraphic section at the Jellico Mountain (JM) locality, TN. B) Photograph showing the occurrence of Floyds Knob Bed at the contact between the underlying Grainger and overlying Fort Payne formations.

## 6.2 Petrographic and Megascopic Characterization of the Floyds Knob Glauconite interval

The Floyds Knob interval is a glauconitic, phosphate-rich interval that occurs throughout the study area. The Floyds Knob interval is extensively burrowed and bioturbated, and glauconite pellets are mostly concentrated in burrows and trails (Fig. 6.27). The unit is abundantly fossiliferous, including gastropods, foraminifera, brachiopods, corals, echinoderms, pelecypods, bryozoans, and crinoids (Whitehead, 1976, 1978). Abundant pyrite, ooids, chertified fossils, ferroan dolomitic mud, and secondary calcite deposits are recognized in association with the Floyds Knob interval in Kentucky. Phosphorite nodules and phosphatic fossil remains are also common in the Floyds Knob interval.

Samples from the Floyds Knob interval were collected for petrographic examination and field pictures are used for megascopic examination to develop facies-distribution patterns and to study depositional environments in the study area. These facies were based on glauconite grain-size distribution, other common mineral associations, fossil content, matrix or cement content, and level of bioturbation. Dunham’s carbonate-rock-texture classification scheme is chiefly used to name the rocks. The petrographic studies are shown in Table 6.1, with assigned section identifiers, and a legend for petrographic studies is provided in Figure 6.28. Table 6.1 is arranged according to the facies-distribution patterns and depositional environments outlined in Figure 6.15.

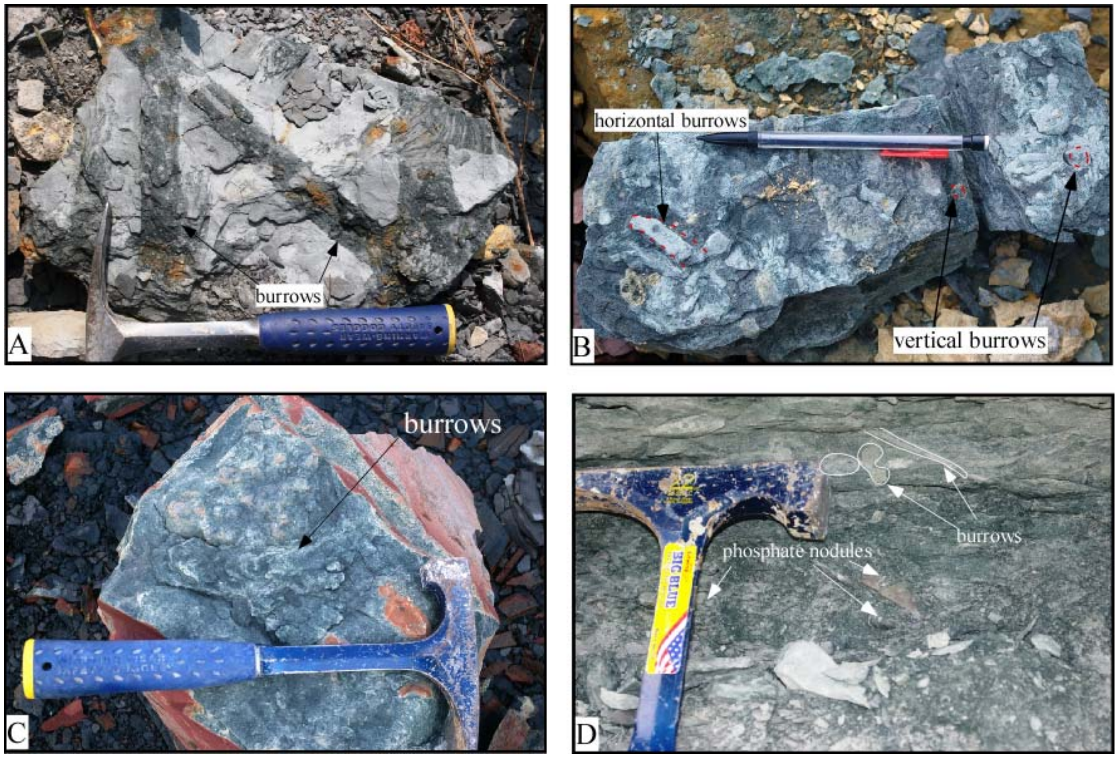



Figure 6.27 – Extensively bioturbated Floyds Knob Bed as observed at different sections in Kentucky. Please note that the glauconite pellets are mostly concentrated in burrows and occur in association with phosphate. A) west of Somerset section (S1), Cumberland Parkway; B) Muldraugh type (MT) section, KY-208; C) Burkesville west (BW) section, KY-90; D) Bighill (BH) section, Bighill, Kentucky.

| Legend for thin section study | |
|---|---|
| gl - Glauconite | em - Echinoderms |
| ph - Phosphate | cr - Crinoid |
| py - Pyrite | bh - Brachiopod |
| ch - Chert | br - Bryozoan |
| Q - Quartz | tr - Trilobite |
| c - Sparry calcite cement | pe - Pelecypod |
| do - Dolomite | o - Ooids |
| | os - Ostracods |
| | bu - Burrows |

Figure 6.28 – Chart showing the legend used for petrographic studies of the Floyds Interval.

Table 6.1 – Petrographic and megascopic descriptions, and interpreted depositional environments for the Floyds Knob interval.

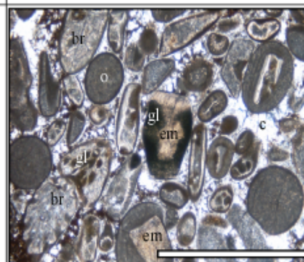
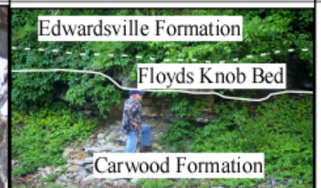
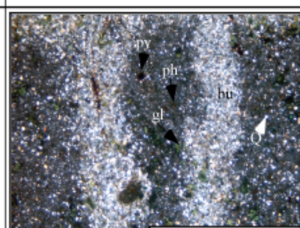
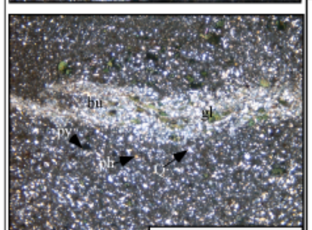
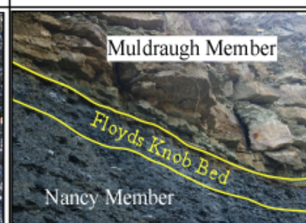
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral associations | Amount and type of bioturbation | Depositional environment and facies. |
|---|---|---|---|---|---|---|---|---|
| Section - IN (type section, Indiana) | 1- distinct bed | 1.65 m | <br>Glauconitic, fossiliferous to oolitic grainstone.<br>Bar scale: 3 mm | <br><br>Floyds Knob Bed at the contact between overlying Edwardsville and underlying Carwood formations of the Borden Group. | No peloidal glauconite grains identified. Glauconite occurs as replacement of echinoderm and bryozoan skeletal materials. | secondary calcite | bioturbated | High-energy distal delta platform at or above normal wave base (10 m). |
| Section - FK (Fort Knox, Hardin County) | 1-distinct bed | 1 m | <br><br>Glauconitic dolo-wackestone<br>Bar scale: 3 mm | <br><br>Floyds Knob Bed at the contact between the overlying Muldraugh and underlying Nancy members of the Borden Formation.<br><br>Small-scale cross-bedding and hummocky bedding. | Fine-grained peloidal, glauconite occurs in dark-gray, ferroan dolomitic matrix with quartz, phosphate, and pyrite; extremely bioturbated; glauconite commonly occurs in burrows. | phosphate, quartz, chert, dolomite, pyrite | extremely bioturbated; both vertical and horizontal burrows common. | Shallow, open-marine, high-energy, delta-front, above storm wave-base, but below normal wave base. |

Table 6.1 (continued)

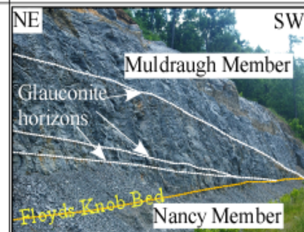
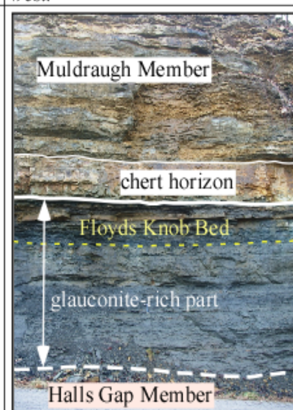
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - BP (Bluegrass Parkway) | 4-distinct granular glauconite horizons.<br><br>1 more horizon occurs within the Muldraugh Member. | 29 m between lower and upper glauconite horizons. | NA | <br>Floyds Knob Bed occurs at the contact between overlying Muldraugh and underlying Nancy members of the Borden Formation. *Dashed lines represent glauconite horizons that merge to the southwest.* | fine- to medium-grained peloidal glauconite in dolosiltite host rock.<br><br>small-scale hummocky cross-beds common. | pyrite, dolomite, iron oxide, phosphate, chert. | extremely bioturbated; small-scale vertical and horizontal burrows common. | Shallow, open-marine, high-energy, delta-front, above storm wave-base, but below normal wave base. |
| Section - MT (Muldraugh type section) | Several granular glauconite horizons.<br><br>1 more horizon occurs within the Muldraugh Member. | 15 m between lower and upper glauconite horizons. | NA | <br>Floyds Knob Bed occurs at the contact between overlying Muldraugh and underlying Halls Gap members of the Borden Formation. | fine- to medium-grained peloidal glauconite in dolosiltite and calcisiltite host rock.<br><br>small-scale hummocky cross-beds and cross-beds are common. | pyrite, dolomite, iron oxide, phosphate, chert. | extremely bioturbated; small-scale vertical and horizontal burrows common. | Shallow, open-marine, high-energy, delta-front, above storm wave-base, but below normal wave base. |

Table 6.1 (continued)

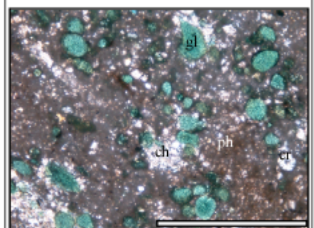
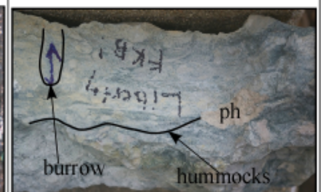
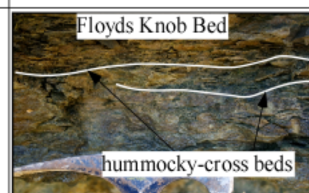
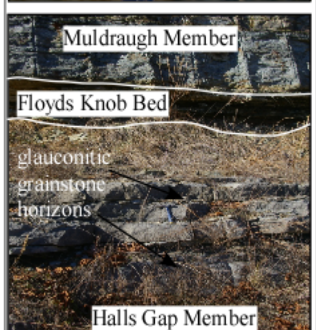
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - L1 (US-127) | 4-distinct granular glauconite horizons | 11.5 m between lower and upper glauconite horizons. | <br>Glauconitic dolo-wackestone<br><br>Bar scale: 3 mm | <br>Floyds Knob Bed occurs at the contact between the overlying Muldraugh and underlying Halls Gap members of the Borden Formation. | Dark-green, peloidal glauconite grains occur with phosphate, and chertified skeletal materials in dark-gray, dolomitic matrix.<br><br>small-scale hummocky cross-beds common. | pyrite, dolomite, iron oxide, phosphate, chert. | extremely bioturbated; horizontal and vertical burrows predominant | High-energy delta-front above storm wave-base, but below normal wave base. |
| Section - L2 (US-127) | 2-distinct granular glauconite horizons.<br><br>2-glauconitic grainstone horizons occur at top of the Halls Gap Member | 8.5 m between lower and upper glauconite horizons. | NA | <br> | Dark-green, peloidal glauconite grains occur with phosphate, and chertified skeletal materials in dark-gray, dolomitic matrix.<br><br>small-scale hummocky cross-beds common. | pyrite, dolomite, iron oxide, phosphate, chert. | extremely bioturbated; horizontal and vertical burrows predominant | High-energy delta-front above storm wave-base, but below normal wave base. |

Table 6.1 (continued)

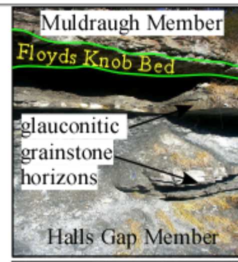
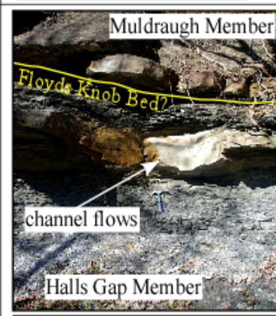
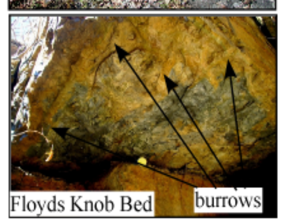
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - S1 (Cumberland Parkway) | 2-distinct granular glauconite horizons.<br><br>2-glauconitic grainstone horizons occur at top of the Halls Gap Member. | 14 m between lower and upper glauconite horizons. | NA |  | Dark-green, peloidal glauconite grains occur with phosphate in dolosiltite host rock.<br><br>hummocky cross-beds common; fossiliferous. | pyrite, dolomite, iron oxide, phosphate, chert. | extremely bioturbated; horizontal and vertical burrows predominant.<br><br>horizontal burrows of 4-5 cm wide and more than 30 cm long dominant. | High-energy delta-front above storm wave-base, but below normal wave base. |
| Section - S2 (Cumberland Parkway) | none in the Floyds Knob Bed;<br><br>1 - granular glauconite horizon occurs within the Muldraugh Member above the Floyds Knob Bed. | 10 m between Floyds Knob Bed and upper glauconite horizon. | NA |  | no granular glauconite; phosphate in dolosiltite host rock.<br><br>hummocky cross-beds, and channel-flows common. | dolomite, iron oxide, phosphate. | extremely bioturbated; horizontal and vertical burrows predominant.<br><br>horizontal burrows of 4-5 cm wide and more than 30 cm long dominant. | High-energy delta-front above storm wave-base, but below normal wave base. |

Table 6.1 (continued)

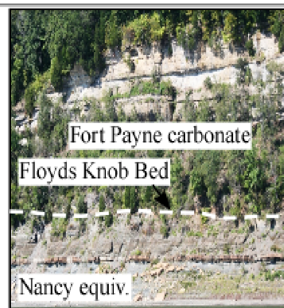
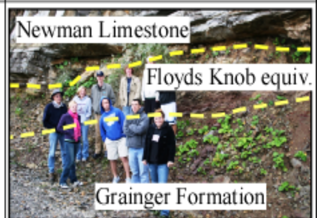
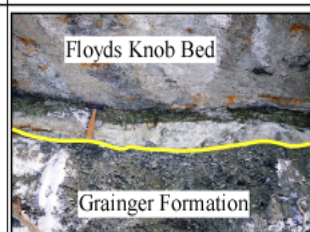
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - L4 (Lake Cumberland) | 1 - distinct granular glauconite horizon | 0.4 m | NA |   Floyds Knob Bed occurs at the contact between the overlying Fort Payne carbonate and underlying Nancy equivalent shales of the Fort Payne Formation. | Dark-green, peloidal glauconite grains occur with phosphate, pyrite in dolosiltite host rock.<br><br>hummocky cross-beds common; fossiliferous. | pyrite, dolomite, iron oxide, phosphate, chert. | extremely bioturbated; horizontal and vertical burrows predominant. | High-energy delta-front above storm wave-base, but below normal wave base. |

Table 6.1 (continued)

| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - PG (Pound Gap) | no granular glauconite horizon; silty shale unit that is equivalent to the Floyds Knob inter-val. | 0.5 m | NA |  <br>Floyds Knob equivalent silty shale occurs at the contact between the overlying Newman Limestone and underlying Grainger Formation. | red and green silty shales.<br><br>hummocky cross beds, and small-scale cross beds common. | siderite nodules, green shales | extremely bio-turbated; horizontal and vertical bur-rows predomi-nant. | prodelta, low-energy, at or near storm wave-base; deeper than delta-front envi-ronment. |
| Section - JM (Jellico Mountain) | 1-distinct granular glauconite horizon. | 0.35 m | NA |  <br>Floyds Knob Bed occurs at the contact between the overlying Fort Payne chert and underlying Grainger Formation. | Dark-green, peloidal, glauc-onite grains in dolomitic matrix.<br><br>hummocky cross beds, and small-scale cross beds common; fos-siliferous. | phosphate, dolomite, pyrite, iron oxide. | extremely bio-turbated; horizontal and vertical bur-rows predomi-nant. | prodelta, low-energy, at or near storm wave-base; deeper than delta-front envi-ronment. |

Note: The Floyds Knob interval (silty shales) at the Pound Gap (PG) and Cumberland Gap (CG) sections occurs at the contact between the underlying Grainger Formation and overlying Newman Limestone. It always occurs at the top of the Grainger Formation, such as at the Jellico Mountain section (JM).

Table 6.1 (continued)

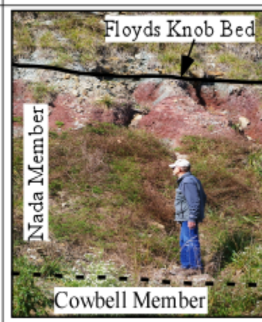
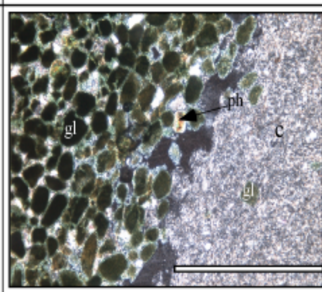
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - OH3 (Interstate-64) | 3-distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Nada Member. | 10.8 m<br><br>between the lowermost glauconite horizon above the Cowbell Member and topmost horizon below the Renfro Member. | NA | <br>Floyds Knob Bed within the Nada Member. | Dark-green, peloidal glauconite abundant; glauconite occurs with phosphate.<br><br>hummocky cross-beds and small scale cross-beds fairly common, | phosphate, pyrite, secondary calcite, iron oxide. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |
| Section - OH1 (Interstate-64) | 3 to 4 distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Nada Member. | 12.5 m<br><br>between the lowermost glauconite horizon above the Cowbell Member and topmost horizon below the Renfro Member. | <br>Glauconitic grainstone. Bar scale: 1.5 mm<br><br>*Floyds Knob Bed within the Nada Member.* | NA | Dark-green, peloidal glauconite abundant; glauconite occurs with phosphate within sparry-calcite cement; glauconite penecontemporaneous with sparry calcite.<br><br>hummocky cross-beds and small-scale cross-beds abundant within the section. | phosphate, pyrite, secondary calcite, iron oxide. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |

Table 6.1 (continued)

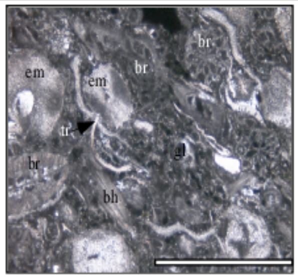
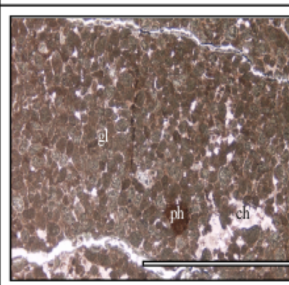
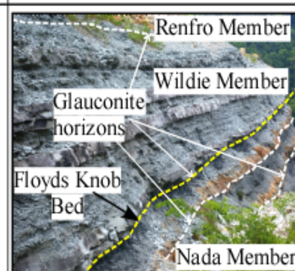
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - OH1 (Interstate-64) | 3 to 4 distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Nada Member. | 12.5 m<br><br>between the lowermost glauconite horizon above the Cowbell Member and topmost horizon below the Renfro Member. | <br>Fossiliferous, glauconitic packstone<br>Bar scale: 1.5 mm<br><br>*Glauconite horizon at the contact between the underlying Cowbell and overlying Nada members.* | NA | Glauconite replacing skeletal materials, chiefly bryozoans.<br><br>hummocky cross-beds and small-scale cross-beds abundant within the section. | Phosphate, secondary calcite, pyrite. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta platform; high-energy, above storm wave base |
| Section - BH (Bighill Road) | 4 distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Nada and Wildie members. | 6 m<br><br>between the lowermost glauconite horizon in the Nada Member and topmost horizon below the Renfro Member. | <br>Glauconitic packstone<br>Bar scale: 1.5 mm<br><br>*Floyds Knob Bed at the contact between the overlying Wildie and underlying Nada members.* |  | Dark-green, peloidal glauconite abundant; occurs with phosphate and chert in glauconitic matrix.<br><br>hummocky cross-beds and small-scale cross-beds abundant within the section. | Phosphate, secondary calcite, chert. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |

Table 6.1 (continued)

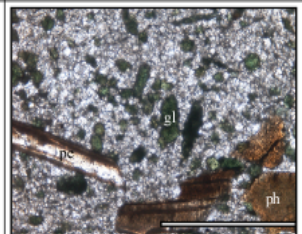
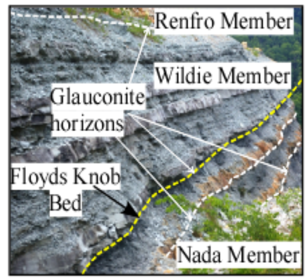
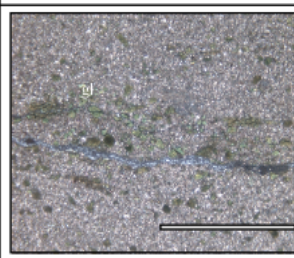
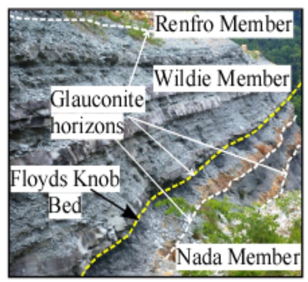
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - BH (Bighill Road) | 4 distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Nada and Wildie members. | 6 m | <br>Fossiliferous glauconitic dolo-wackestone<br>Bar scale: 1.5 mm<br><br>Nada Member*: glauconite horizon below first dolomite bed* |  | Dark-green, peloidal, glauconite occurs with phosphatized pelecypod and other skeletal materials in dolomite. | Phosphate, secondary calcite, chert, dolomite. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |
| Section - BH (Bighill Road) | | 6 m | <br>Glauconitic dolo-wackestone<br>Bar scale: 3 mm<br><br>Nada Member*: glauconite horizon below second dolomite bed.* |  | Dark-green peloidal glauconite abundant; occurs within partings in dolomite.<br><br>hummocky cross-beds and small-scale cross-beds abundant within the section. | Phosphate, secondary calcite, chert, dolomite. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |

Table 6.1 (continued)

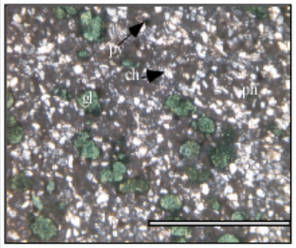
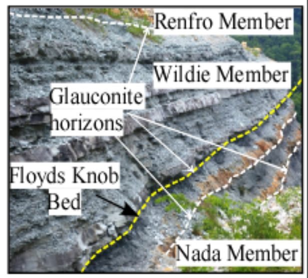
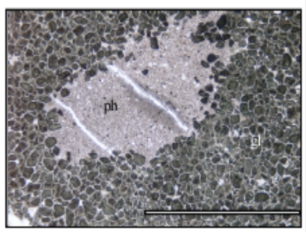
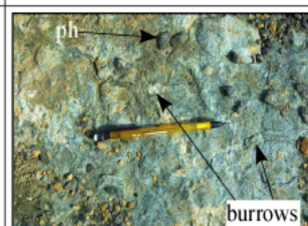
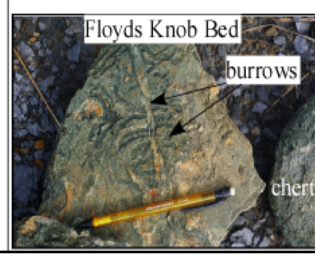
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - BH (Bighill Road) | 4 distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Nada and Wildie members. | 6 m | <br>Glauconitic dolo-wackestone<br>Bar scale: 1.5 mm<br><br>Wildie Member*: glauconite horizon at the contact between the Wildie and Renfro members* |  | Dark-green, peloidal, glauconite occurs with pyrite, phosphate, and chert materials in dark-gray dolomite cement. | Phosphate, secondary calcite, chert, dolomite. | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |
| Section - BD (Brodhead section) | 4 distinct granular glauconite horizons;<br><br>glauconitic clay and granular glauconites are diffused in the silts and shales of the Wildie Member. | 10 m<br><br>between the lowermost glauconite horizon above the Halls Gap Member and topmost horizon below the Renfro Member. | <br>Glauconitic packstone.<br>Bar scale: 1.5 mm<br><br>*Floyds Knob Bed within the Wildie Member.* | <br> | Dark-green, peloidal glauconite abundant; in glauconitic matrix. Glauconite penecontemporaneous with phosphate.<br><br>hummocky cross-beds and small-scale, cross-beds abundant within the section. | Phosphate, secondary calcite, chert, dolomite, pyrite | extremely bioturbated; horizontal and vertical burrows predominant. | Proximal delta-platform; high-energy, above storm wave base. |

Table 6.1 (continued)

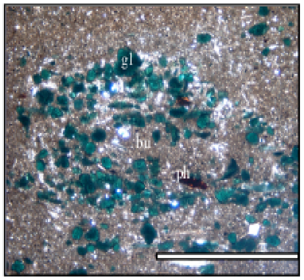
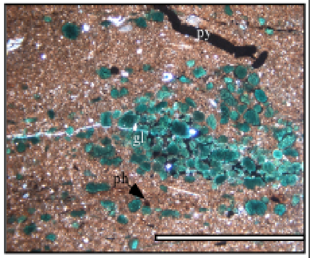
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - C5 (Core C-505) | 1- distinct granular glauconite horizon. | 1.27 m |   Glauconitic dolo-wackestone. Bar scale: 3 mm |   Floyds Knob Bed at the contact between the overlying Fort Payne carbonate and underlying Rockford Limestone of the Fort Payne Formation. | Dark-green peloidal, glauconite grains abundant. Glauconite chiefly occurs inside burrows with phosphate and pyrite in medium to dark-gray, ferroan dolomitic matrix; extremely bioturbated. small scale cross-beds and ripple marks common. | Phosphate, dolomite, pyrite, chert | extremely bioturbated; horizontal and vertical burrows predominant. | Low-energy, distal delta, basinal deposit at or near storm wave-base relatively deeper than delta-front environment. |

Table 6.1 (continued)

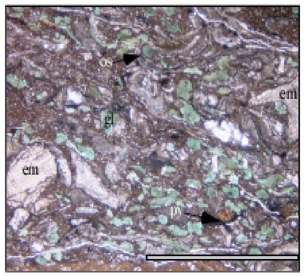
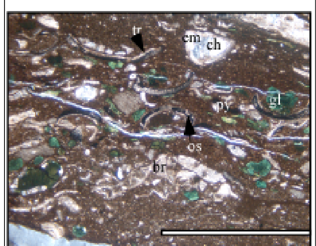
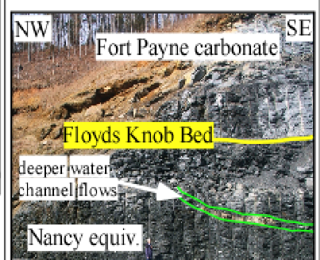
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - BW (Burkesville west ) | 1- distinct granular glauconite horizon. | 1.5 m |  Fossiliferous, glauconitic dolo-packstone Bar Scale: 3 mm.  Fossiliferous, glauconitic, chertified dolo-wackestone. Bar Scale: 3 mm. |     Floyds Knob Bed at the contact between the overlying Fort Payne carbonate and underlying Nancy equivalent shales of the Fort Payne Formation. | Dark-green, peloidal, glauconite abundant; extremely bioturbated; glauconite occurs with abundant skeletal materials, pyrite, phosphate, and chert in ferroan dolomite matrix. small scale ripple marks, and channel-flows common. | Phosphate, dolomite, pyrite, chert, secondary calcite. | extremely bioturbated; horizontal and vertical burrows predominant. | Low-energy, distal-delta, basinal near storm wave-base; relatively deeper than the delta-front environment. |

Table 6.1 (continued)

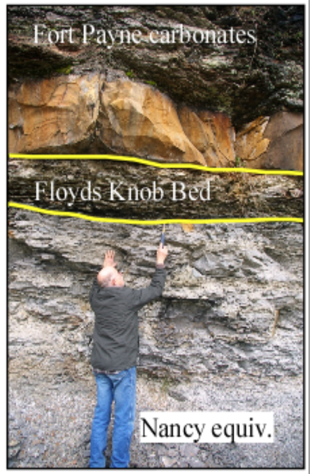
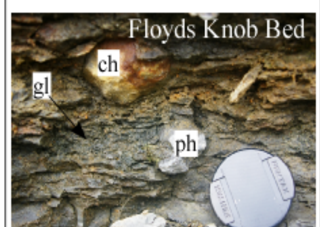
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - SR (Swanpond Road) | 1- distinct granular glauconite horizon. | 0.4 m | NA |     Floyds Knob Bed at the contact between the overlying Fort Payne carbonate and underlying Nancy equivalent shales of the Fort Payne Formation. | Dark-green, peloidal, glauconite abundant; extremely bioturbated; glauconite occurs with abundant skeletal materials, pyrite, phosphate, chert, and dolomite.<br><br>small scale ripple marks common. | Phosphate, dolomite, pyrite, chert, secondary calcite | extremely bioturbated; horizontal and vertical burrows predominant. | Low-energy, distal-delta, basinal near storm wave-base relatively deeper than delta-front environment. |

Table 6.1 (continued)

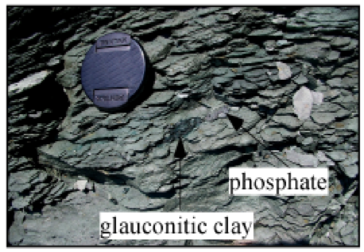
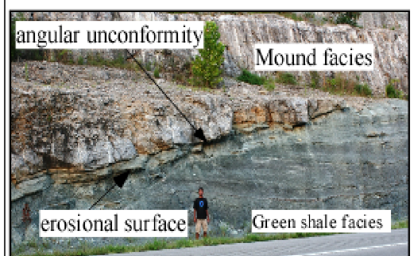
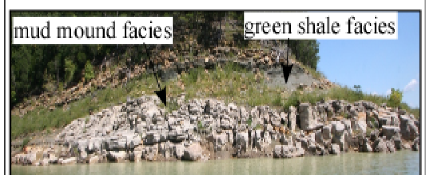
| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - BN3 (Burkesville north ) | glauconite diffused; represented by carbon-ate-mud mounds and associated glauconitic green shales. | 17.7 m | NA |  <br>Green, glauconitic shales<br> <br>Green-shale facies below and above the mud mounds. | Calcareous glau-conitic shale occurs with phosphates below and above the mud mound facies.<br><br>Large scale cross-beds are common. | Phosphate, chlorite, siderite, chert, secondary calcite. | extremely bioturbated | Distal, high-energy, basinal uplift, reefal environment at or near the storm wave-base. |

Table 6.1 (continued)

| Sections | Glauconite content | Thickness range | Petrography | Megascopic examination | Descriptions | Other mineral association | Type and amount of bioturbation | Facies and paleo-position of delta |
|---|---|---|---|---|---|---|---|---|
| Section - LC1 (Lake Cumberland) | glauconite diffused; represented by carbon-ate-mud mounds and associated glauconitic green shales. | 8 m | NA |   Green-shale facies below and above the mud mounds. | Calcareous glau-conitic shale occurs with phosphates below and above the mud mound facies.<br><br>Large scale cross-beds are common. | Phosphate, chlorite, siderite, chert, secondary calcite. | extremely bioturbated | Distal, high-energy, basinal uplift, reefal environment at or near the storm wave-base. |

# CHAPTER 7: $^{40}Ar/^{39}Ar$ ANALYSIS OF AUTHIGENIC GLAUCONITIC MINERALS

## 7.1 Results

For $^{40}Ar/^{39}Ar$ analyses, 12 glauconite samples were collected from the Lower-Middle Mississippian rocks of the western Appalachian and eastern Illinois basins in Kentucky. Eleven samples were collected from the Floyds Knob interval and one sample was collected from the Kinderhookian, glauconite-rich Maury Shale of the Illinois Basin. Of the 11 samples, three samples were collected from the Bluegrass Parkway (BP) section, which is in the Illinois Basin. The other eight samples were collected from the Floyds Knob interval situated in the western Appalachian Basin, in south-central, east-central, and northeastern Kentucky. A location map for the sampled sections is shown in Figure 7.1. A detailed sampled-outcrop and data-horizon identifier is provided in Table 7.1 (see Appendix 1 for detailed lithology of the sampling horizons with respect to the outcrop identifiers). Of the 12 samples analyzed, one analysis was not taken into consideration because of the experimental error (see Table 7.1).

The $^{40}Ar/^{39}Ar$ data for the glauconites irradiated in a vacuum are summarized in Table 7.2, and the age spectra are given in Appendix 2. Overall, the recoil losses of $^{39}Ar$ for irradiated grains ranged from 20.9% to 30.3%. The total gas ages (equivalent to conventional $^{39}K/^{40}Ar$) of all the glauconites from the study area are highly variable and show much younger ages than the estimated biostratigraphic ages (Fig.7.2). Sample BS of glauconite-rich clay from the Maury Shale in the Illinois Basin, which was analyzed by this technique, gives an apparent age of 278.78 ± 0.682 Ma, which is mid-Permian in age (Table 7.2).

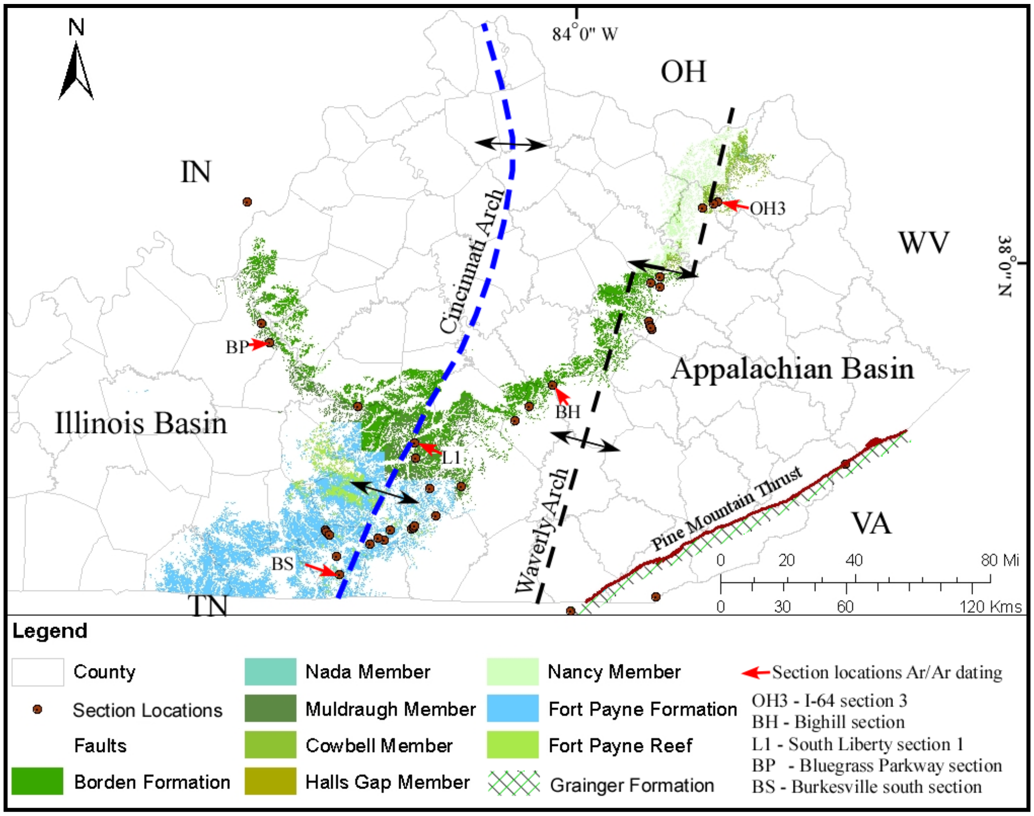



Figure 7.1 - Sampling locations for glauconite Ar/Ar dating. Three samples each were collected from the Bluegrass Parkway (BP), Big Hill (BH), and I-64 (OH3) sections, and two samples from South Liberty (L1) section respectively. A sample from the KY 61S (BS) section was collected from the glauconite-rich Kinderhookian Maury Shale. Please note that the Bluegrass Parkway and KY 61S sections are in the Illinois Basin west of the Cincinnati Arch, whereas the South Liberty, Big Hill, and I-64 sections are in the Appalachian Basin east of the Cincinnati Arch.

Table 7.1 – Summary of sampling locations for $^{40}Ar/^{39}Ar$ of glauconitic minerals from Kentucky.

| | **Table 7.1 - Summary of sampling locations for $^{40}Ar/^{39}Ar$ of glauconitic minerals from Kentucky** | | | |
|---|---|---|---|---|
| **Sample** | **Outcrop Location** | **Outcrop identifier** | **Sample identifier** | **Sample Horizon** |
| 1 | South of Liberty | L1 | L1-1 | Halls Gap Member, lowermost glaucony horizon |
| 2 | South of Liberty | L1 | L1-2 | Floyds Knob Bed, base of the Muldraugh Member |
| 3* | Bighill | BH | BH-1 | Nada Member, Lowermost glaucony horizon below the first dolomite body |
| 4 | Bighill | BH | BH-2 | Floyds Knob Bed, contact between the Nada and Wildie members |
| 5 | Bighill | BH | BH-3 | Glaucony horizon, contact between the Renfro and Wildie members |
| 6 | I-64 stop 3 | OH3 | OH3-1 | Glaucony horizon, contact between the Cowbell and Nada members |
| 7 | I-64 stop 3 | OH3 | OH3-2 | Floyds Knob Bed, within the Nada Member |
| 8 | I-64 stop 3 | OH3 | OH3-3 | Glaucony horizon, below the Renfro Member |
| 9 | Bluegrass Parkway | BP | BP-1 | Floyds Knob Bed, base of the Muldraugh Member |
| 10 | Bluegrass Parkway | BP | BP-2 | First glaucony horizon above the Floyds Knob Bed |
| 11 | Bluegrass Parkway | BP | BP-3 | Second glaucony horizon above the Floyds Knob Bed |
| 12 | Burkesville KY-61S | BS | BS | Maury Shale |
| | *** Analysis will not be taken into consideration because of experimental error** | | | |

Table 7.2 – Summary of $^{40}Ar/^{39}Ar$ data for glauconitic minerals from Kentucky.

**Table 7.2 - Summary of $^{40}Ar/^{39}Ar$ results for glauconitic minerals from Kentucky**

| Sample identifier | Irradiation conitions | $^{39}Ar$ loss (%) | Retention age (Ma) | Total gas/Apparent age (Ma) | Remarks |
|---|---|---|---|---|---|
| L1-1 | In vacuo | 25.9 | 373.572 ±1.408 | 286.523 ± 1.111 | |
| L1-2 | In vacuo | 20.9 | 362.826 ± 0.9 | 295.858 ± 0.74 | Floyds Knob Bed |
| BH-2 | In vacuo | 22.4 | 370.003 ± 1.051 | 295.805 ± 0.843 | Floyds Knob Bed |
| BH-3 | In vacuo | 23.7 | 371.059 ±1.121 | 292.578 ± 0.896 | |
| OH3-1 | In vacuo | 21.2 | 369.352 ± 1.137 | 299.302 ± 0.943 | |
| OH3-2 | In vacuo | 24.4 | 372.886 ± 1.489 | 291.067 ± 1.226 | Floyds Knob Bed |
| OH3-3 | In vacuo | 30.3 | 379.156 ± 5.601 | 276.977 ± 3.13 | |
| BP-1 | In vacuo | 21.6 | 354.278 ± 0.929 | 285.492 ± 0.761 | Floyds Knob Bed (Illinois Basin) |
| BP-2 | In vacuo | 21.8 | 358.67 ±0.917 | 289.082 ± 0.734 | |
| BP-3 | In vacuo | 22.3 | 355.449 ± 0.942 | 284.599 ± 0.747 | |
| BS | In vacuo | 26.5 | 367.736 ±0.902 | 278.78 ± 0.682 | Maury Shale (Illinois Basin) |

**Note**: Ages were calculated relative to an age of 520.4±1.7 Ma for the McClure Mountains, Colorado hornblende (MMhb-1) standard used as the neutron-flux density monitor for all samples (Samson and Alexander, 1987). All errors are ± 1σ. Total gas/Apparent age is used as the equivalent to a K-Ar age.

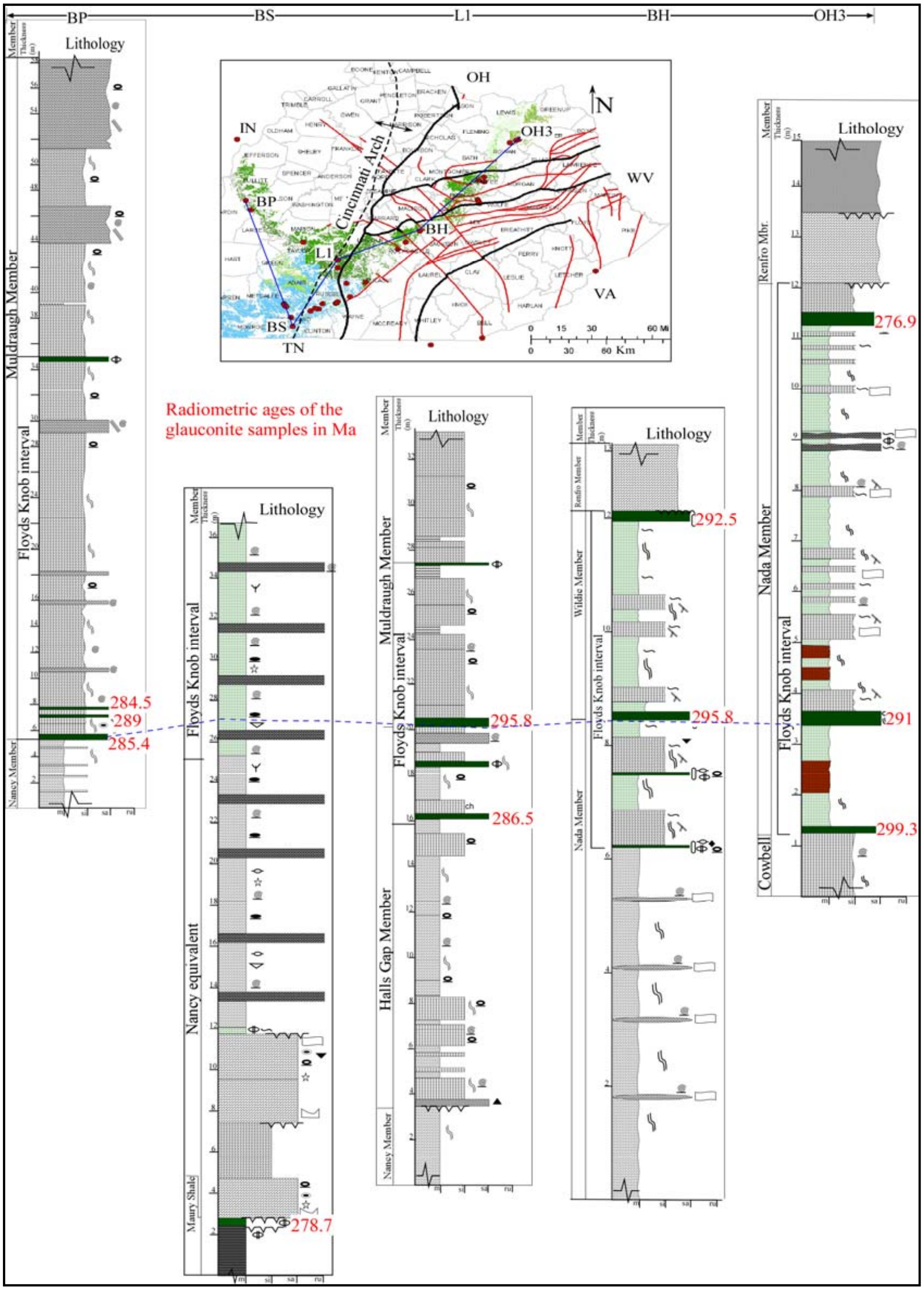



Figure 7.2 – Stratigraphic cross-section showing the radiometric ages of glauconite samples collected from different sections across the western Appalachian and eastern Illinois basins. Index map included at top. Not to scale.

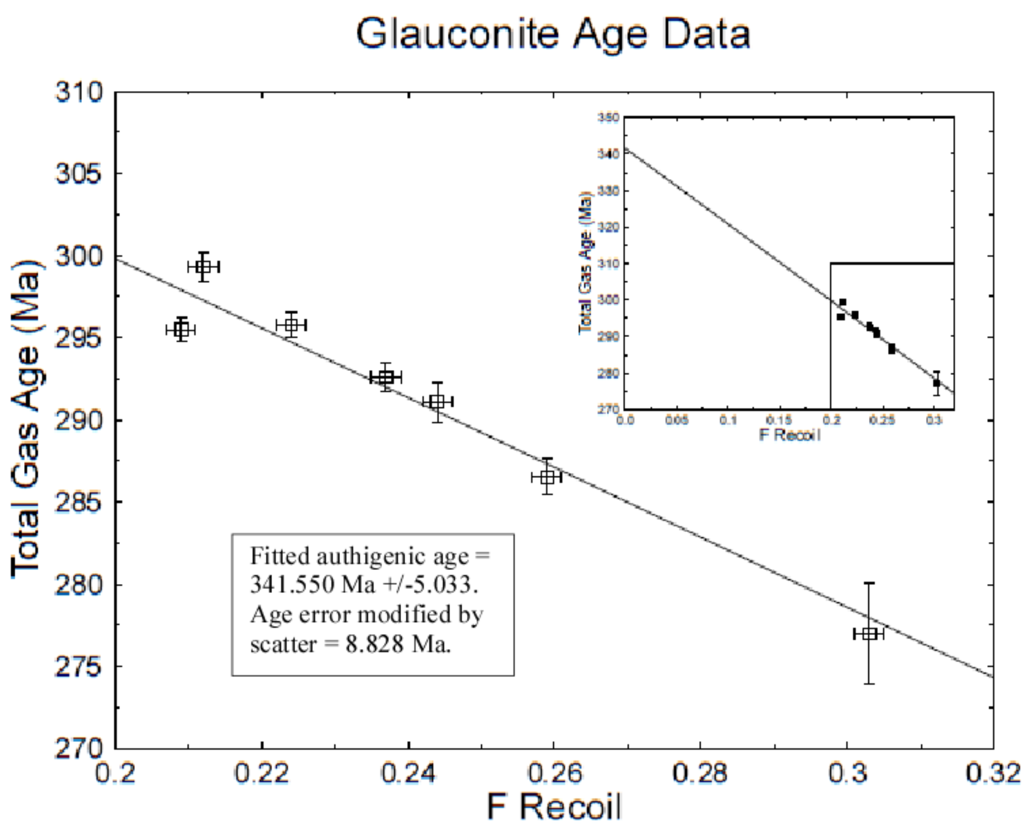
This age is much younger than what was suggested by biostratigraphic studies of extracted conodonts from the Maury Shale. The conodont studies have suggested that the Maury Shale may represent sedimentation during parts of the Kinderhookian and early Osagean stages, which ranges roughly from 359.2 Ma to 345.3 Ma (Conant and Swanson, 1961; Leslie et al., 1996; Davydov et al., 2004). The age discrepancy indicates that sample BS (Maury Shale) was probably affected by a later resetting (i.e., thermal or tectonic) event that caused a variable amount of radiogenic argon loss.

Similarly, the other 10 samples from the Floyds Knob interval in the western Appalachian and eastern Illinois basins largely show apparent ages younger than 300 Ma, which is Early Permian in age (Table 7.2). These apparent ages are much younger than what has been suggested by biostratigraphic studies. Mega-fossil studies of the Keokuk-type brachiopod fauna and extracted conodonts point to a late Osagean age (~ 343–341 Ma) (Butts, 1922; Stockdale, 1939; Weller et al., 1948; Goodman, 1975; Whitehead, 1976, 1978; Shaver, 1985). Anomalous ages for all the samples are interpreted to have resulted from partial to complete resetting by some later thermal or tectonic event.

## 7.2 Interpretations

### 7.2.1 Statistical Calculation

For all the glauconite grains, the recoil loss of $^{39}$Ar was in range from 20.9% to 30.3%. The recoil loss is the loss of $^{39}$Ar that occurs because the recoil energy following irradiation is sufficient to displace the atom to a distance of ~0.1 µm, which is a significant distance relative to the small grain size (~500-1000 nm thick) of clay minerals (Brereton, 1972; Turner and Cadogan, 1974). These recoil losses were fitted into a statistical calculation that shows recoil losses versus apparent ages to obtain a meaningful interpretation for all the analyzed data. All the samples collected and analyzed from the western Appalachian Basin were then fitted onto a best-fit line that gave an age range of 341.550 ± 8.828 Ma at zero recoil loss of $^{39}Ar$ (Fig. 7.3). This age compares well with the estimated biostratigraphic ages that point to a late Osagean age for the Floyds Knob interval (~ 343–341 Ma) (Butts, 1922; Stockdale, 1939; Weller et al., 1948; Goodman, 1975; Whitehead, 1976, 1978; Shaver, 1985), and also compare well with the recent international time scale (Fig. 7.4) (Davydov et al., 2004). In addition to the radiometric ages of the glauconites, a trilobite specimen was collected from the Floyds Knob Bed, Burkesville west (BW) section, Cumberland County (Appendix 1). The trilobite specimen (Fig. 7.5) has been identified as the species *Exochops portlocki* of Keokuk (late Osagean) age (D. Brezinski, 2011, pers. comm.). *Exochops portlocki* is a common trilobite of late Osagean age, which is present in the Keokuk and Warsaw formations of the Midcontinent and the upper Lake Valley Formation of New Mexico (Brezinski, 1999); however, this is the first reported occurrence of *Exochops portlocki* from Kentucky.




Calculation

| | | | | | | |
|---|---|---|---|---|---|---|
| 2.590000E-0001 | 2.000000E-0003 | 1.721116E-0001 | 7.146716E-0004 | 0.000000E+0000 | 5.020686E-0004 | 4.640114E-0004 |
| 2.090000E-0001 | 2.000000E-0003 | 1.779736E-0001 | 4.570655E-0004 | 0.000000E+0000 | 3.060067E-0003 | 1.156752E-0003 |
| 2.240000E-0001 | 2.000000E-0003 | 1.781695E-0001 | 5.224475E-0004 | 0.000000E+0000 | -1.089750E-0003 | -5.382260E-0004 |
| 2.370000E-0001 | 2.000000E-0003 | 1.760815E-0001 | 5.867118E-0004 | 0.000000E+0000 | -5.215924E-0004 | -3.248878E-0004 |
| 2.120000E-0001 | 2.000000E-0003 | 1.804574E-0001 | 5.888948E-0004 | 0.000000E+0000 | -1.722352E-0003 | -1.080811E-0003 |
| 2.440000E-0001 | 2.000000E-0003 | 1.751041E-0001 | 7.816322E-0004 | 0.000000E+0000 | -3.108868E-0004 | -3.436843E-0004 |
| 3.030000E-0001 | 2.000000E-0003 | 1.659557E-0001 | 2.003497E-0003 | 0.000000E+0000 | 8.244496E-0005 | 5.988166E-0004 |

slope= -1.38161652465518E-0001 +/- 1.47070271572098E-0002 mod 2.57956881963559E-0002
int= 2.08428894989583E-0001 +/- 3.37143555489807E-0003 mod 5.91339768524356E-0003
sums= 1.53820583047120E+0001 mswd= 3.07641166094240E+0000
xbar= 2.27996356500972E-0001 ybar= 1.76928541619291E-0001
Fitted authigenic age = 341.550 Ma +/- 5.033
Age error modified by scatter = 8.828 Ma

Figure 7.3 – Statistical calculations showing the best-fit line of modified ages for seven glauconite samples obtained from the Appalachian Basin.

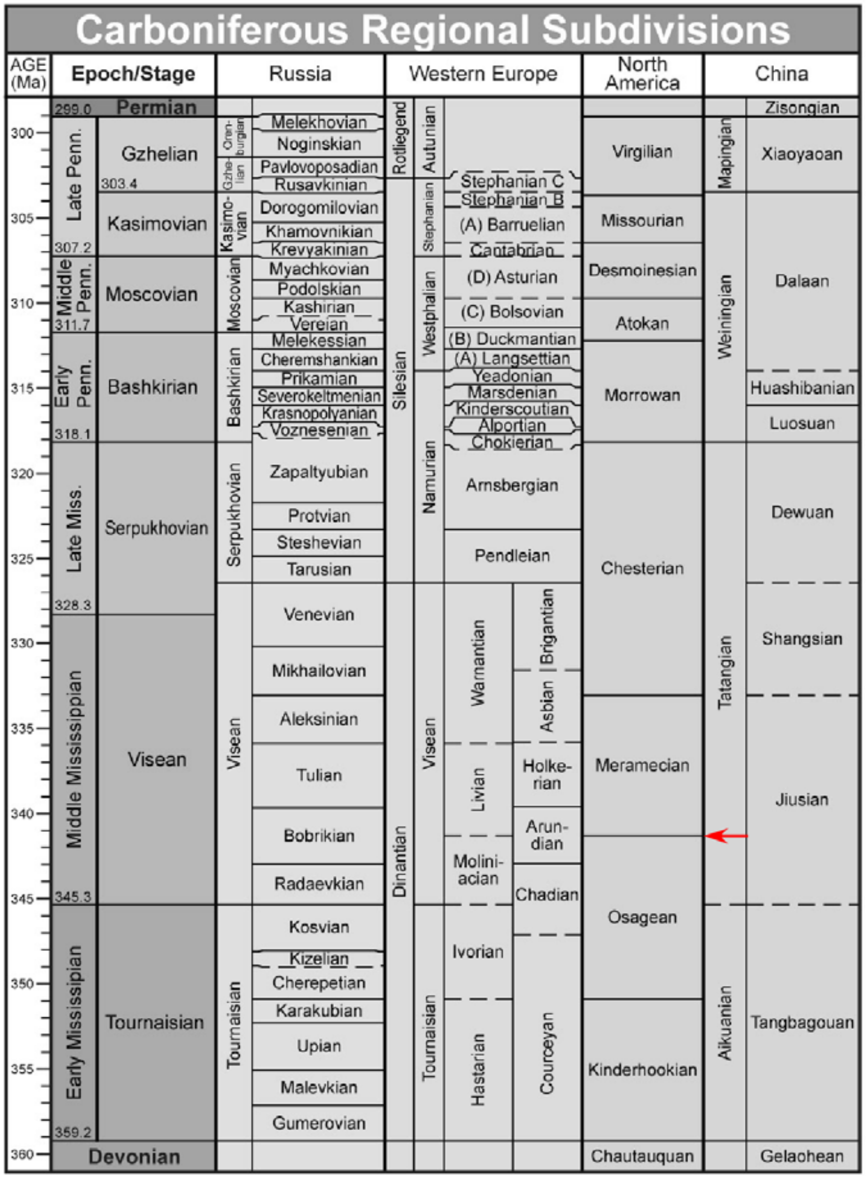



Figure 7.4 - Correlation of the international subdivisions of the Carboniferous System with selected regional stage and sub-stage nomenclature (modified after Davydov et al., 2004). Red arrow points to the Osagean–Meramecian boundary (341 Ma).

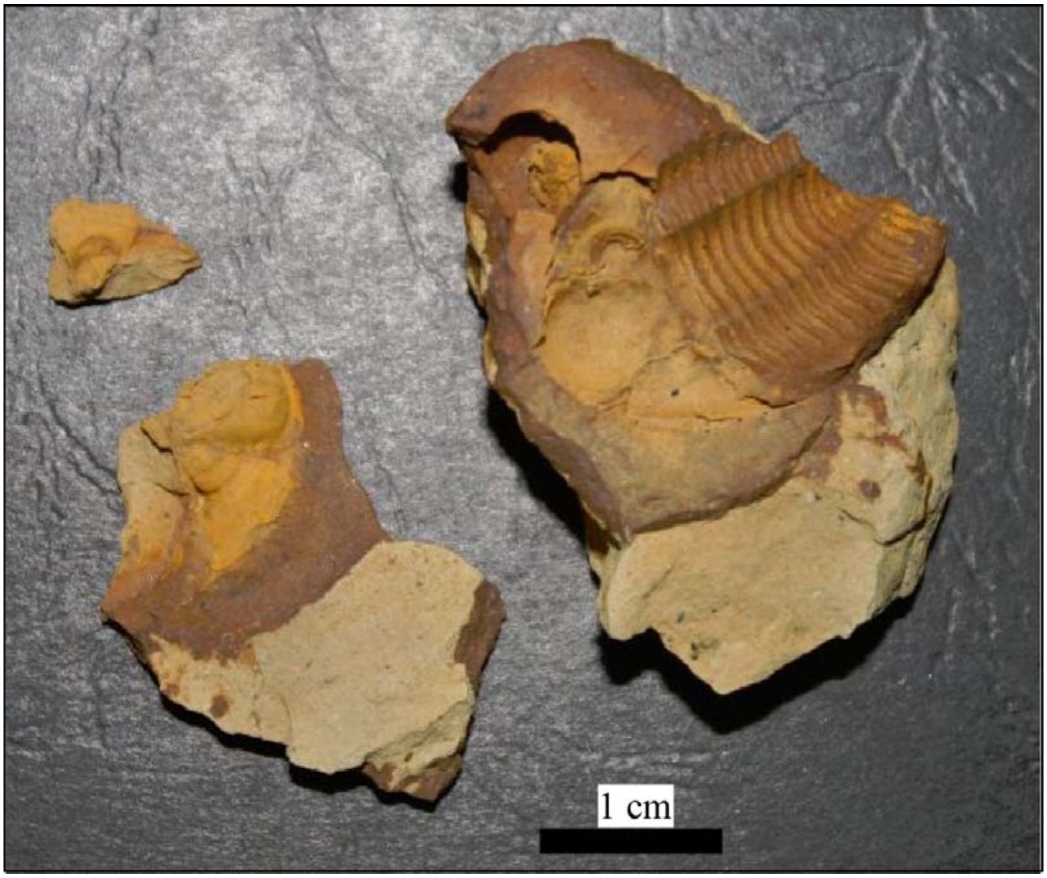



Figure 7.5 – Late Osagean (Keokuk) trilobite species *Exochops portlocki* from the Floyds Knob Bed, Burkesville west (BW) section (Kentucky Highway 90).

### 7.2.2 Resetting of the K–Ar system and the Maury Shale

The sampled area is in the western Appalachian and eastern Illinois basins, an area that was distal to the Appalachian orogen, and hence, experienced fewer effects from the various Appalachian orogenies. This area, which overlies parts of the Rome Trough, Cincinnati Arch, Grenville Front, and East Continent Rift Basin, is characterized by both E-W and N-S normal and reverse faults. These faults were originally the result of E-W compressive and extensional movements that developed during the middle Proterozoic (Keweenawan) Midcontinent Rift System, late Proterozoic Grenville Orogeny, and the latest Proterozoic-earliest Paleozoic Iapetan rifting. Although these structures may have been reactivated during various Paleozoic orogenies, there was no evidence that any of them would have contributed any tectonic thickening significant enough to have contributed to recrystallization or metamorphic activity.

However, the Ar data for the glauconites do show that apparent ages can be correlated with the advent of the Alleghanian Orogeny, which took place during Late Mississippian–Early Pennsylvanian–Permian time, between 328-265 Ma (Ettensohn, 2008). The Alleghanian Orogeny, moreover, may have tectonically thickened some units on the footwall side of the Pine Mountain Thrust, especially in eastern parts of the study area, or contributed altering hydrothermal solutions (McKee et al., 1967; Oliver, 1986; Friedman, 1987; Hearn et al., 1987; Elliot and Aronson, 1993). Hence, the glauconite ages obtained by the Ar-Ar technique (Table 7.2) were apparently reset during this phase of tectonic activity with a corresponding loss of the original depositional/diagenetic radiogenic Ar. Due to the fine-grained nature of the glauconite crystallites, the amount of radiogenic Ar loss could have been significant, resulting in total gas ages that are much younger than the estimated biostratigraphic ages.

The reported total gas age (278.78 ± 0.682 Ma; middle Permian) of the Maury Shale from the Illinois Basin presents a special problem with respect to the estimated biostratigraphic ages. The estimated biostratigraphic ages for the Maury Shale have suggested sedimentation during parts of the Kinderhookian and early Osagean stages (Conant and Swanson, 1961; Leslie et al., 1996). The Floyds Knob interval glauconites occur stratigraphically above the Maury Shale, but show total gas ages much older than the Maury Shale (Table 7.2). The Maury Shale is a glauconitic clayshale, and it can be interpreted that due to the fine-grained nature, it was prone to lose more radiogenic Ar ($^{40}Ar$), compared to the granular glauconites of the Floyds Knob interval. For such cryptocrystalline materials, various factors are responsible for the radiogenic Ar loss: 1) structural disruption of the clay minerals caused by $H_2O$ loss during laboratory heating (Evernden et al., 1960), 2) various alteration phases present inside the clay minerals may lose significant radiogenic Ar during neutron bombardment (Hess and Lippolt, 1986), and 3) Ar loss during later thermal or tectonic events contributing hydrothermal fluids.

The reported middle Permian total gas of the Maury Shale from the Illinois Basin (Figs. 7.1 and 7.2; Table 7.2) compares well with many previous studies, which suggest that hydrothermal-fluid circulation and tectonic thickening were playing major roles in sediment diagenesis and mineralization in the Illinois Basin. In particular, the Mississippi Valley-type fluoride mineralization from the Fluorspar district in the Illinois Basin of Kentucky and Illinois have been determined to have occurred during middle Permian time (Brannon et al., 1992; Chesley et al., 1994). Fluid-inclusion temperature measurements from the Fluorspar district range from 120°C to 175°C (Richardson and Pinckney, 1984; Taylor et al., 1992). These high temperatures and hydrothermal-fluid migration may have affected the Maury Shale, resulting in significant radiogenic Ar loss. Orogenesis and uplift of the Ouachita fold and thrust belt, which started in the Pennsylvanian and continued into the middle Permian time along the southern margin of Laurussia (Kolata and Nelson, 1991), are also likely to have produced the topographically driven northward hydrothermal fluid flow responsible for lead-zinc deposits of Arkansas, Missouri, and Kansas (Bethke et al., 1988; Graven et al., 1993). These northward-driven hydrothermal fluids may have contributed significantly in radiogenic Ar loss in the Maury Shale. At the eastern margin of the Illinois Basin, tectonic-stratigraphic models and fluid-inclusion temperatures suggest that the Cincinnati Arch and Nashville Dome were buried by 1-2 km of Late Pennsylvanian through Early Permian sediment (Stearns and Reesman, 1986; Beaumont et al., 1987). This tectonic thickening and elevated temperatures may also have resulted in variable amounts of radiogenic Ar loss from the Maury Shale.

For this study, however, only one sample from the Maury Shale was collected for the Ar-Ar analysis (Figs. 7.1 and 7.2). The result from this one analysis has proven to be inconclusive, and data collected are inadequate to provide a meaningful conclusion. In the future, more studies and more analyses will be needed to determine more accurate depositional ages for the Maury Shale.

# CHAPTER 8: INTERPRETATION

The Floyds Knob Bed is interpreted to have formed a thin, continuous layer on top of the Borden delta. It represents a widespread temporal marker horizon that was most probably deposited on a southward-facing paleo-slope along foresets of the Borden-Grainger delta front during a time of sediment starvation following the end of clastic influx (Stockdale, 1939; Kepferle, 1970, 1977, 1971, 1978; Sedimentation Seminar, 1972; Kepferle and Lewis, 1974; Pryor and Sable, 1974; Whitehead, 1978; Sable and Dever, 1990). Previous studies have suggested that the strata above and below the Floyds Knob Bed do not intertongue with each other, which implies that strata above and below are not lateral facies equivalents, but rather record two separate depositional episodes (Peterson and Kepferle, 1970; Kepferle, 1971; Sedimentation Seminar, 1972; Whitehead, 1978; Sable and Dever, 1990; Ettensohn et al., 2004). However, multiple glauconite-rich beds and intervals occur in some areas, so the Floyds Knob is better interpreted as an interval rather than a bed in most of the study area. The glauconites associated with the Floyds Knob interval largely record the replacement of fecal pellets that were concentrated during a time of sediment starvation and high organic activity, prolonged exposure of clay-size material at the sediment-water interface, and ingestion by organisms (Van Wie, 1971). The glauconite grains associated with the Floyds Knob interval are dark-green, microcrystalline, medium- to fine-sand sized (up to 0.5 mm in diameter) pellets that are concentrated along the bedding planes and in burrows. The important question now arises, what are the possible causes and implications of such widespread sediment starvation and suboxic water conditions that persisted briefly over such an extensive area?

## 8.1 Depositional Environments

Despite the fact that glauconite is typically deposited in suboxic, sediment-depleted settings,  petrology (Table 6.1), stratigraphic occurrence (Fig. 8.1), and paleogeographic reconstruction (Fig. 8.2) from the present study indicate that the glauconite deposition spanned several major depositional settings, again reinforcing the largely synchronous nature of the unit. These observed depositional settings will be described below.

### 8.1.1 Distal delta platform

The Floyds Knob interval in southern Indiana is characterized by basal, post-Borden erosion and deposition of a glauconitic crinoidal packstone-grainstone facies (Fig. 8.3). This facies is suggested to mark the beginning of a basin-wide transgression on an erosional surface (Whitehead, 1976, 1978). Petrographic examination of this facies indicates that the Floyds Knob Bed is composed largely of carbonate skeletal materials with abundant ooids that have been replaced by glauconite (Table 6.1, section identifier-IN). No peloidal glauconite grains were identified, but the presence of abundant ooids and skeletal materials suggests that the unit was deposited in high-energy conditions at or near the wave base (10 m) on a distal-delta-platform environment (Fig. 8.2). The area was apparently far enough removed from clastic sources to allow almost wholly pure carbonate deposition.

This platform very abruptly transformed into a delta front in northern Hardin County. The change occurs at the point where unnamed surface faults with a probable basement expression cross the outcrop (Figs. 8.2 and 6.16), which suggests that the delta platform–delta front termination may have been coeval with subsidence on the fault.

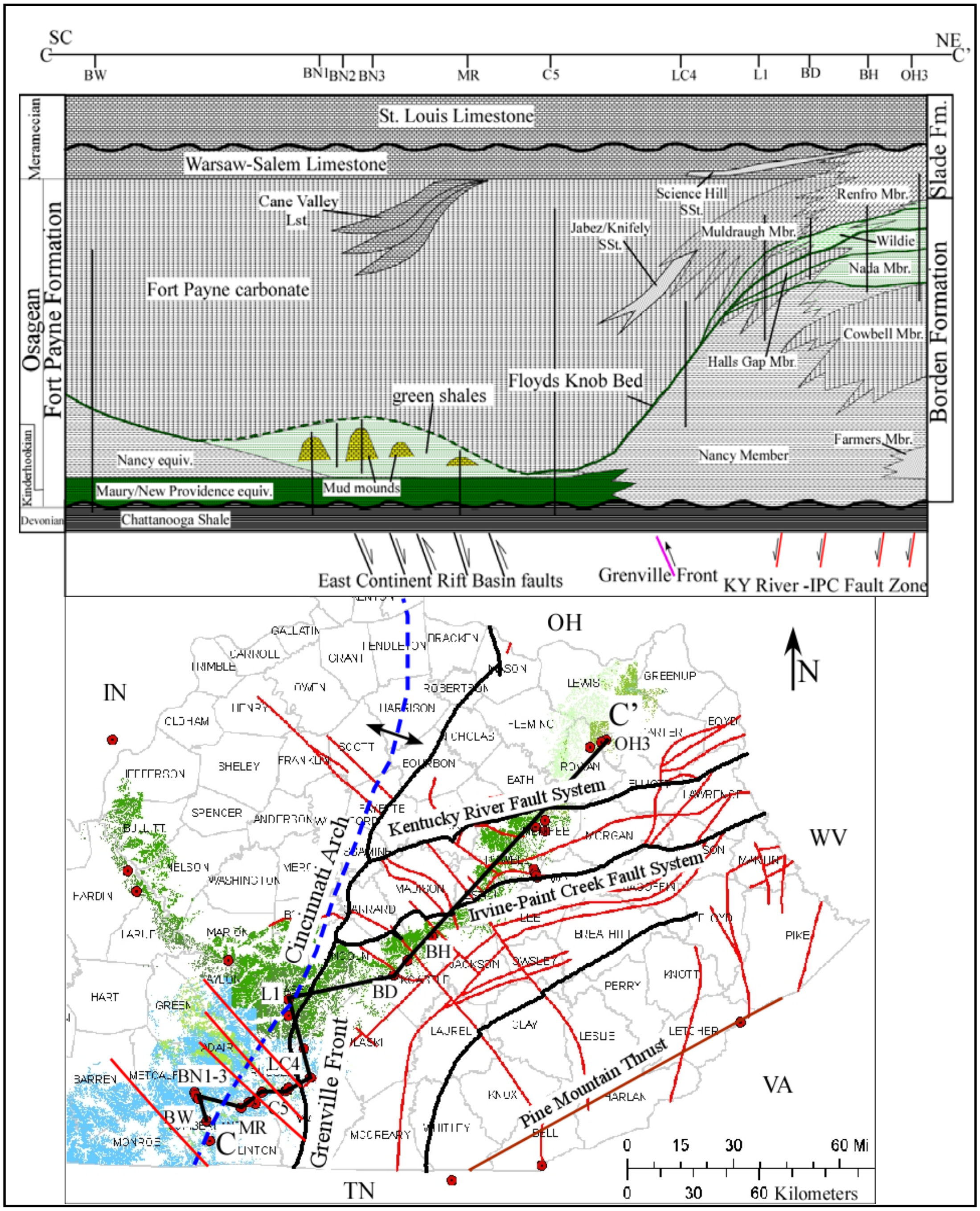



Figure 8.1 – Cross-section C-C' from northeastern to south-central Kentucky through east-central Kentucky showing the distribution of different units associated with the Floyds Knob Bed/interval in the western Appalachian and eastern Illinois basins. Datum is the top of the Upper Devonian Chattanooga Shale. Index map included below. Data from geological quadrangle maps were used, where study locations are absent. Not to scale.

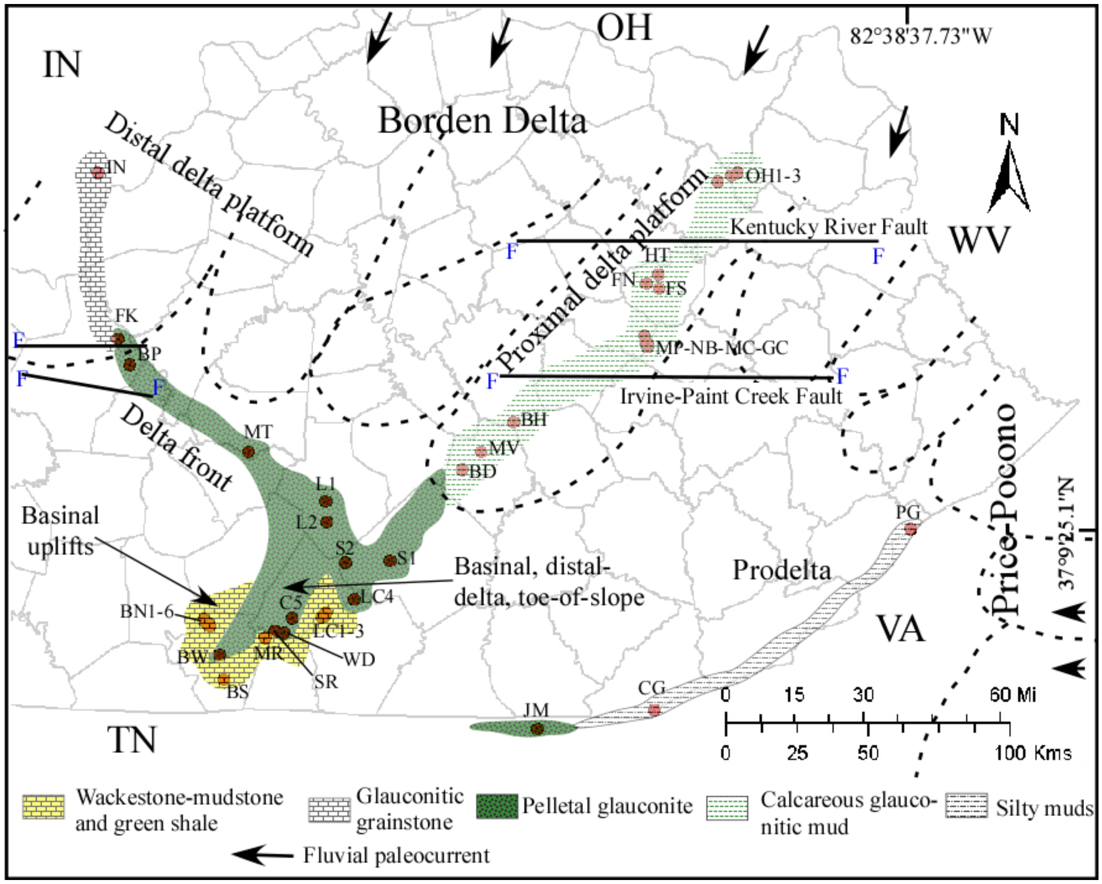
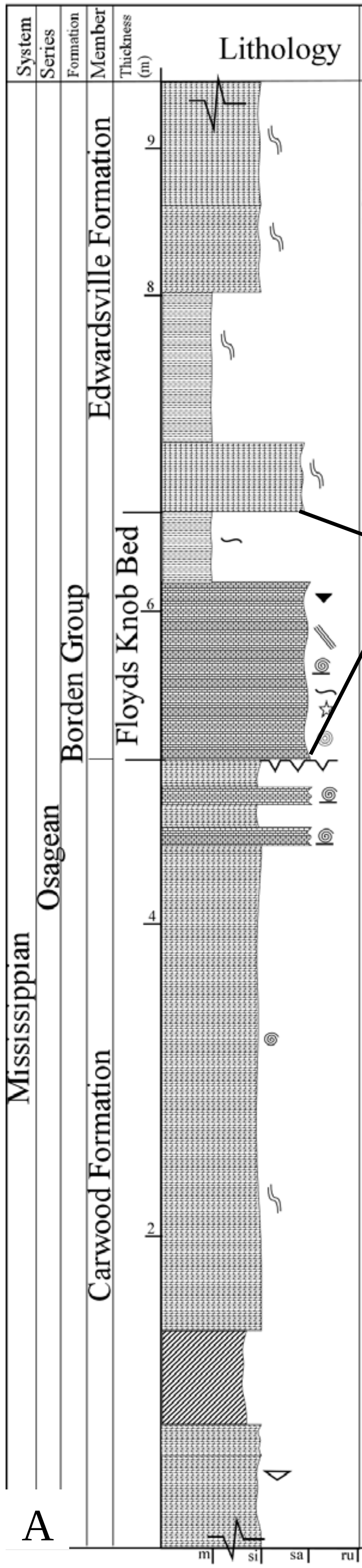



Figure 8.2 – Facies map for the Floyds Knob interval in Kentucky and adjacent states relative to the outcrop belt, and the inferred position of delta lobes (position of the delta lobes after Kepferle, 1977). Inferred faults were from geological quadrangle maps.



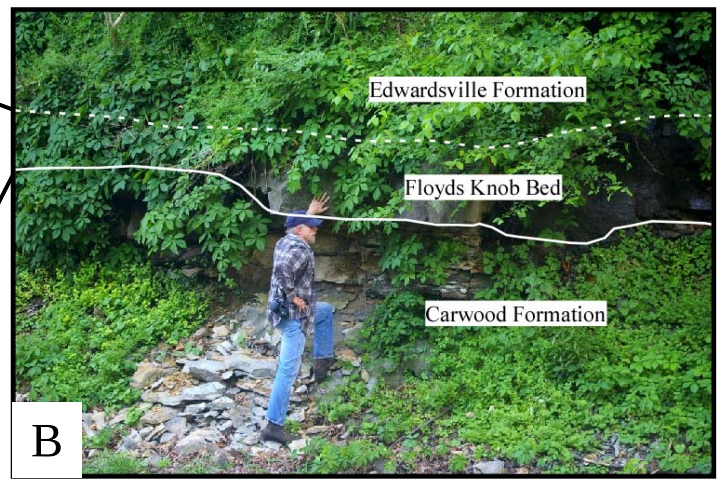




Figure 8.3 – A) Measured stratigraphic section at the Floyds Knob type (IN) section, Indiana. B) Field photograph of the type section.

### 8.1.2 Delta front

The Floyds Knob interval in west-central and south-central Kentucky, from Hardin County in the northwest to Russell County in the southeast at sections FK, BP, MP, L1, L2, S1, S2, and LC4 (Figs. 8.1, 8.2 and 8.4), is characterized by dark-green pelletal glauconite grains that occur with phosphate and chertified skeletal materials in a dark-gray dolomitic matrix (Table 6.1, section identifiers - FK and L1). The interval is extremely bioturbated and the glauconite is mostly concentrated in burrows and trails (Fig. 6.27A and B). In addition, the presence of small-scale hummocky cross-beds (Fig. 8.5) indicates that the interval was deposited in low-energy, sediment-starved conditions below normal wave base, but at or near storm wave base (~ 60 m) on a delta-front environment (Fig. 8.2). A major depocenter for this facies occurs in northern Hardin County and adjacent parts of LaRue County, where faults of Rome Trough and Rough-Creek Graben with probable basement expression cross the outcrop belt (Figs.8.2 and 6.16). This depocenter may be related to subsidence along the two faults, or the position and topography of the delta lobes (Fig. 8.2).

### 8.1.3 Prodelta

The Floyds Knob interval in southeastern Kentucky and western Virginia at sections PG and CG (Fig. 8.2) is characterized by a thin layer of medium-gray to greenish-gray silty muds that occur at the contact between the overlying Newman Limestone and underlying Grainger Formation (Fig. 8.6). The interval is bioturbated and has abundant chert and iron-oxide nodules, small-scale hummocky cross-beds, and alternate red shales (Fig. 8.6). These features indicate that the interval in this part of the basin was deposited in low-energy conditions below the normal wave base, but at or near the storm wave base in a prodelta environment, but deeper than the delta-front facies.

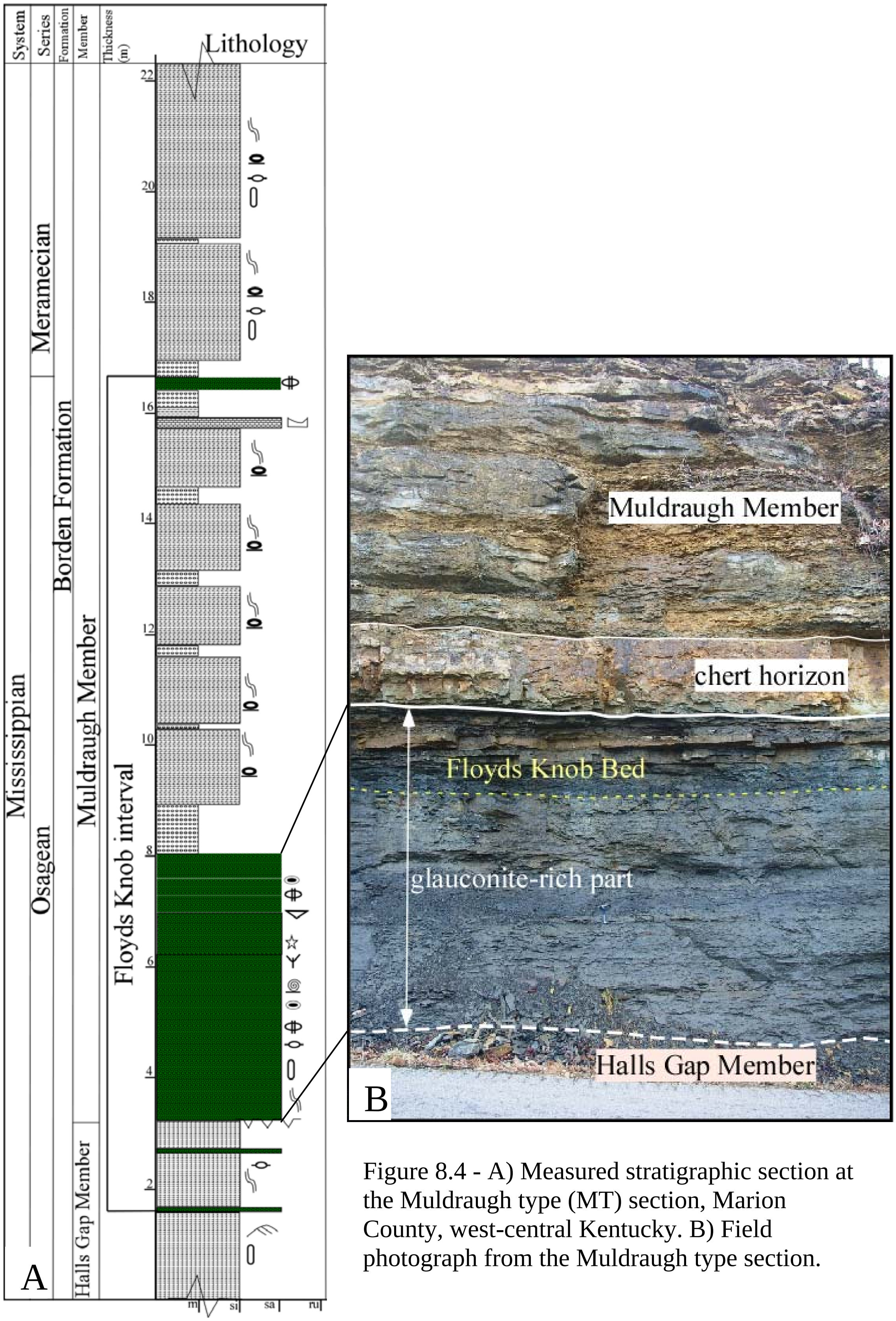



Figure 8.4 - A) Measured stratigraphic section at the Muldraugh type (MT) section, Marion County, west-central Kentucky. B) Field photograph from the Muldraugh type section.

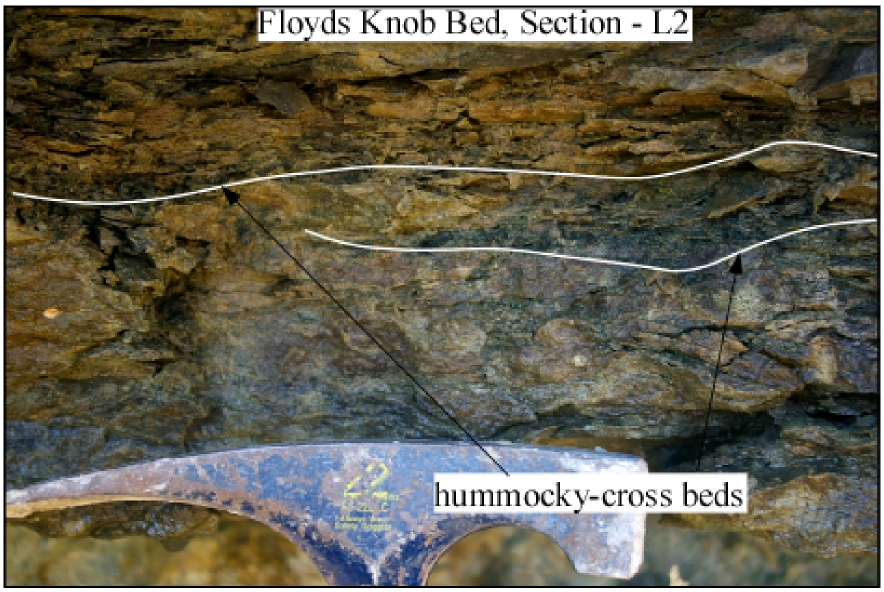



Figure 8.5 – Small-scale hummocky cross beds within the Floyds Knob Bed at the south end of the Liberty section 2 (L2). Presence of hummocky cross-beds indicates deposition at or near storm wave base.

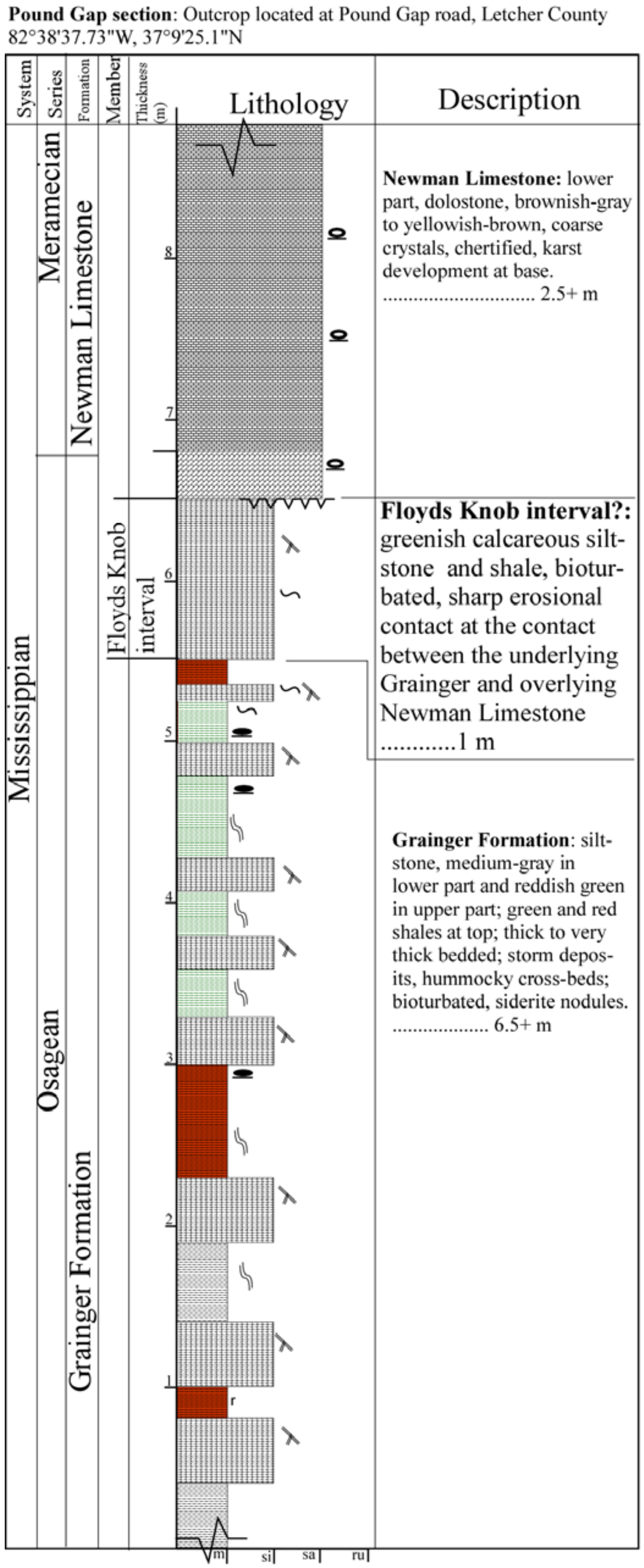



Figure 8.6 – Measured stratigraphic section at Pound Gap (PG), US Highway 119.

### 8.1.4 Basinal

The Floyds Knob interval in Cumberland and Russell counties, south-central Kentucky (Fig. 8.2, section identifiers C5, SR, and BW) is characterized by dark-green pelletal glauconite grains that occur with phosphate and chertified skeletal materials in a dark-red dolomitic matrix (Table 6.1, section identifiers - C5 and BW). The Floyds Knob occurs at the contact between the overlying Fort Payne carbonates and underlying Nancy-equivalent silty shales, suggesting that the area in south-central Kentucky experienced sediment-starved conditions (Fig. 8.7). The interval is extremely bioturbated and the glauconite is mostly concentrated in burrows and trails (Fig. 6.27C); small-scale ripple marks (Fig. 8.8) indicate that the interval was deposited in low-energy conditions below normal wave base, but at or near storm wave base (~ 60 m) in a deep, distal, basinal environment, deeper than typical delta-front and prodelta facies (Fig. 8.2) .

The presence of dolomitic concretionary units that outline channels in Nancy-equivalent silty shales below the Floyds Knob Bed at the Burkesville west (BW) section (Fig. 8.9) may reflect the fact that deeper water, bottom-hugging currents were transporting sediments from the northwest along deep parts of the delta-front.

The isopach map for the Floyds Knob interval (Fig. 6.16) in this area shows a substantial decline in thickness in this basinal area compared to adjacent delta-front areas to the north and northeast and surrounding mud-mound areas to the east and southwest (Fig. 6.16). It seems likely that the distal nature of the area (Fig. 8.2), its presence at the delta-slope toe (Fig. 8.1), and the fact that it was largely surrounded by an elevated mud-mound facies (Figs. 6.16, 8.1 and 8.2) effectively isolated the area, thereby contributing to the general thinness of the unit in this area.

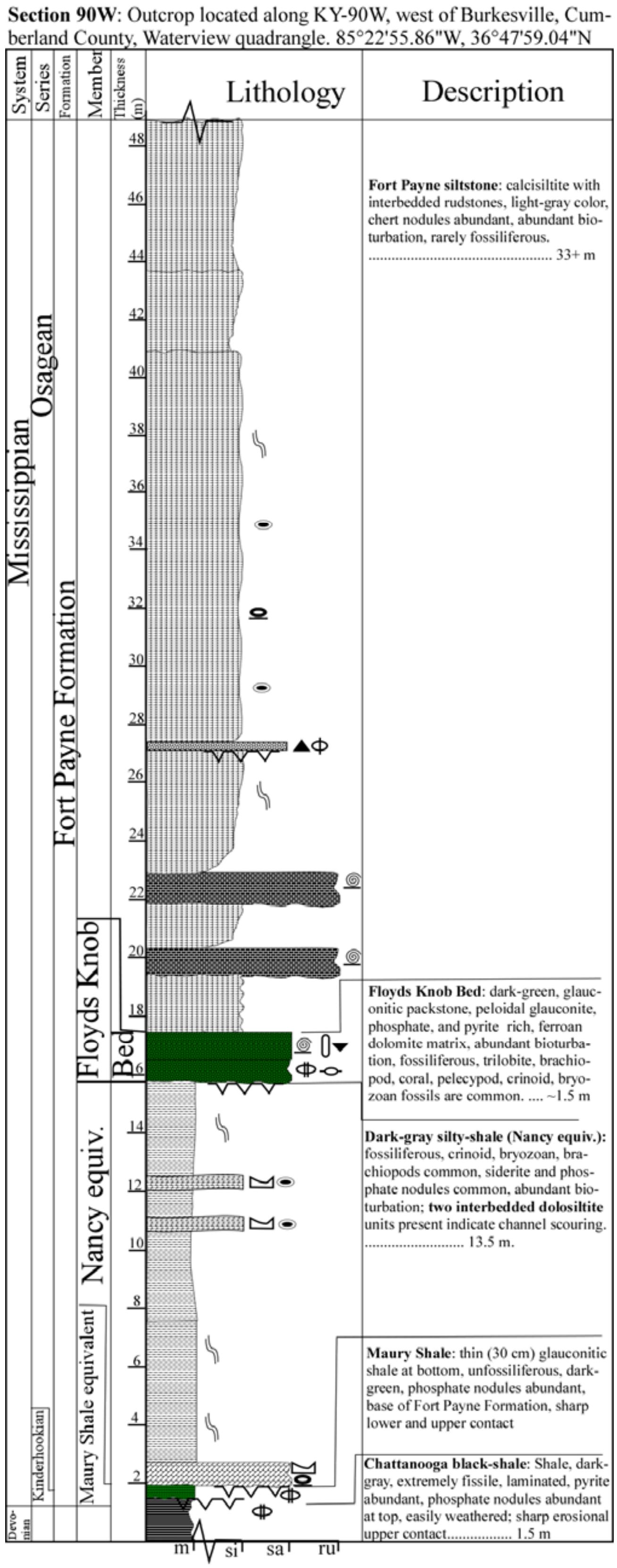



Figure 8.7 – Measured stratigraphic section at the Burkesville west section (BW).


Figure 8.8 – Floyds Knob Bed from the Burkesville west (BW) section showing small-scale ripple marks and wavy bedding. This suggests that the unit was deposited at or above the storm wave base, so that storms periodically reworked the glauconite.

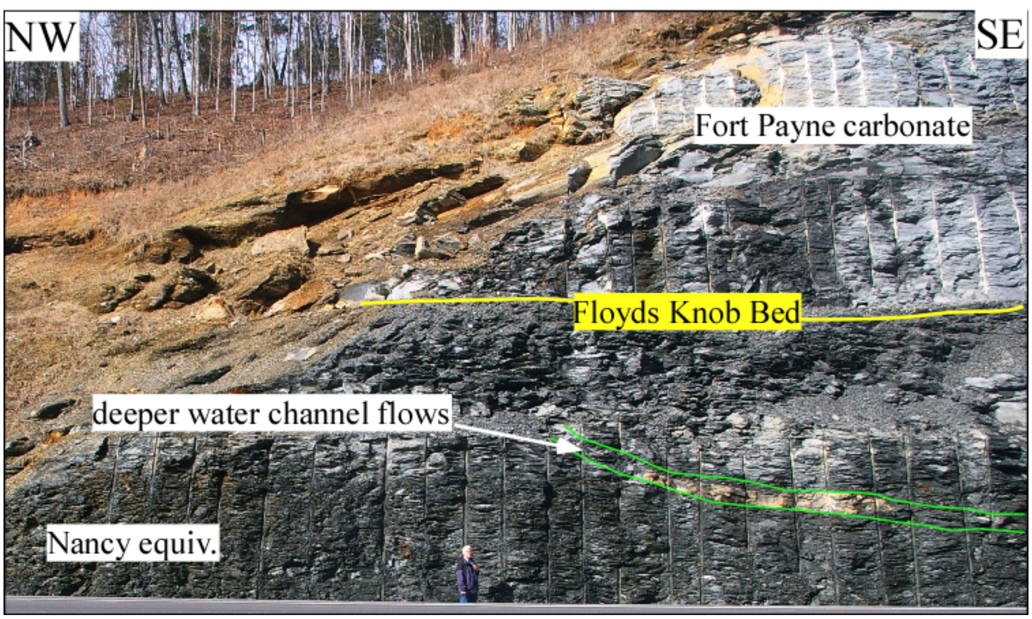



Figure 8.9 – Section photograph from the Burkesville west (BW) section showing the evidence for deeper water channel flows during the deposition of Nancy-equivalent shales.

### 8.1.5. Proximal delta platform

The Floyds Knob interval in east-central and south-central Kentucky occurs within the Nada and equivalent Wildie members (Figs. 6.18, 8.1 and 8.10). The interval is characterized by dark-green, pelletal glauconite grains that occur with phosphate, secondary calcite, and glauconitic replacement of skeletal materials (Table 6.1, section identifiers - BD, BH, OH3). The interval is extremely bioturbated and the glauconite is mostly concentrated in burrows and trails (Fig. 6.27D). Small-scale hummocky cross-beds, glauconite-rich shales and siltstones, as well as glauconite-rich horizons along the partings in siltstones (Figs 6.18 and 8.10; Appendix 1), suggest that the areas may have experienced sediment starvation in open-marine, shallow-water environmental conditions that were influenced by episodic storm events across the proximal delta platform at the top of an abandoned delta lobe during a sea-level low stand (Fig. 8.2) (Chaplin, 1980; Lane and Dubar, 1983; Kepferle, 1977; Ettensohn, 1979, 1980, 1981; Gauthier, 1988; Ettensohn et al., 2004). Moreover, the occurrence of red shales in Nada and equivalent Wildie members in east-central and northeastern Kentucky may reflect the reworking and transportation of red muds from the shallower peritidal Maccrady environment to the east during a sea-level lowstand (Fig. 6.18).

The outcrop belt in east-central Kentucky seems more or less to follow an individual delta lobe to the southwest (Fig. 8.2). Although Floyds Knob-equivalent units like the Nada and Wildie naturally thicken to the northeast, a small depocenter between northern Menifee County, and Powel and Wolfe counties occurs between the Kentucky River and Irvine-Paint Creek fault systems (Fig. 6.16), suggesting that the basement precursors of these faults were probably active during Floyds Knob deposition and later

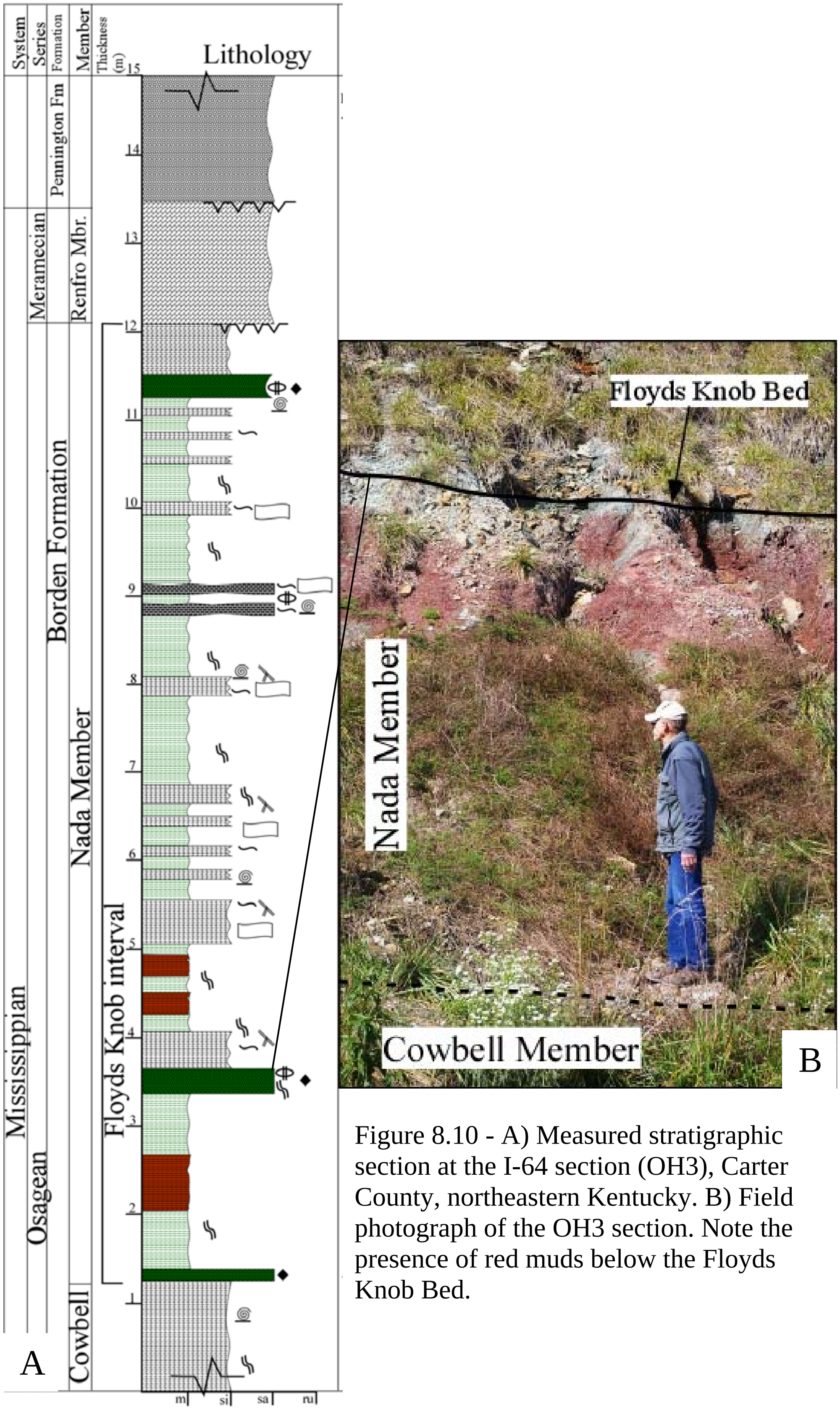



Figure 8.10 - A) Measured stratigraphic section at the I-64 section (OH3), Carter County, northeastern Kentucky. B) Field photograph of the OH3 section. Note the presence of red muds below the Floyds Knob Bed.

during Mississippian carbonate deposition (Sable and Dever, 1990; Dever, 1995; Wilhelm, 2008).

In contrast to the relatively thin, pure carbonates that were being deposited at the time on the distal delta platform (Figs. 6.16 and 8.2), the thicker, more clastic-rich sediments on the proximal delta platform reflect this lobe's more proximal position relative to eastern source areas, which suggests that the thickness variations in the Floyds Knob interval may also be associated with the position and topography of the delta lobe (Fig. 8.2).

**8.1.6 Toe-of-slope carbonate-mud mounds**

The Floyds Knob interval in Russell, Clinton, and Cumberland counties, south-central Kentucky (Fig. 8.2, section identifiers - LC1, LC2, LC3, MR, BN1, BN2, and BN3), is represented by carbonate mud mounds and the associated green fossiliferous shale facies (Figs. 6.22 and 8.1). The mud mounds and the green shales are situated at the top of Maury/New Providence-equivalent, glauconitic- and phosphate-rich shale (Figs. 6.7, 6.22, 8.1, and 8.11). The green fossiliferous shales surrounding the mud mounds are characterized by very finely disseminated glauconite- and chlorite-rich clays, and occur with phosphate nodules (Fig. 6.14; Table 6.1, section identifier-BN3).

Most of the more recent research has suggested that the carbonate-mud mounds present in the lower part of the Fort Payne Formation in south-central Kentucky and north-central Tennessee were deposited in relatively deeper water, but within the photic zone on a southward facing paleoslope in front of the abandoned Borden delta (Fig. 8.12) (MacQouwn and Perkins, 1982; Ausich and Meyer, 1990; Meyer et al., 1995; Khetani and Read, 2002; Krause et al., 2002; Krause and Meyer, 2004; Greb et al., 2008). The thin-bedded, flat-lying, green fossiliferous shales above the Maury Shale, which act as the background sediment in which the mud mounds developed, are interpreted to have been produced by turbidity currents, slumps, and slides on the delta paleoslope (Lewis and Potter, 1978; Ausich and Meyer, 1990; Meyer et al., 1995; Krause et al., 2002; Krause and Meyer, 2004). These mud mounds most likely developed on paleotopographic highs, created by the differential sediment accumulation on the basin-floor (Lumsden, 1988; Ausich and Meyer, 1990; Stapor and Knox, 1995).

However, the Fort Payne mud mounds and associated green shales may also have developed over deep, structurally, uplifted areas, (Fig. 8.2), in shallower, warm waters within the photic zone, as evident by the occurrence of coral communities (Fig. 8.13). Jeffery (1997) has suggested that carbonate mud mounds are relatively common atop structures that can elevate themselves into shallower, sunny, more active waters. The presence of rugose and tabulate corals (Fig. 8.13) along with an abundance of echinoderm debris in the Fort Payne mud mounds indicates the presence of active waters that kept colonies clean and supplied nutrient- and oxygen-rich waters. In addition, the presence of rugose and tabulate corals, which are assumed to have contained algal symbionts, like their modern ancestors, calls for well-lit water less than 100 m deep. This is also confirmed by the presence of clotted carbonate muds (Fig. 8.14), which have been attributed to algal mats and other forms of algae apparently living on the mound surfaces (Krause and Meyer, 2004). The distal location of these mounds, as well as their elevated nature, would have insured a relatively clastic-free setting.

The mound area overlies basement faults of the Precambrian East Continent Rift Basin and Grenville Front. These structures may have been reactivated to elevate overlying areas.  Migrating Neoacadian tectonic bulge may also have caused their uplift. Moreover, synsedimentary growth structures and angular unconformities associated with the mud-mound section (Figs. 8.11, 8.15, 8.16 and 8.17) may well support the reactivation of these structures at depth. These growth structures could also be related to slope processes and sediment compaction. Periodic storms apparently kept the mound tops clean and well-exposed in well-lit, active waters. However, the same storms would have reworked nearby delta-front and prodelta muds, not to mention nearby glauconitic muds. These muds would have accumulated in quiet, low places between the mounds, and with rising sea level, would have eventually buried the mounds. While the mounds were active, gravity- and storm-reworking of skeletal debris from the top of the mounds would have generated the many grainstone and packstone layers found in the surrounding green shales.

**Section 61N-3**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°25'46.74"W, 36°54'0.6"N

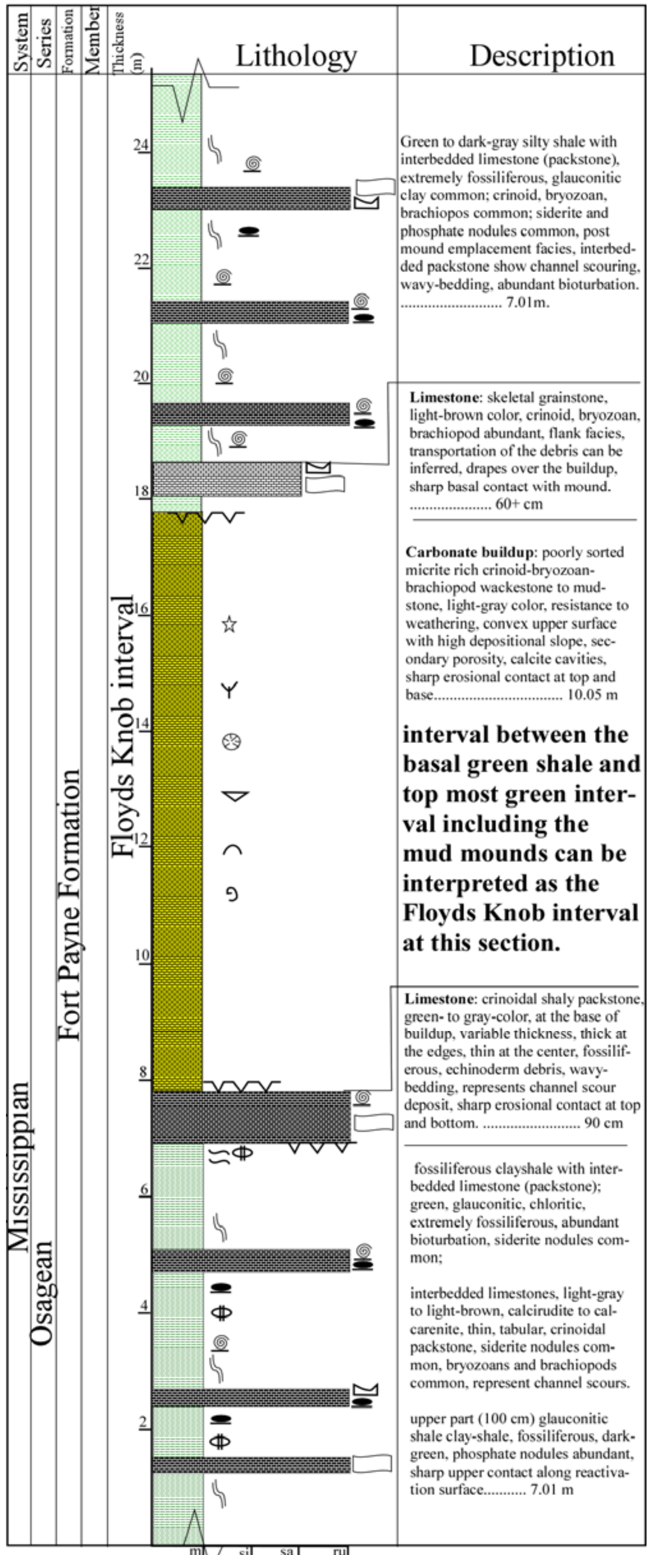



Figure 8.11 – Measured stratigraphic section at the Burkesville north (BN3) section.

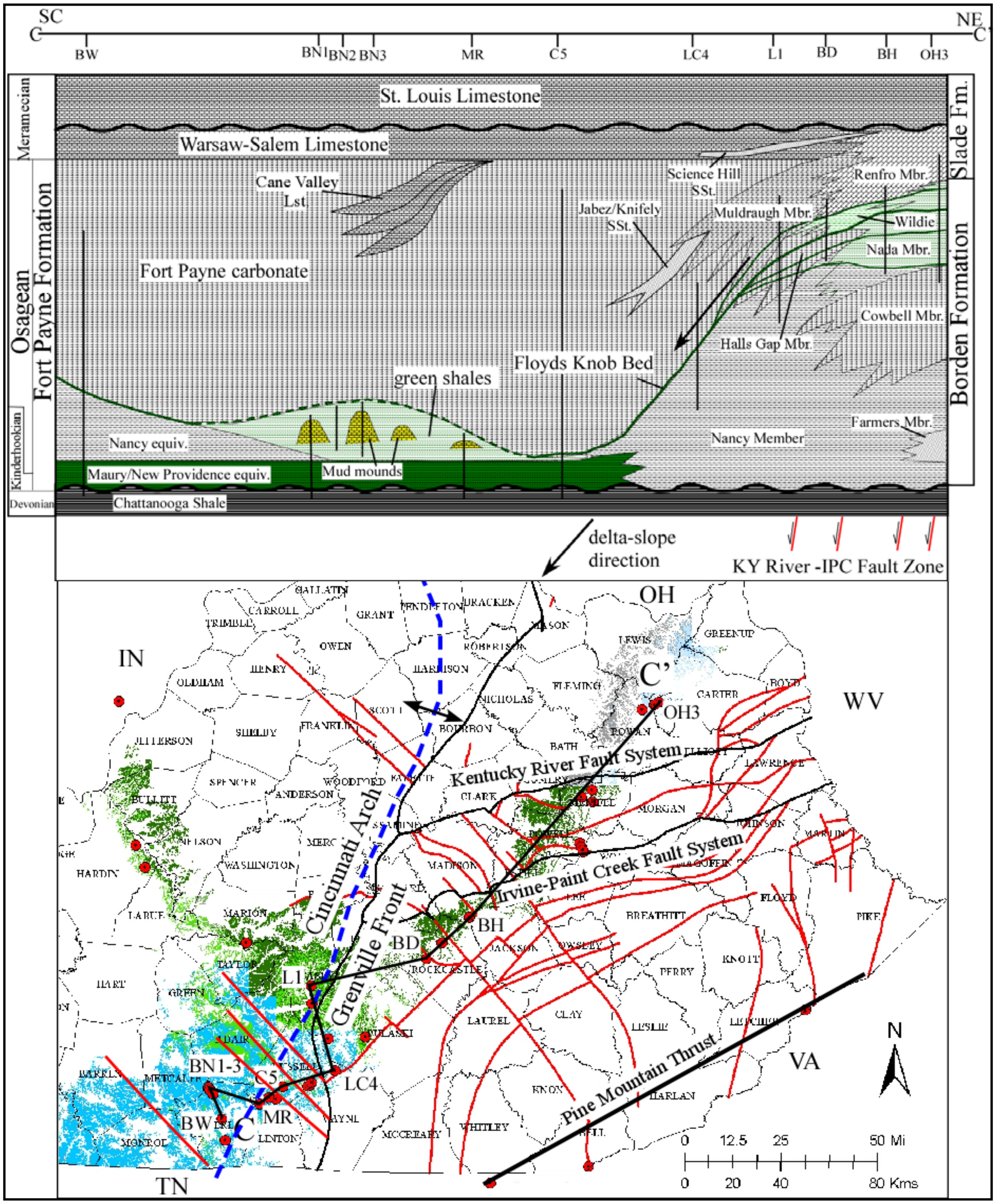



Figure 8.12 – Interpreted lithostratigraphic relationships between the Borden siliciclastic and the Fort Payne carbonates across the western Appalachian and eastern Illinois basins (Kinderhookian–Osagean). Datum is the top of the Upper Chattanooga Shale. Index map included at bottom.

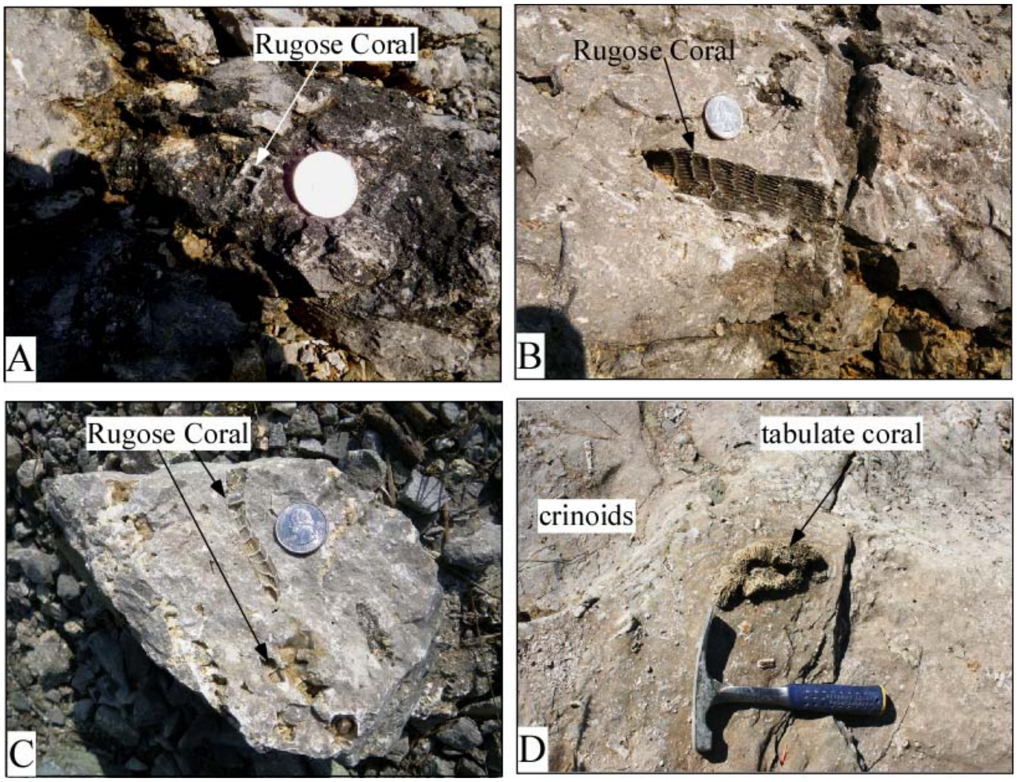



Figure 8.13 – Observed coral and fossil communities from the mud mounds. (A, B, C) from the Burkesville north (BN3) section; D) from the Lake Cumberland (LC2) section.

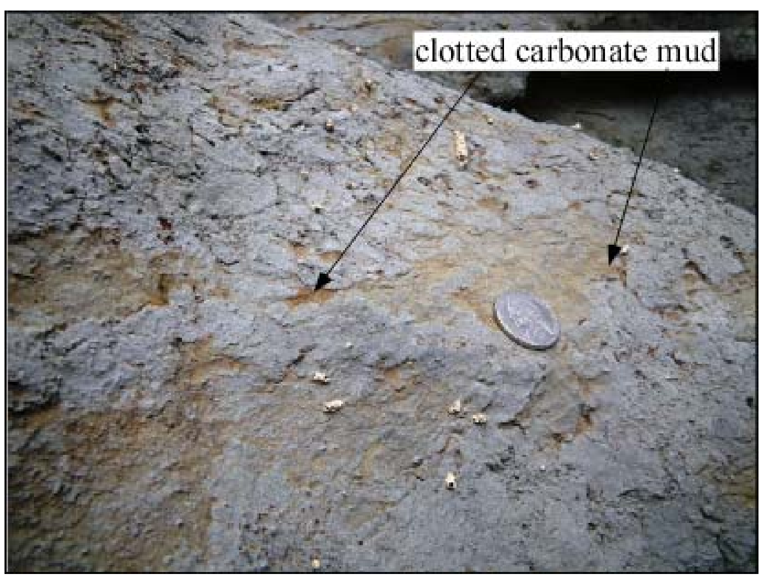



Figure 8.14 – Clotted carbonate muds on the mud mounds with fossils. Photograph from the Mantown Road (MR) section, Clinton County.

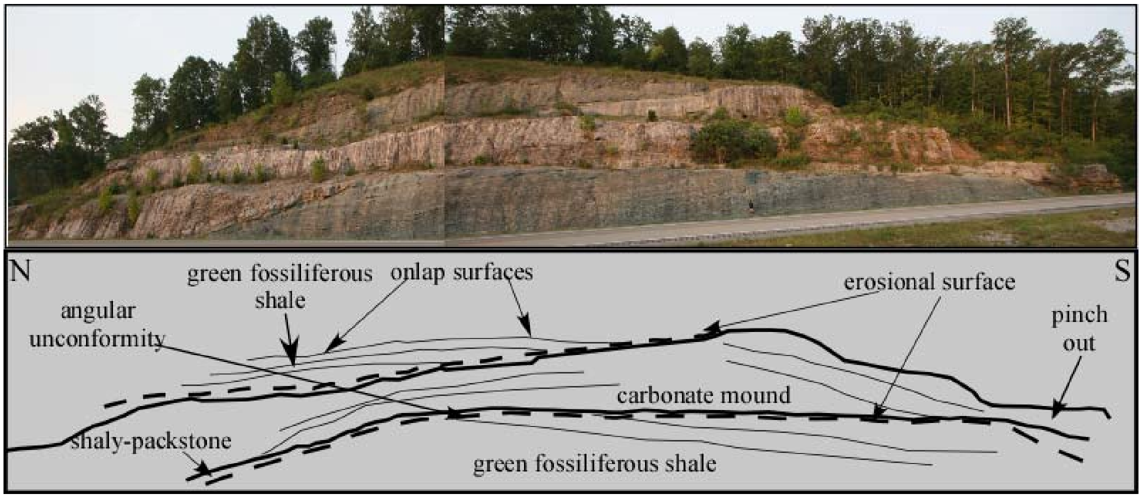



Figure 8.15 – Carbonate mud-mound photograph and interpretations from the Burkesville north section 3 (BN3). Mound core and post-mound facies drape over, pinch out, and show angular relationships with the undeformed mound facies.

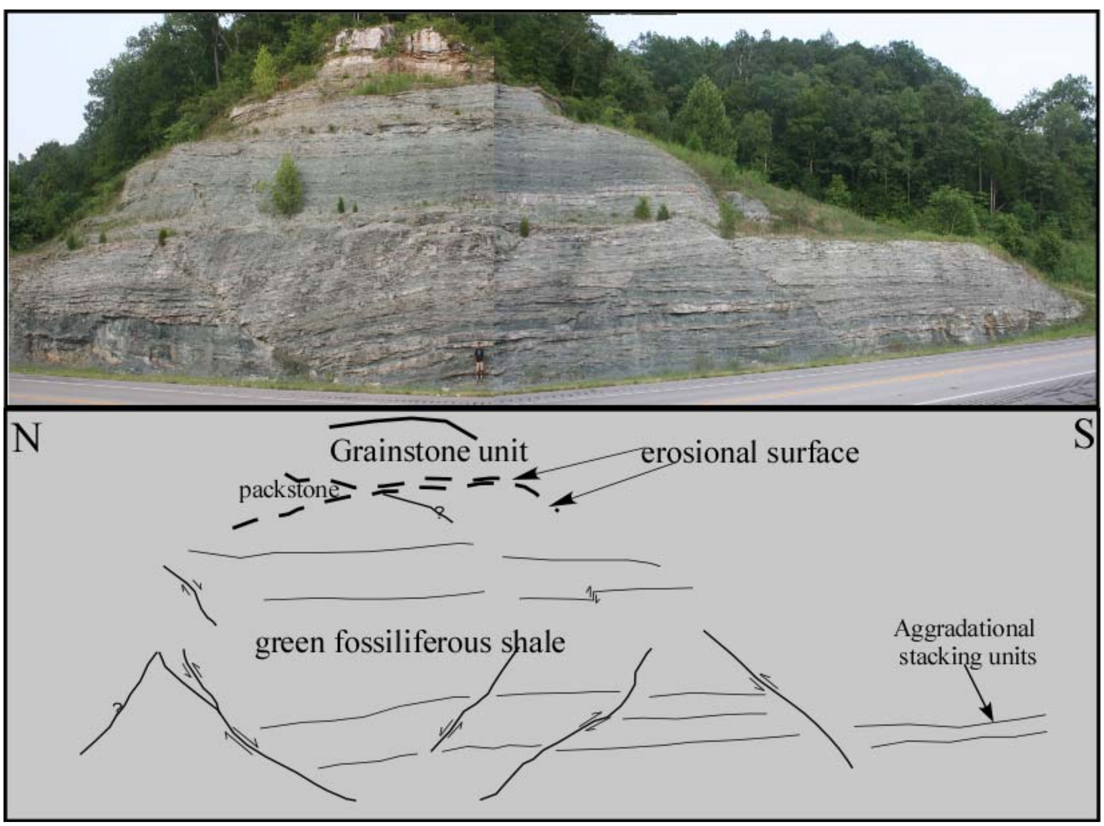



Figure 8.16 – Synsedimentary growth structures in the green fossiliferous shales surrounding the mud mounds at the Burkesville north (BN2) section.

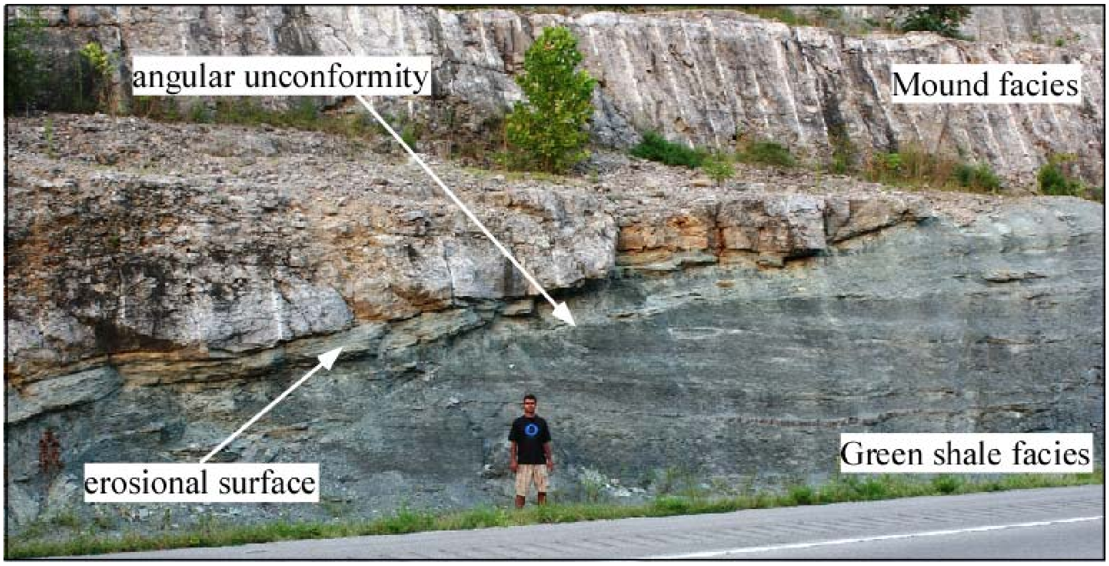



Figure 8.17 – Carbonate-mud mound from the Burkesville north section, Cumberland County, showing angular unconformable relationship between green-shale facies and mound facies.

### 8.2 Timing of deposition of the Floyds Knob interval

It has been postulated that the Floyds Knob interval records a break in deposition between the clastic-dominated Borden-Grainger deltaic sequence and the carbonate-dominated Slade Formation during late Osagean–early Meramecian time (Kepferle, 1971; Whitehead, 1976, 1978, Sable and Dever, 1990). The nature of glauconite deposition and its occurrence across such a widespread area suggests that the deposition event was largely penecontemporaneous across several different environments. $^{40}Ar/^{39}Ar$ absolute dating (341.55 Ma) of glauconites from the Floyds Knob interval suggests a late Osagean time, but likely experimental error indicates the possibility of an early Osagean to early Meramecian time (Fig. 7.2). However, mega-fossil studies of Keokuk-type brachiopod fauna, miospore biostratigraphic studies, and conodonts point to a late Osagean age 341 Ma) (Butts, 1922; Stockdale, 1939; Weller et al., 1948; Goodman, 1975; Whitehead, 1976, 1978; Shaver, 1985; Richardson and Ausich, 2004). Widespread development of the Floyds Knob interval across central and eastern Kentucky and in parts of Indiana and Tennessee at this time suggests a regional causative event, either eustatic, tectonic, or a combination of both.

#### 8.2.1 Tectonic-eustatic events

Before the deposition of the Floyds Knob interval in late Osagean time, vast amounts of clastic debris from the Borden-Grainger delta complex (Figs. 8.1 and 8.2) were deposited across the craton to the west of the orogenic front in a subsiding foreland basin during the final Acadian/Neoacadian tectophase, reflecting the loading-type relaxation and equilibrium stages of a lithospheric flexural response to orogeny (Ettensohn, 1993, 1994, 2004; Ettensohn et al., 2004) (Figs. 8.18 and 8.19). Most of the clastics from the orogenic

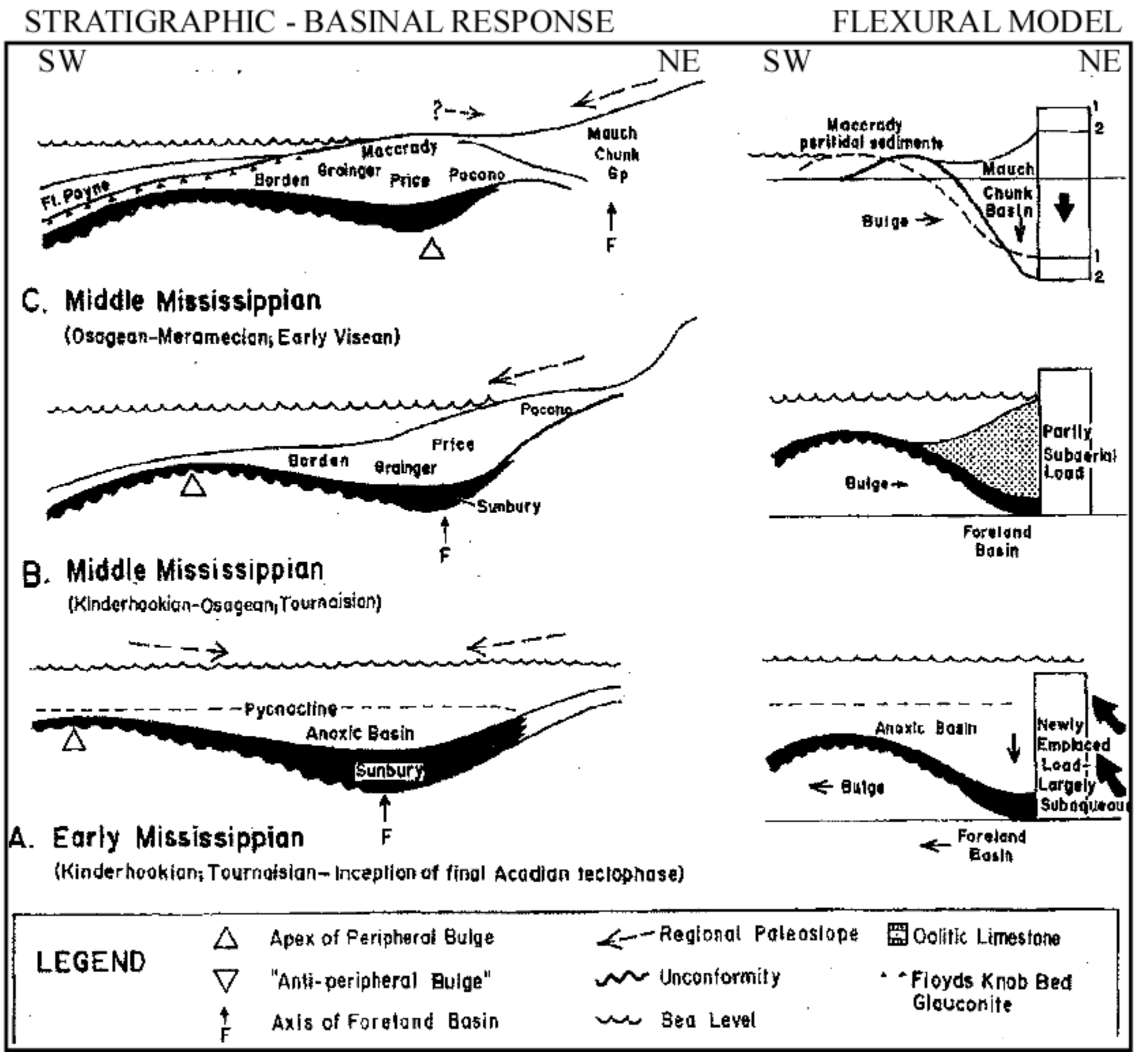



Figure 8.18 – Schematic southwest-northeast cross-section across central Appalachian Basin showing Mississippian units and lithologies with respect to the flexural events of the Early–Middle Mississippian Neoacadian tectophase of Acadian Orogeny (adapted from Ettensohn et al., 2004).

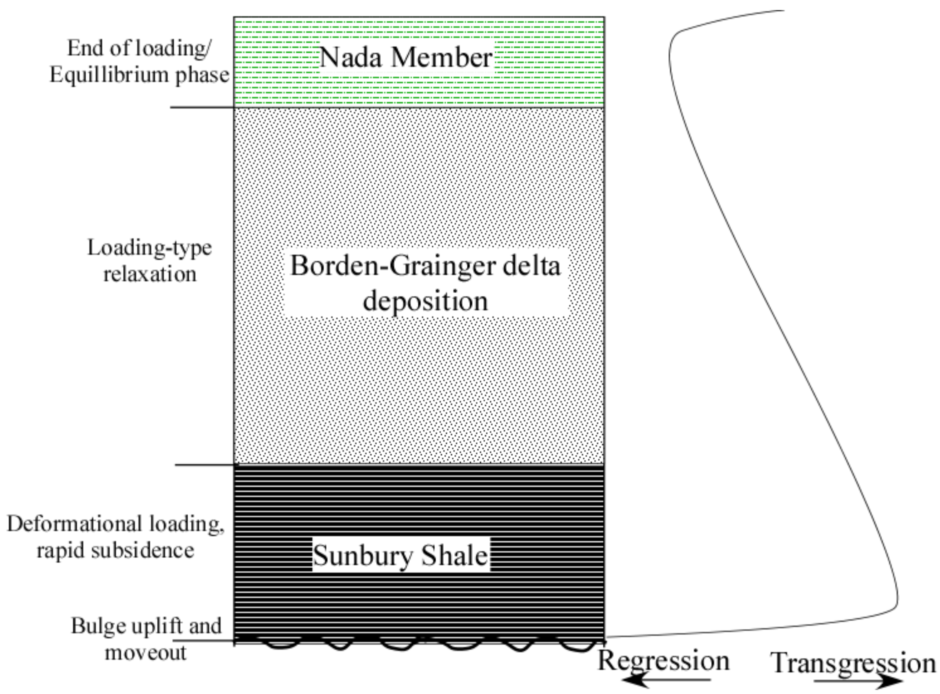



Figure 8.19 – Early flexural stratigraphic sequence, showing flexural events, accompanying lithologies, and a relative sea-level curve (modified from Ettensohn et al., 2002, Figure 11).

load were derived from the convergence of the Carolina terrane with the New York and Virginia promontories of the eastern Laurussia (Ettensohn, 1994, 2008; Merschat and Hatcher, 2007).

The Sunbury Shale and its equivalents in the upper Chattanooga and New Albany shales (Falling Run Bed; Fig. 5.2) represent the sedimentary response to initial convergence between the continent and terrane that created major deformation and deformational loading in the Appalachian Basin. South-central, west-central, and east-central Kentucky were so far distal that only very thin Sunbury equivalents or thin concretionary zones (Falling Run Bed) were deposited (Fig. 5.2). Once the cratonward movement of the load ended, loading-type relaxation of the crust below the now static load ensued, deepening the foreland basin and causing the forebulge to move cratonward. By this time, the load was eroding and vast amounts of clastic debris were shed westward into the foreland basin as the Price-Pocono-Borden-Grainger delta complex (Figs. 8.18 and 8.19). The distal most part of the Borden-Grainger in south-central Kentucky, however, is represented by the thin Maury Shale/New Providence equivalent glauconite-rich clayey shale facies. It occurs immediately above the Falling Run Bed across an unconformity, and was possibly deposited in sediment-starved conditions in deeper water, anoxic environment. The fine-grained nature of the glauconite in the Maury could be attributed to the absence of burrowing animals in deeper, anoxic environment, which prohibited significant fecal matter accumulation. This all happened during middle-late Osagean time. At the same time, the region was experiencing a major sea-level drawdown (Fig. 8.20), probably related to increased glacial ice volume on Gondwana (Ross and Ross, 1988; Mii et al., 1999; Davydov et al., 2004; Haq and Schutter, 2008).

The eastwardly migrating bulge effectively formed a regional barrier, blocking farther westward sediment influx into the western Appalachian Basin, while sea-level drawdown (Fig. 8.20) generated delta-destruction facies like the Nada and Wildie equivalents and high-energy carbonate facies on more distal delta platforms (Fig. 8.2). In these settings, peritidal and evaporitic sediments developed on the bulge in the Maccrady Formation (Fig. 8.18; Warne, 1990) to the east (Virginia, West Virginia, and Tennessee), whereas farther to the west in Kentucky, central Tennessee,

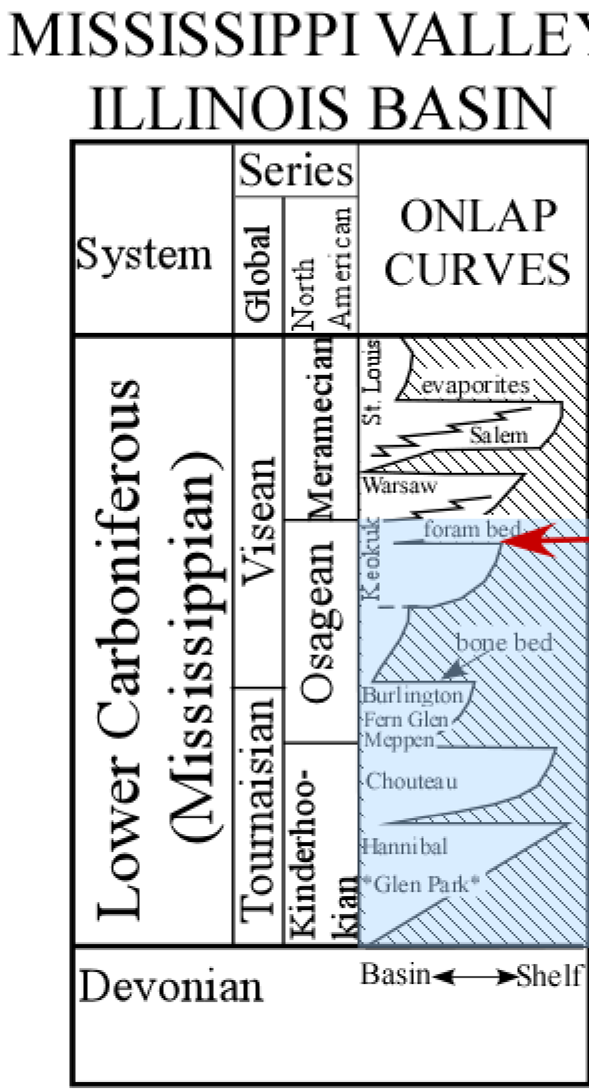



Figure 8.20 – Relative coastal onlap curve for the Mississippi Valley/Illinois Basin type (Keokuk) section (from Ross and Ross, 1988). Blue rectangle represents the study interval in the Appalachian and Illinois basins of Kentucky and adjacent states. Red arrow represents the period of onlap/offlap for the Floyds Knob interval in the Borden and Fort Payne formations. Five episodes of onlap can be seen during Kinderhookian–Osagean time on the North American craton.

and southern Indiana, the Floyds Knob interval developed in sediment-starved, sub-oxic conditions on top of and in front of the abandoned Borden delta (Chaplin, 1980; Lane and Dubar, 1983; Kepferle, 1977; Ettensohn, 1980, 1981, 1994, 2002; Gauthier, 1988; Ettensohn et al., 2004). In fact, the Floyds Knob interval effectively represents the boundary between clastic-rich parts of the Borden-Grainger complex and the Fort Payne Formation, and overlying carbonate-rich parts of the Borden (Nada, Wildie, Muldraugh, and lower Edwardsville (Figs. 6.8, 6.18, and 8.1) and Fort Payne Formation (Figs. 6.8 and 8.1). In uplifted conditions high above the poorly oxygenated, basinal bottom waters, and during the lowstand conditions, coeval carbonate mud mounds developed wherever they could in starved-basin Fort Payne environments. Hence, the Floyds Knob interval throughout the study area is most likely related to a combination of eustatic and tectonic events. These same events set the stage for future Meramecian and Chesterian carbonate deposition throughout the Appalachian Basin and mid-continent region.

# CHAPTER 9: CONCLUSIONS

The glauconite- and phosphate-rich Floyds Knob Bed is described as a late Osagean temporal marker horizon that is recognized in the western Appalachian and eastern Illinois basins throughout central and eastern Kentucky and in parts of Indiana and Tennessee. It is also associated with three to four more granular glauconite-rich horizons, and glauconite-rich muds reaching thickness of up to 30 m in some places, atop and in front of the abandoned Borden-Grainger delta, effectively representing an interval, rather than a single bed. The Floyds Knob interval represents sediment-starvation and suboxic conditions following the end of major synorogenic (Neoacadian), sediment influx onto foreland parts of the craton. This interval also marks the transition between dominantly clastic facies to dominantly carbonate facies during a sea-level lowstand in the early phase of loading-type relaxation associated with the Neoacadian tectophase of the Acadian Orogeny.

The Floyds Knob interval was previously thought to have been deposited only in sediment-depleted settings atop the Borden-Grainger delta slope, but this study has found that the Floyds Knob interval was deposited across several major depositional settings in the western Appalachian and eastern Illinois basins. Basement structures may have played a major role in defining the nature and thickness of the sediments, combined with the position and depositional topography of the abandoned delta lobes. More importantly, the Floyds Knob interval in south-central Kentucky does not occur at the base of the carbonate-dominated Fort Payne Formation with the glauconite-rich Maury/New Providence equivalent shales; rather, it is represented by a thick pelletal glauconite-rich horizon that separates basal Fort Payne clastics from overlying Fort Payne carbonates.

Mineralogical studies of the green shales associated with the carbonate-mud mounds suggest that the green shales are composed of glauconite and chloritic-clay-rich verdine facies, and the stratigraphic occurrence of the mud mounds and associated green shales suggest that they represent the Floyds Knob interval in south-central Kentucky, and that the mounds may have developed on structural highs associated with the Grenville Front and East Continent Rift Basin.

Radiometric dating of the glauconites from the western Appalachian Basin and biostratigraphic study of the trilobite species *Exochops portlocki* from the Fort Payne Formation in the eastern Illinois Basin suggest a late Osagean origin for the Floyds Knob interval with errors indicating possible early Osagean to early Meramecian origin. These results are similar to the existing biostratigraphic studies, which point to a late Osagean origin for the Floyds Knob interval.

Closer examination of the carbonate-mud mounds of the Fort Payne Formation in south-central Kentucky, including the presence of non-reef coral communities, suggest that these mud mounds must have developed in active water within the photic zone in a water column dominated by episodic storms. The mud mounds were apparently topographically higher than surrounding basinal environments, and must have nucleated on paleotopographic features. These features may have resulted from the reactivation of the basement faults underlying the area during the Neoacadian Orogeny and/or have been created by sediment accumulation of variable thicknesses on the basin-floor, generated along the delta-front by turbidity currents, slumps, slides, and other mass flows.

## APPENDIX-1

(Measured Stratigraphic Sections)

Table TA1 - List of measured sections.

| Section no | Section name | ID | Coordinates | County | Quadrangle |
|---|---|---|---|---|---|
| 1 | I-64, Stop1 | OH1 | 83°22'31.62"W, 38°16'34.2"N | Rowan | Cranston |
| 2 | I-64, Stop2 | OH2 | 83°18'59.28"W, 38°17'32.76"N | Carter | Soldier |
| 3 | I-64, Stop3 | OH3 | 83°17'40.02"W, 38°18'6"N | Carter | Soldier |
| 4 | Mountain Parkway | MP | 83°41'1.32"W; 37°47'34.98"N | Powell | Slade |
| 5 | KY-11S Natural Bridge | NB | 83°40'37.92"W, 37°46'35.22"N | Powell | Slade |
| 6 | KY-11S Lake, Mill Creek Lake | MC | 83°40'22.14"W, 37°45'58.44"N | Wolfe | Slade |
| 7 | KY-11S Glen Caren Fault | GC | 83°40'11.7"W, 37°45'32.34"N | Wolfe | Slade |
| 8 | HillTop Church, KY-36 | HT | 83°37'14.4"W, 37°59'10.74"N | Menifee | Scranton |
| 9 | US-460 N Frenchberg | FN | 83°40'17.34"W, 37°57'35.1"N | Menifee | Frenchburg |
| 10 | US-460 S Frenchberg | FS | 83°37'11.52"W, 37°56'33.18"N | Menifee | Scranton |
| 11 | Bighill, Bighill Road | BH | 84°12'40.98"W; 37°31'43.98"N | Madison | Bighill |
| 12 | I-75S Mt. Vernon | MV | 84°20'30.72"W, 37°26'9.54"N | Rockcastle | Wildie |
| 13 | US 150/KY 70 Broadhead | BD | 84°24'59.28"W, 37°22'42.06"N | Rockcastle | Brodhead |
| 14 | Indiana Floyds Knob type section | IN | 85°54'1.38"W, 38°17'12.9"N | Floyd (Indiana) | |
| 15 | Fort Knox; KY-313 | FK | 85°47'4.2"W, 37°48'9.3"N | Hardin | Colesburg |
| 16 | BlueGrass Pkway | BP | 85°44'18.54"W, 37°43'16.32"N | Hardin | Nelsonville |
| 17 | Muldraugh type section (KY-208) | MT | 85°15'49.8"W, 37°26'38.58"N | Marion | Spurlington |
| 18 | US-127 South Liberty | L1 | 84°57'31.38"W, 37°17'8.4"N | Casey | Liberty |
| 19 | US-127S South Liberty section 2 | L2 | 84°57'25.62"W, 37°13'11.04"N | Casey | Phil |
| 20 | Cumberland Parkway, Somerset section-1 | S1 | 84°42'33.48"W, 37°5'45.12"N | Pulaski | Delmer |
| 21 | Cumberland Parkway, Somerset section-2 | S2 | 84°52'59.34"W, 37°5'22.26"N | Pulaski | Eli |
| 22 | Lake Cumberland, Stop 1 | LC1 | 84°58'43.8"W, 36°55'3.36"N | Russell | Jabez |
| 23 | Lake Cumberland, Stop 2 | LC2 | 84°58'2.28"W, 36°55'18.36"N | Russell | Jabez |
| 24 | Lake Cumberland,Stop 3 | LC3 | 84°57'44.52"W, 36°55'48.66"N | Russell | Jabez |
| 25 | Lake Cumberland, Floyds Knob Section, Stop 4 | LC4 | 84°51'4.08"W, 36°58'21.06"N | Wayne | Mill Springs |
| 26 | Wolf Creek Dam section | WD | 85°7'44.7"W, 36°52'9.36"N | Russell | Cumberland City |
| 27 | South Lake Cumberland; Swanpond Road | SR | 85°9'43.74"W, 36°52'34.44"N | Russell | Wolf Creek Dam |
| 28 | Mantown Road (Mudmound) | MR | 85°12'15.78"W, 36°51'11.16"N | Clinton | Wolf Creek Dam |
| 29 | KY-61N Section 1 | BN1 | 85°25'22.38"W, 36°53'24.36"N | Cumberland | Breeding |
| 30 | KY-61N Section 2 | BN2 | 85°25'41.88"W, 36°53'47.82"N | Cumberland | Breeding |
| 31 | KY-61N Section 3 | BN3 | 85°25'46.74"W, 36°54'0.6"N | Cumberland | Breeding |
| 32 | KY-61N Section 4 | BN4 | 85°25'54.36"W, 36°54'7.02"N | Cumberland | Breeding |
| 33 | KY-61N Section 5 | BN5 | 85°26'16.14"W, 36°54'17.46"N | Cumberland | Breeding |
| 34 | KY-61S | BS | 85°21'59.94"W, 36°43'14.7"N | Cumberland | Frogue |
| 35 | KY-90W Burkesville | BW | 85°22'55.86"W, 36°47'59.04"N | Cumberland | Waterview |
| 36 | KY-61N; Fort Payne Siltstone | BN6 | 85°26'36.3"W, 36°54'53.76"N | Cumberland | Breeding |
| 37 | Core C-505 | C5 | 85°5'48.919"W, 36°54'52.088"N | Russell | Jamestown |
| 38 | Pound Gap | PG | 82°38'37.73"W, 37°9'25.1"N | Letcher | |
| 39 | Cumberland Gap Tunnel | CG | 83°40'36.96"W, 36°36'21.01"N | Claiborne (VA) | |
| 40 | Jellico Mountain TN | JM | 84°8'9.96"W, 36°33'12.25"N | Campbell (TN) | |

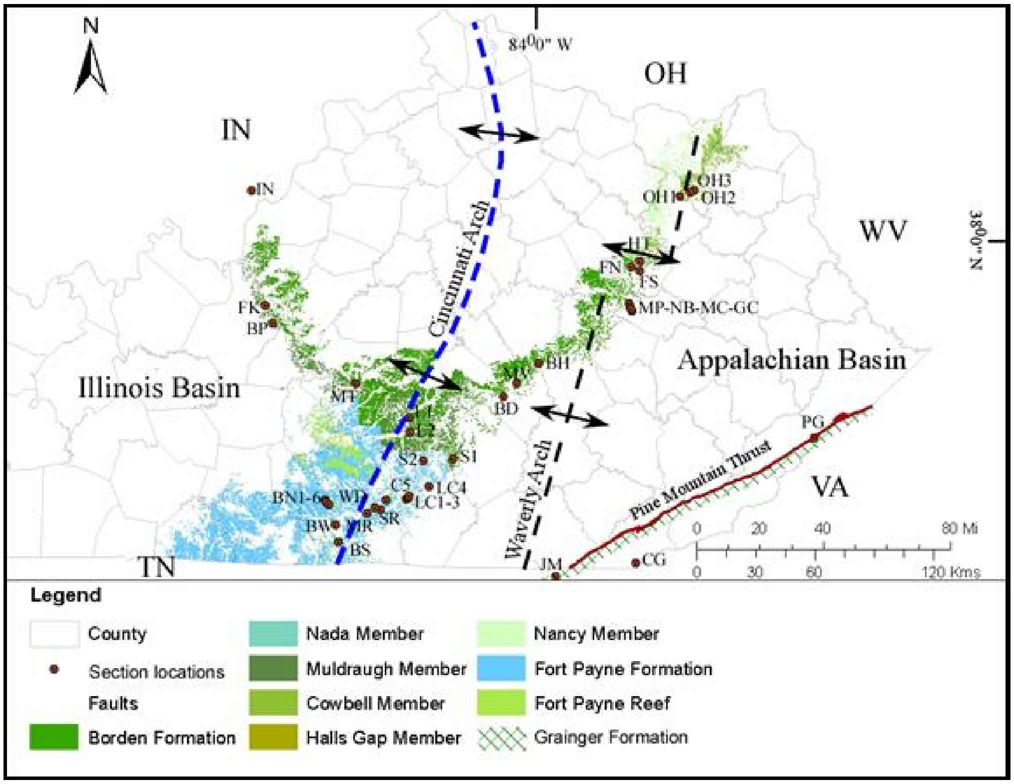



Figure FA1 – Location map of the measured stratigraphic sections in Kentucky and adjacent states.

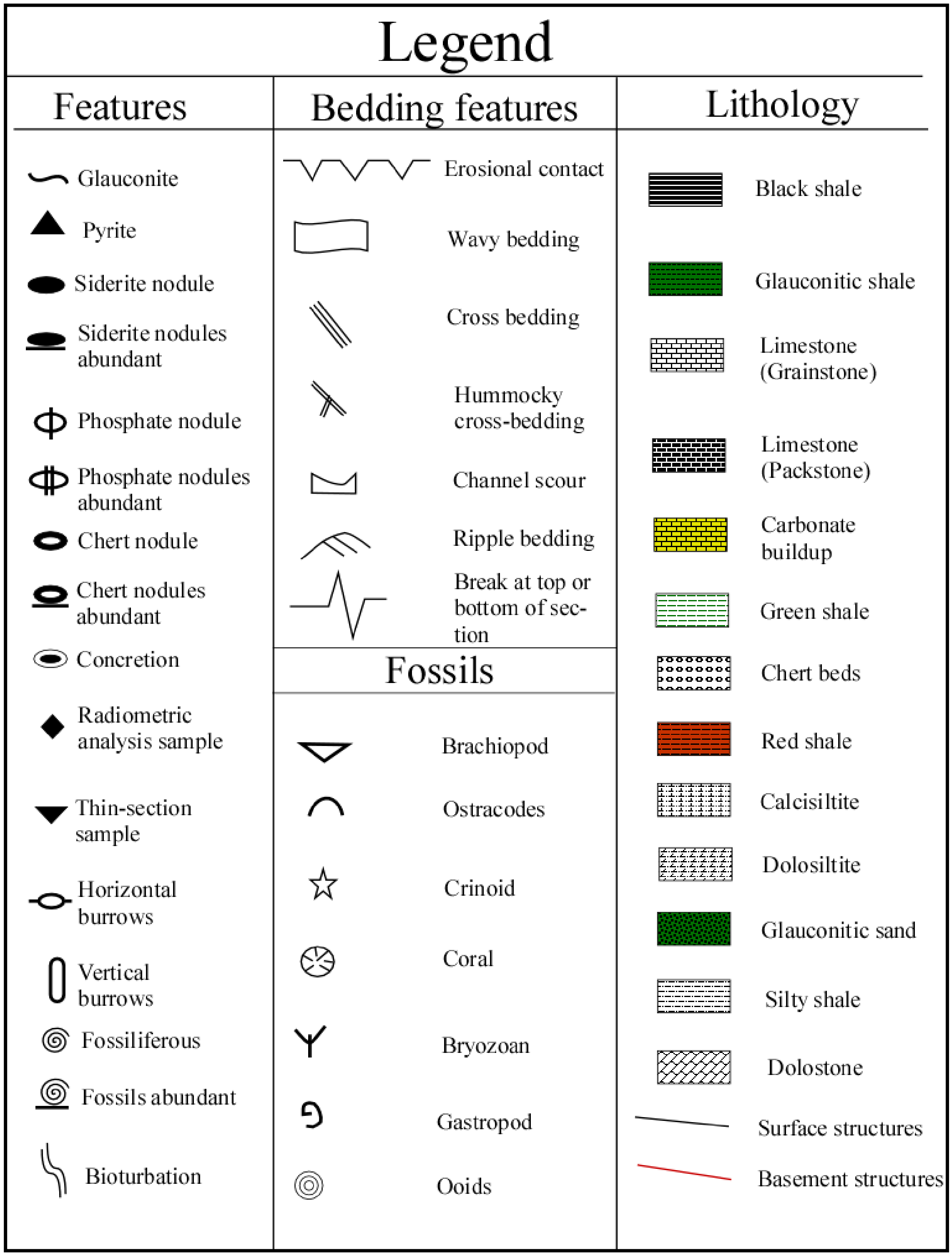



Figure FA2 – Legend for measured stratigraphic sections.

**I-64 section-1**: Outcrop located along I-64E, Rowan County, Cranston quadrangle. 83°22'31.62"W, 38°16'34.2"N

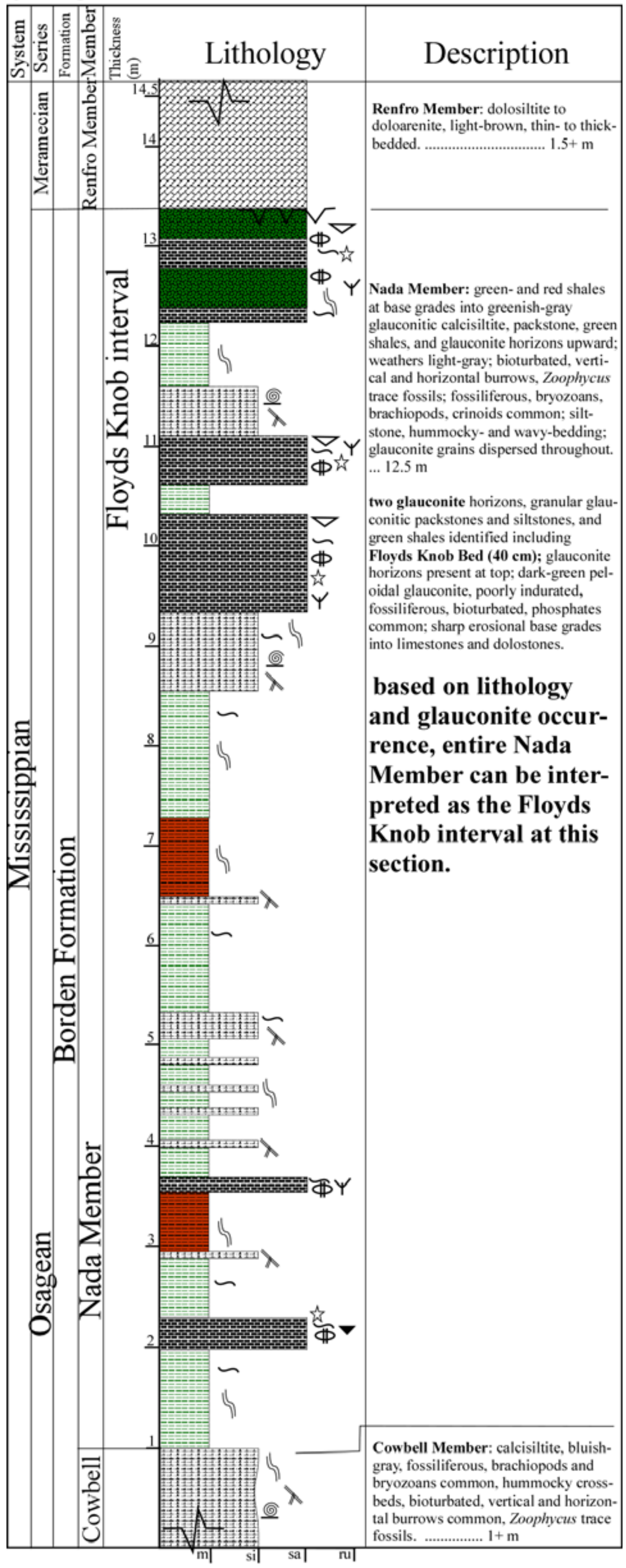



Figure FA3 – Measured stratigraphic section at the section OH1.

**I-64 section-2**: Outcrop located along I-64W, Carter County, Soldier quadrangle. 83°18'59.28"W, 38°17'32.76"N

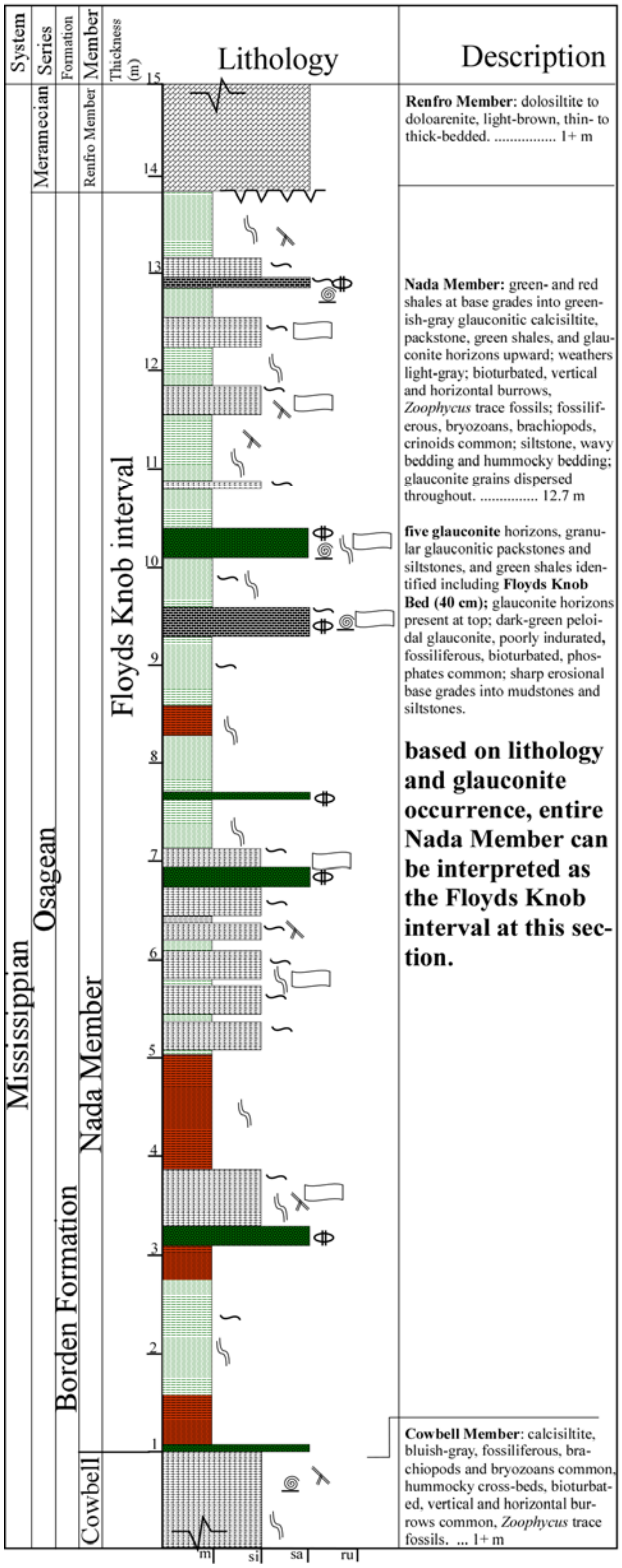



Figure FA4 – Measured stratigraphic section at the section OH2.

**I-64 section-3**: Outcrop located along I-64W, Carter County, Soldier quadrangle. 83°17'40.02"W, 38°18'6"N

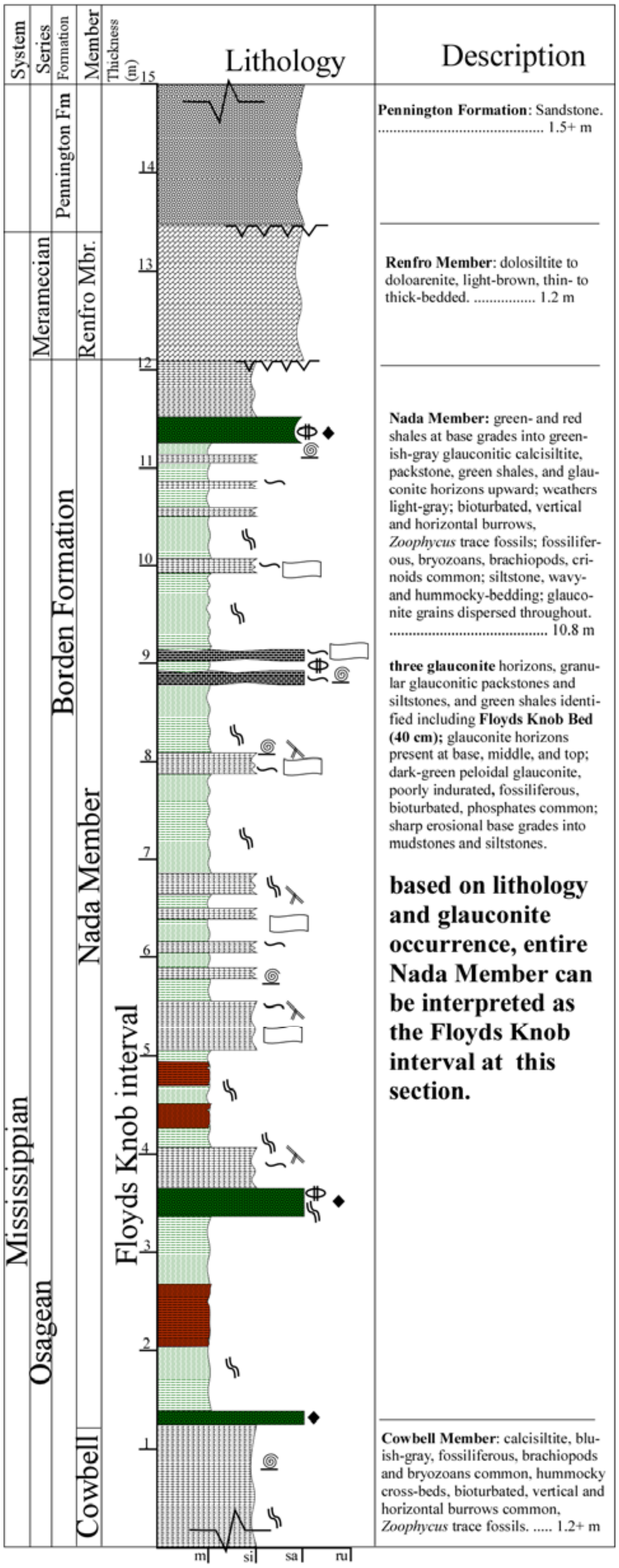



Figure FA5 – Measured stratigraphic section at the section OH3.

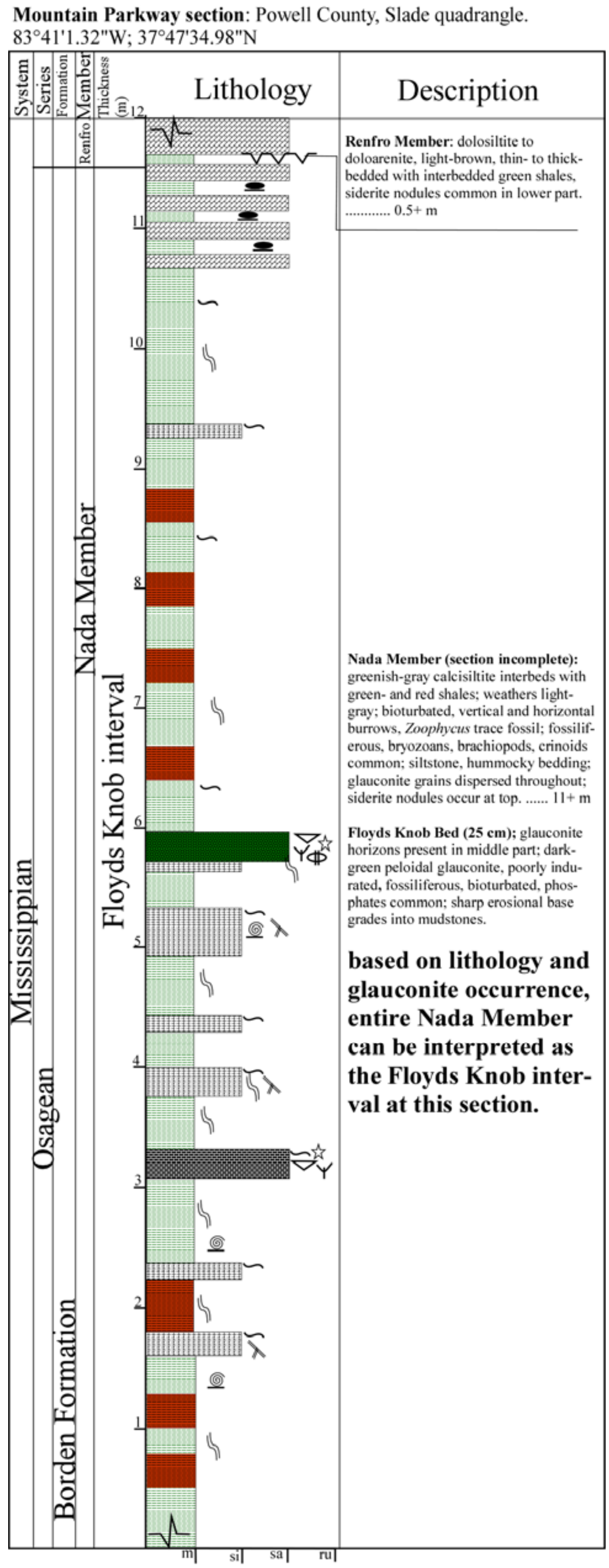



Figure FA6 – Measured stratigraphic section at the section MP.

**Natural Bridge section**: Outcrop located along KY-11S, Powell County, Slade quadrangle. 83°40'37.92"W, 37°46'35.22"N

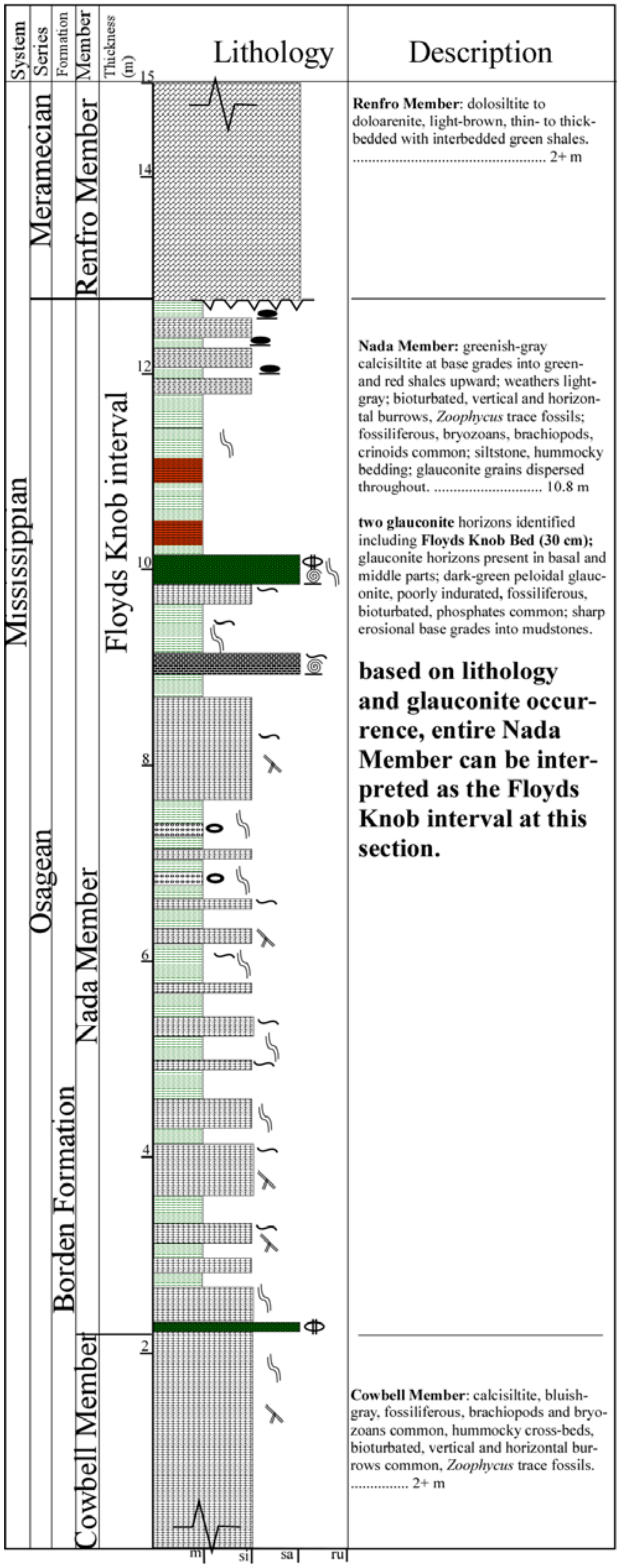



Figure FA7 – Measured stratigraphic section at the section NB.

**KY-11 Lake section**: Outcrop located along KY-11S, Wolfe County, Slade quadrangle. 83°40'22.14"W, 37°45'58.44"N

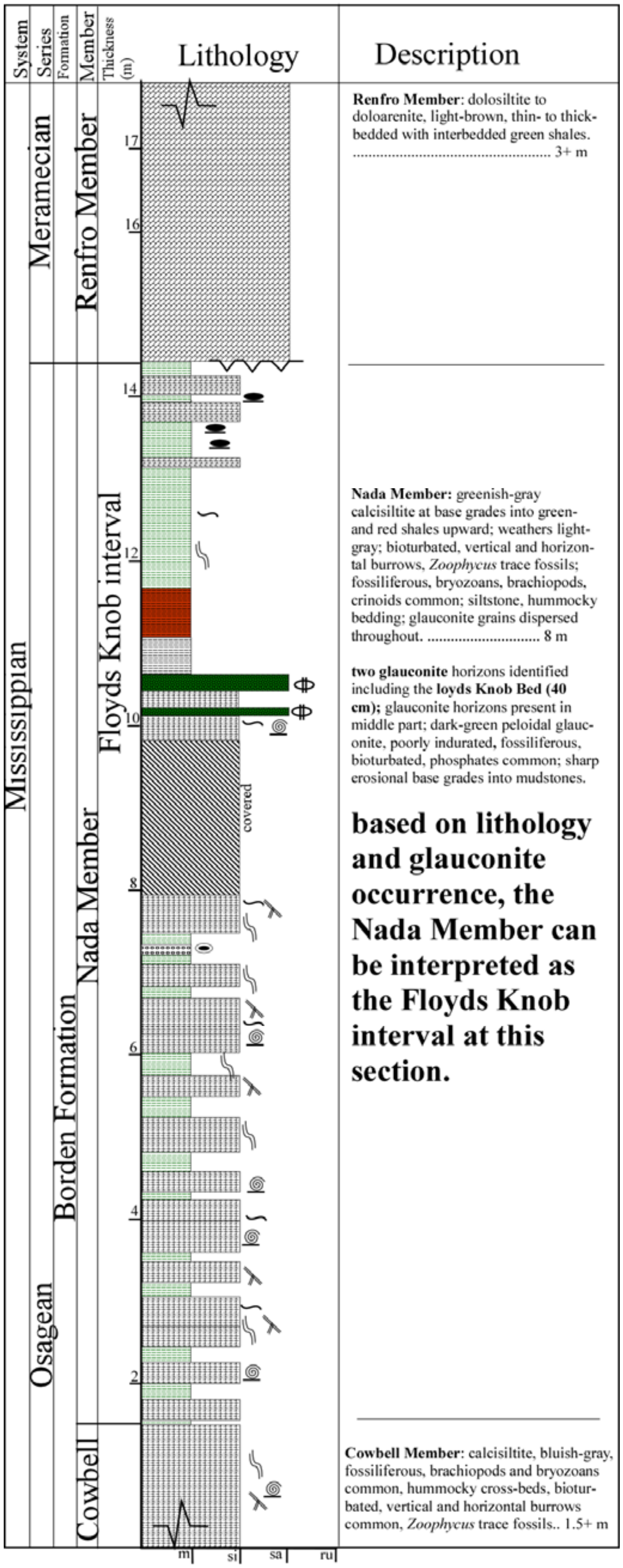



Figure FA8 – Measured stratigraphic section at the section MC.

**Glenn Caren Fault section**: Outcrop located along KY-11S, Wolfe County, Slade quadrangle. 83°40'11.7"W, 37°45'32.34"N

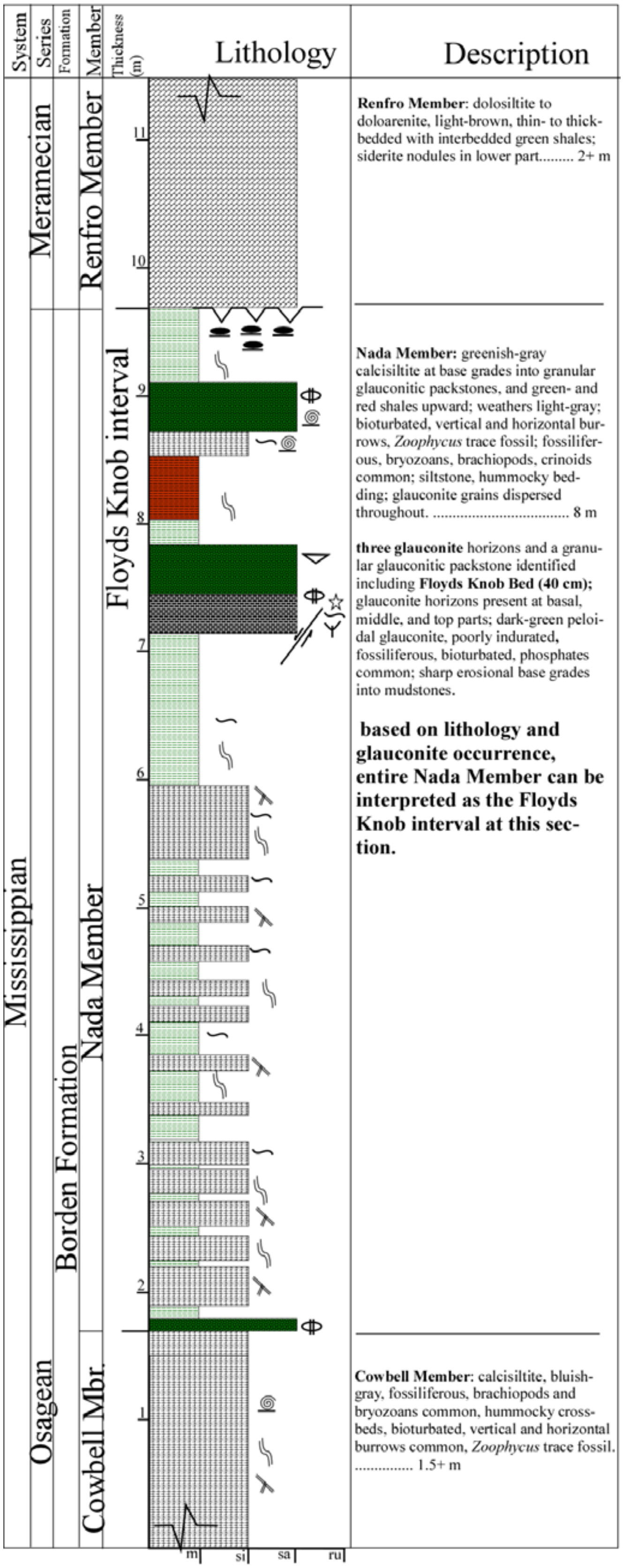



Figure FA9 – Measured stratigraphic section at the section GC.

**Hilltop Church section**: Outcrop located along KY-36, near Frenchburg, Menifee County, Scranton quadrangle. 83°37'14.4"W, 37°59'10.74"N

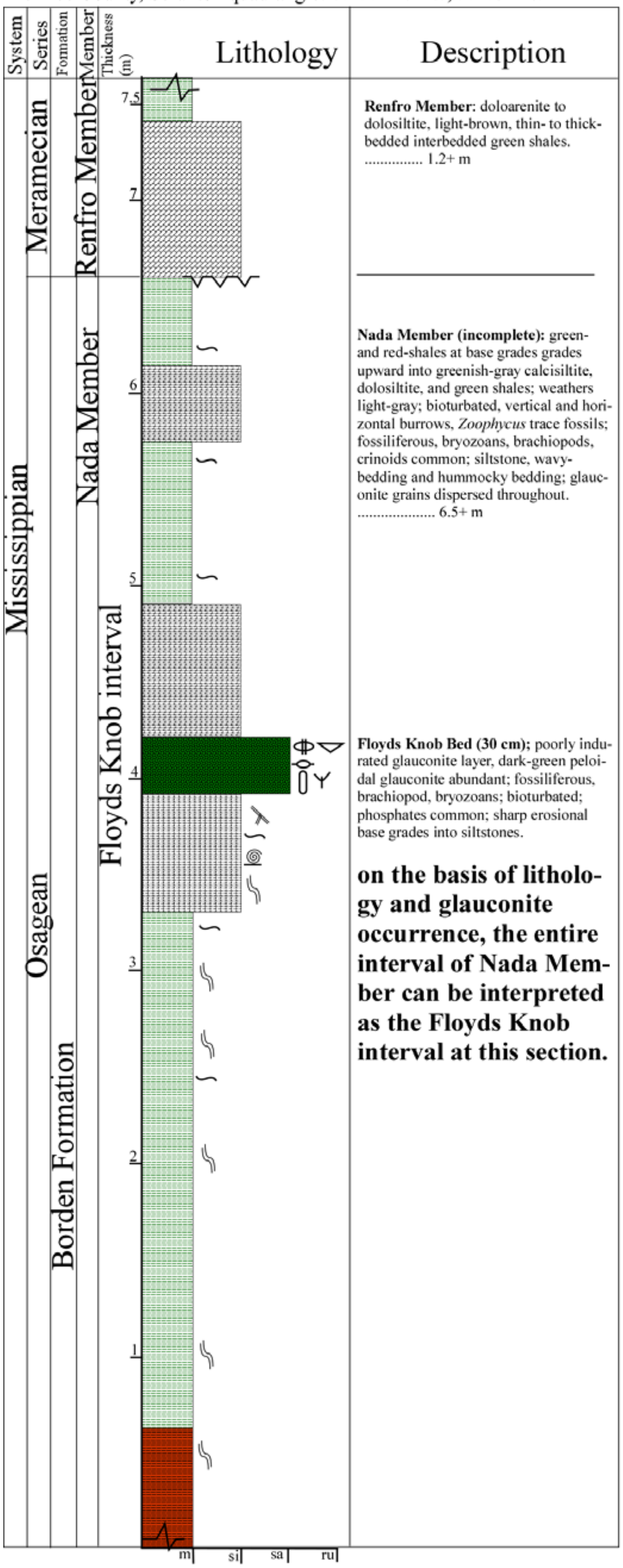



Figure FA10 – Measured stratigraphic section at the section HT.

**Frenchburg north section**: Outcrop located along US-460, Menifee County, Frenchburg quadrangle. 83°37'11.52"W, 37°56'33.18"N

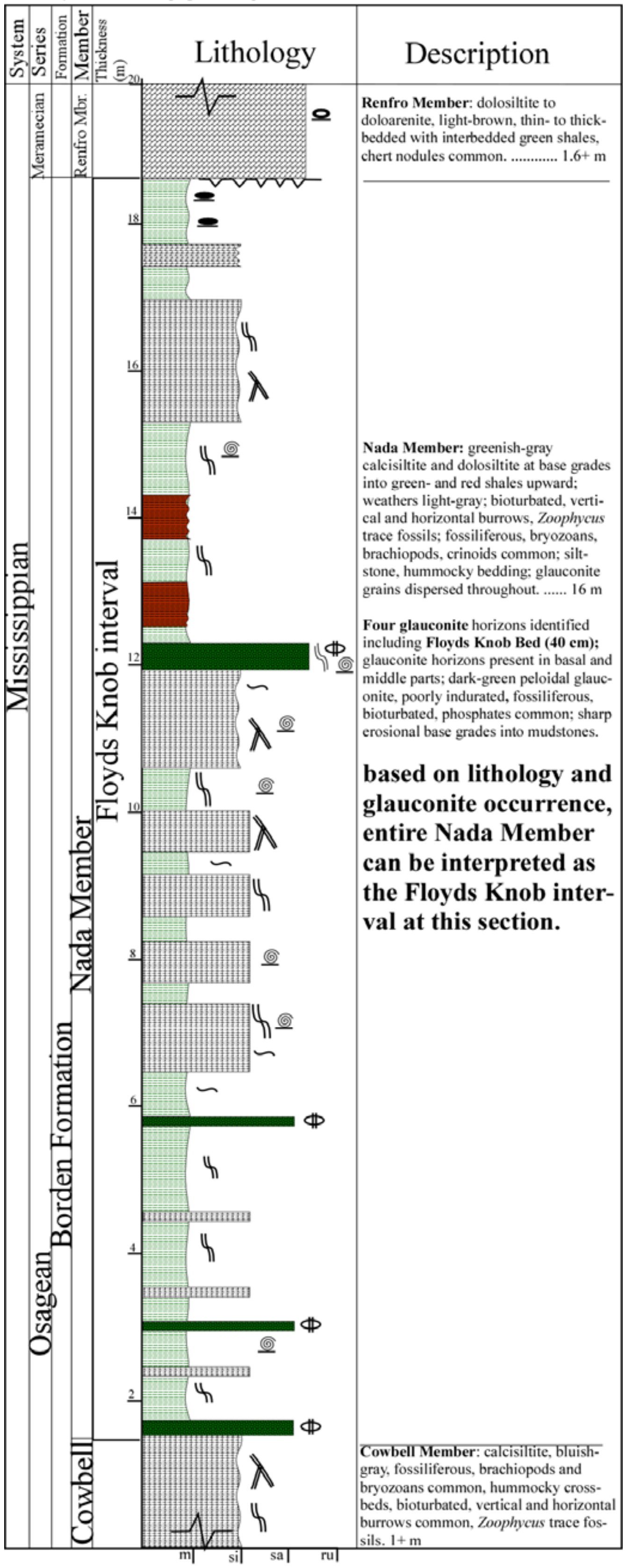



Figure FA11 – Measured stratigraphic section at the section FN.

**Frenchburg south section**: Outcrop located along US-460, Menifee County, Scranton quadrangle. 83°37'11.52"W, 37°56'33.18"N

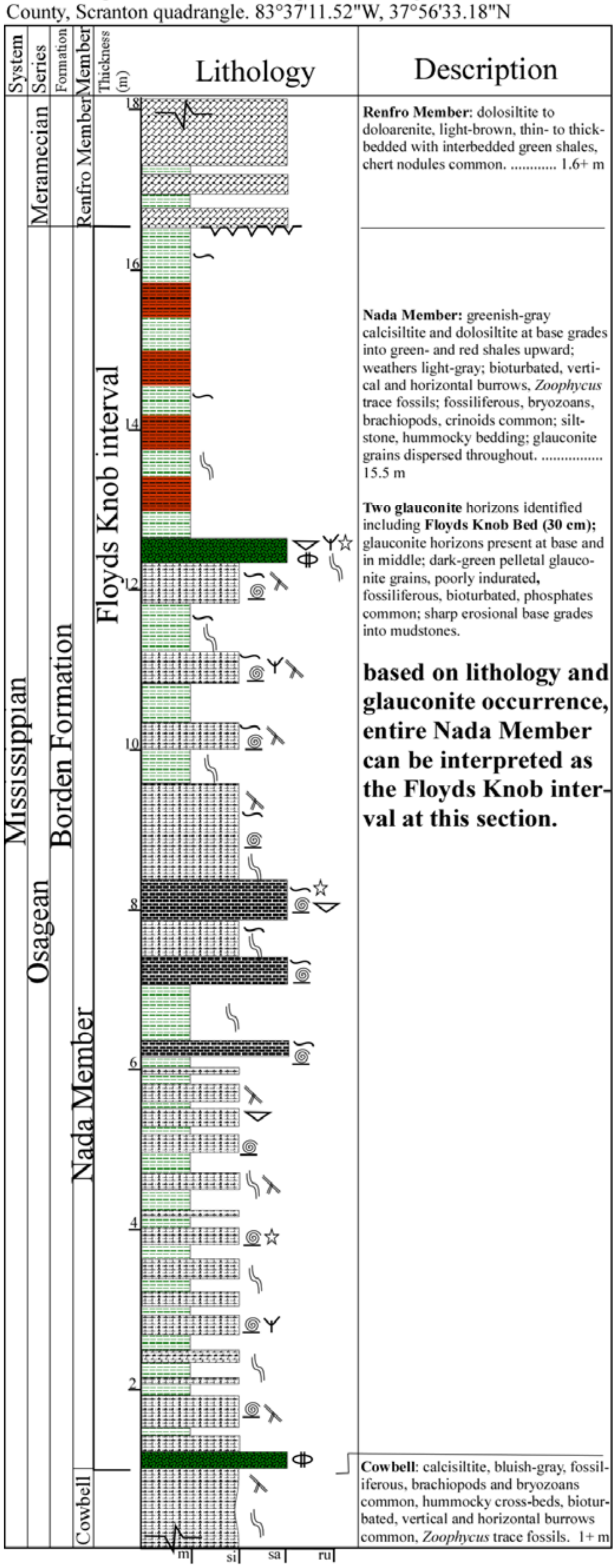



Figure FA12 – Measured stratigraphic section at the section FS.

**Bighill section**: Outcrop located along Bighill road, near Bighill, Madison County, Bighill quadrangle. 84°12'40.98"W; 37°31'43.98"N

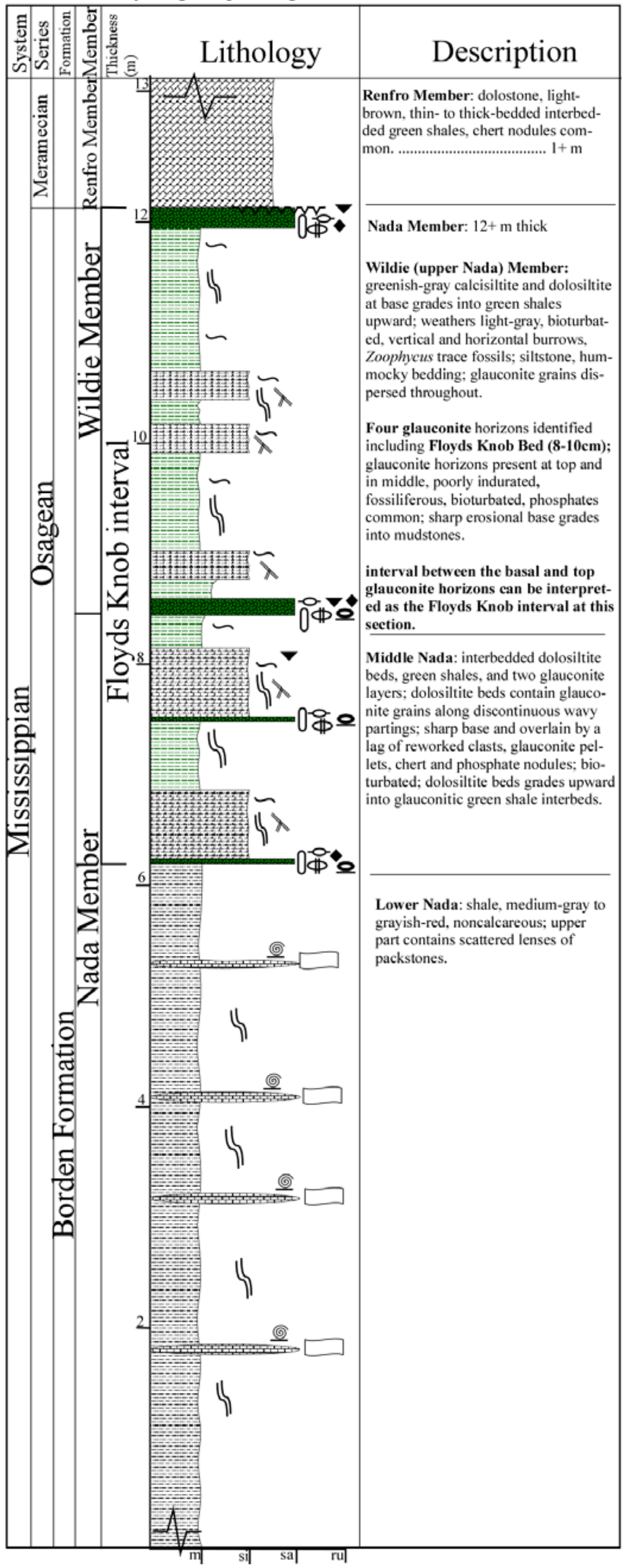



Figure FA13 – Measured stratigraphic section at the section BH.

**Mt. Vernon section**: Outcrop located along I-75 S, near Mt. Vernon, Rockcastle County, Wildie quadrangle. 84°20'30.72"W, 37°26'9.54"N

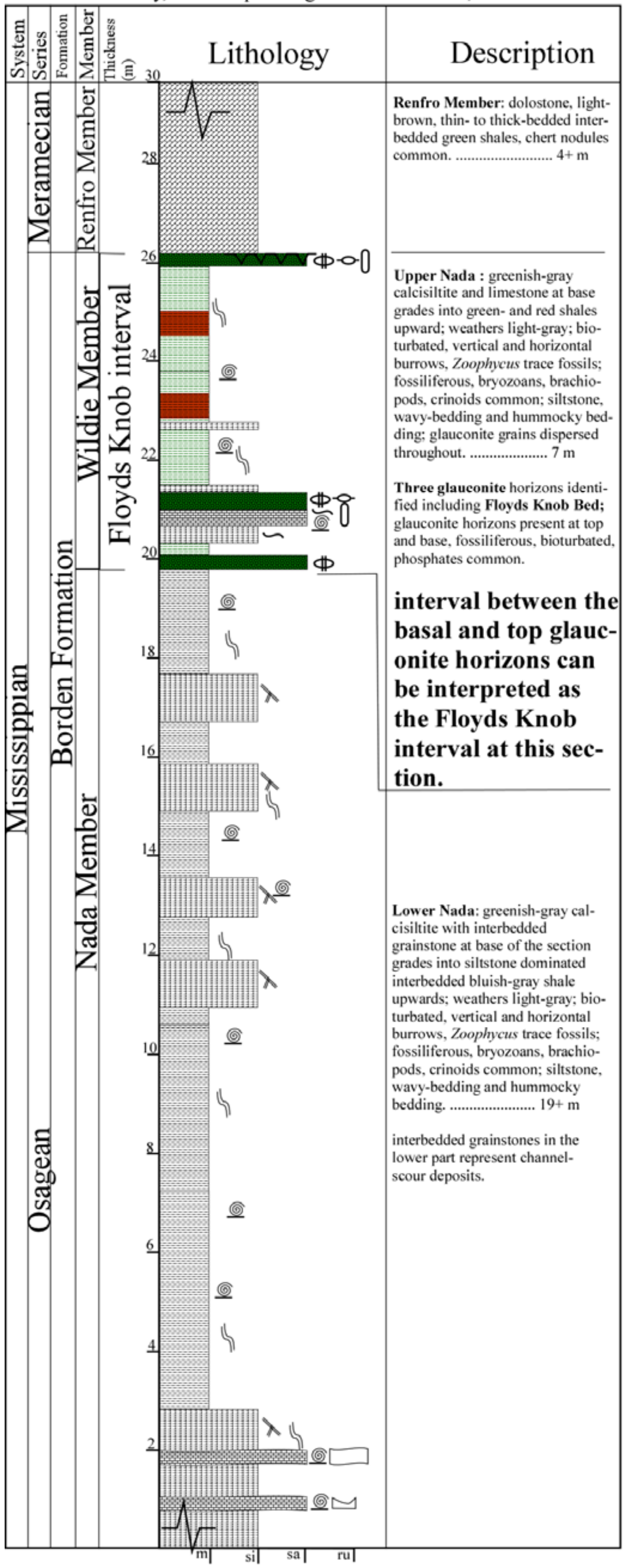



Figure FA14 – Measured stratigraphic section at the section MT.

**Brodhead section**: Outcrop located along KY-70 US-150, near Brodhead, Rockcastle County, Brodhead quadrangle. 84°24'59.28"W, 37°22'42.06"N

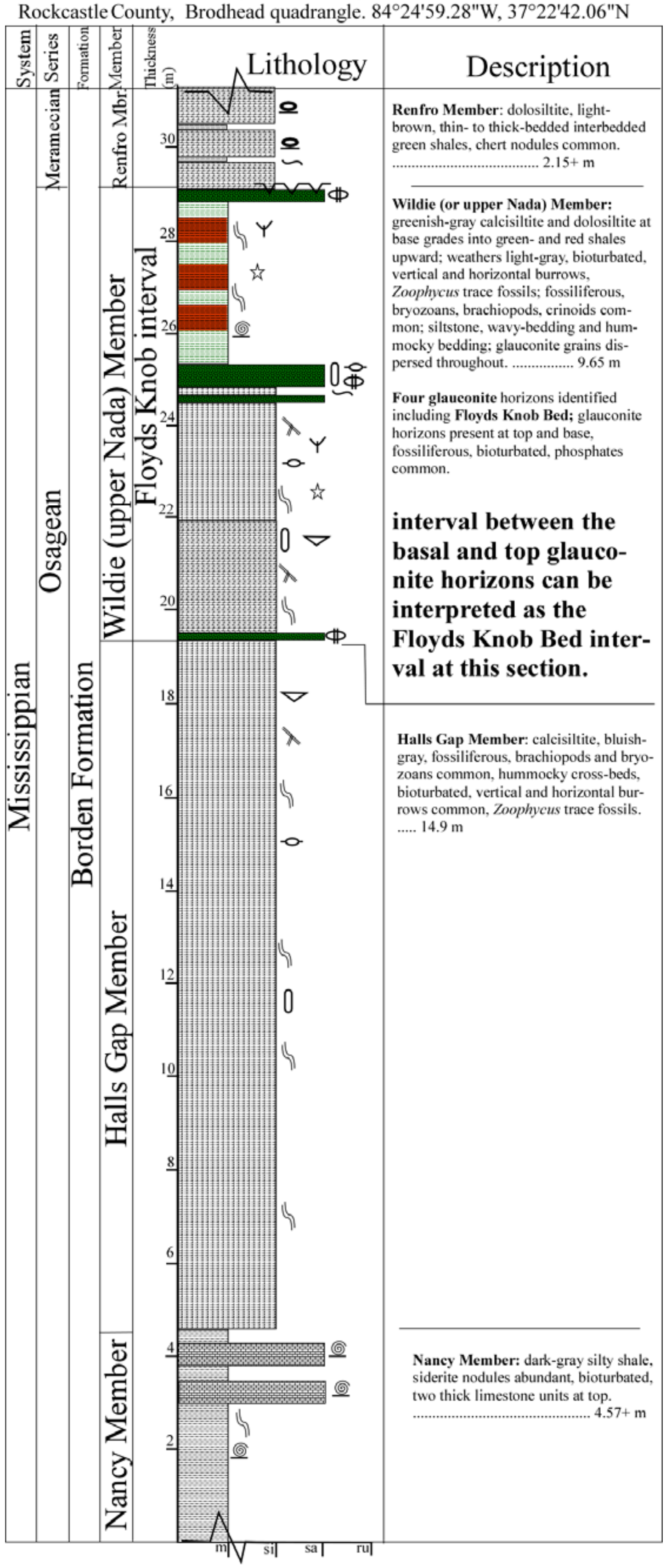



Figure FA15 – Measured stratigraphic section at the section BD.

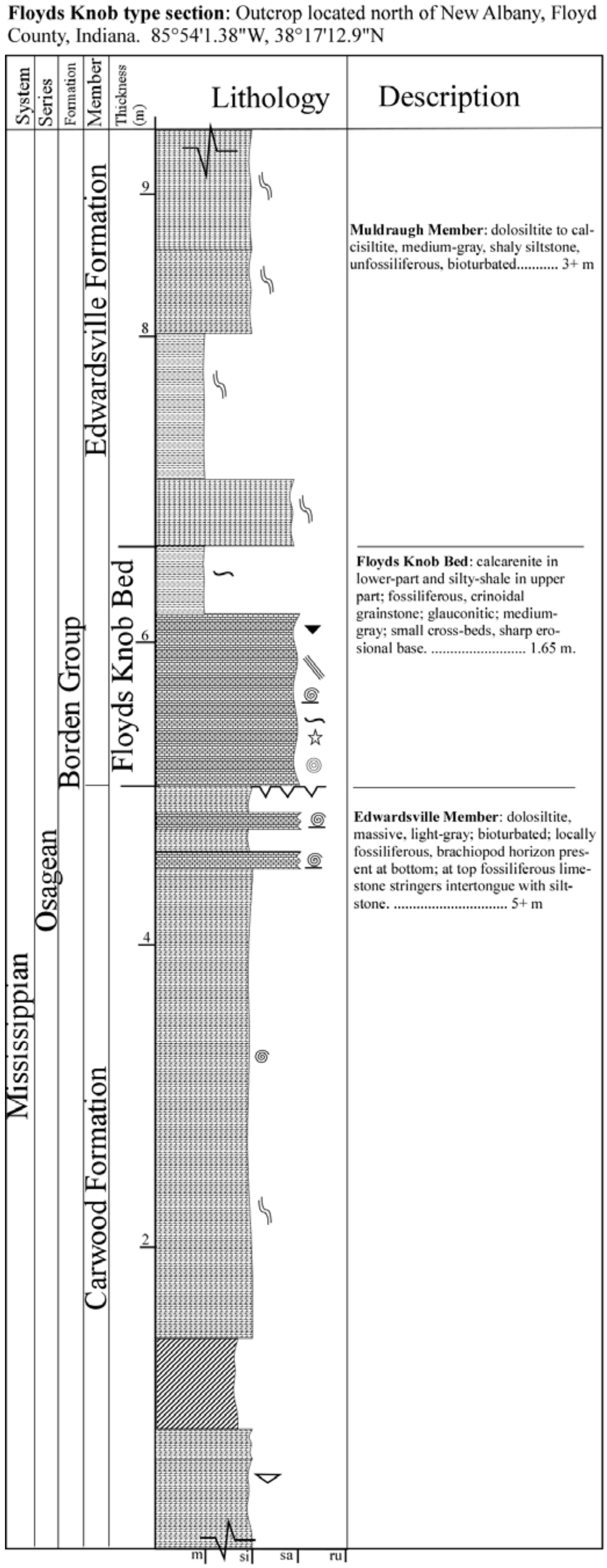



Figure FA16 – Measured stratigraphic section at the section IN.

**Fort Knox section**: Outcrop located along KY-313, south of Fort Knox, Hardin County, Colesburg quadrangle. 85°47'4.2"W, 37°48'9.3"N

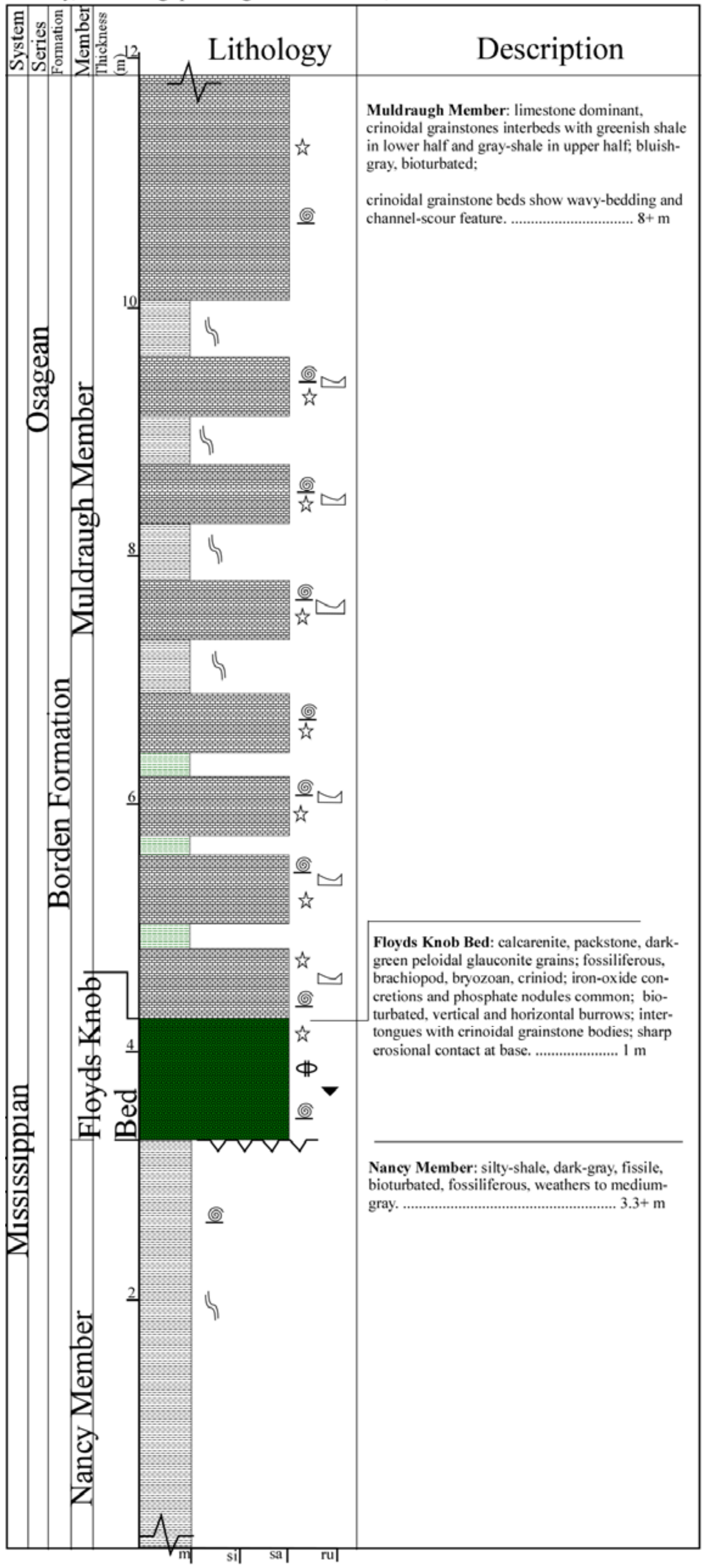



Figure FA17 – Measured stratigraphic section at the section FK.

**Bluegrass Parkway section**: Outcrop located along Bluegrass Parkway, east of Elizabethtown, Hardin County, Nelsonville quadrangle. 85°44'18.54"W, 37°43'16.32"N

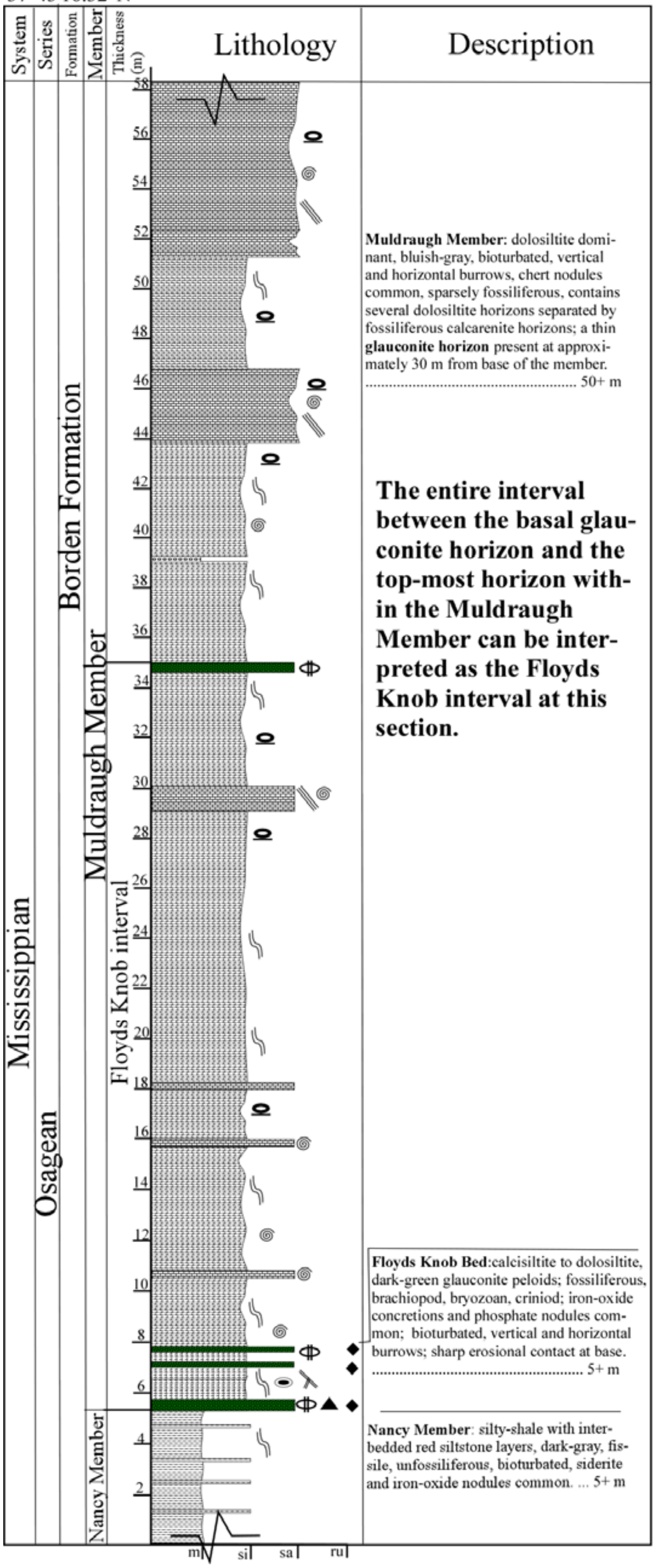



Figure FA18 – Measured stratigraphic section at the section BP.

**Muldraugh type section**: Outcrop located along KY-208, south of Lebanon, Marion County, Spurlington quadrangle. 85°15'49.8"W, 37°26'38.58"N

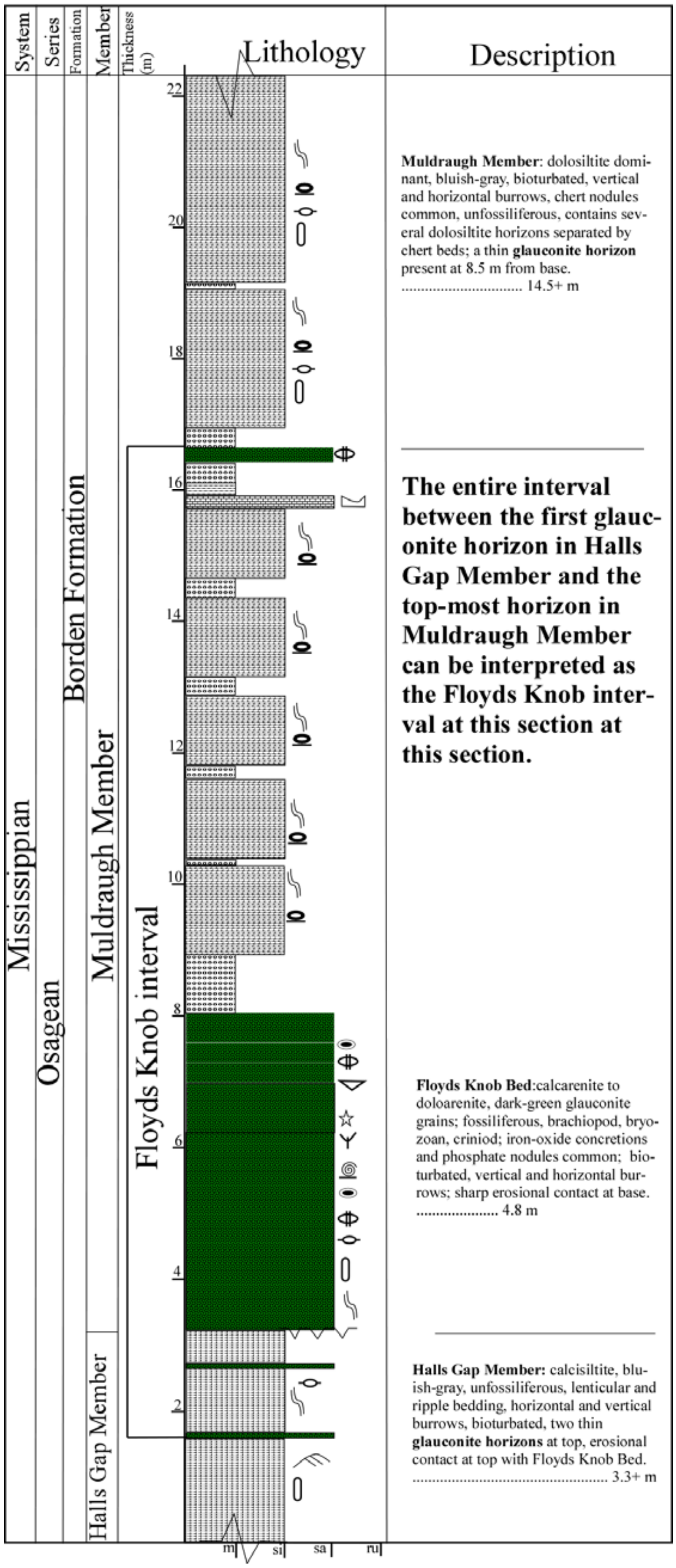



Figure FA19 – Measured stratigraphic section at the section MT.

**Liberty section-1**: Outcrop located along US-127, south of Liberty, Casey County, Liberty quadrangle. 84°57'31.38"W, 37°17'8.4"N

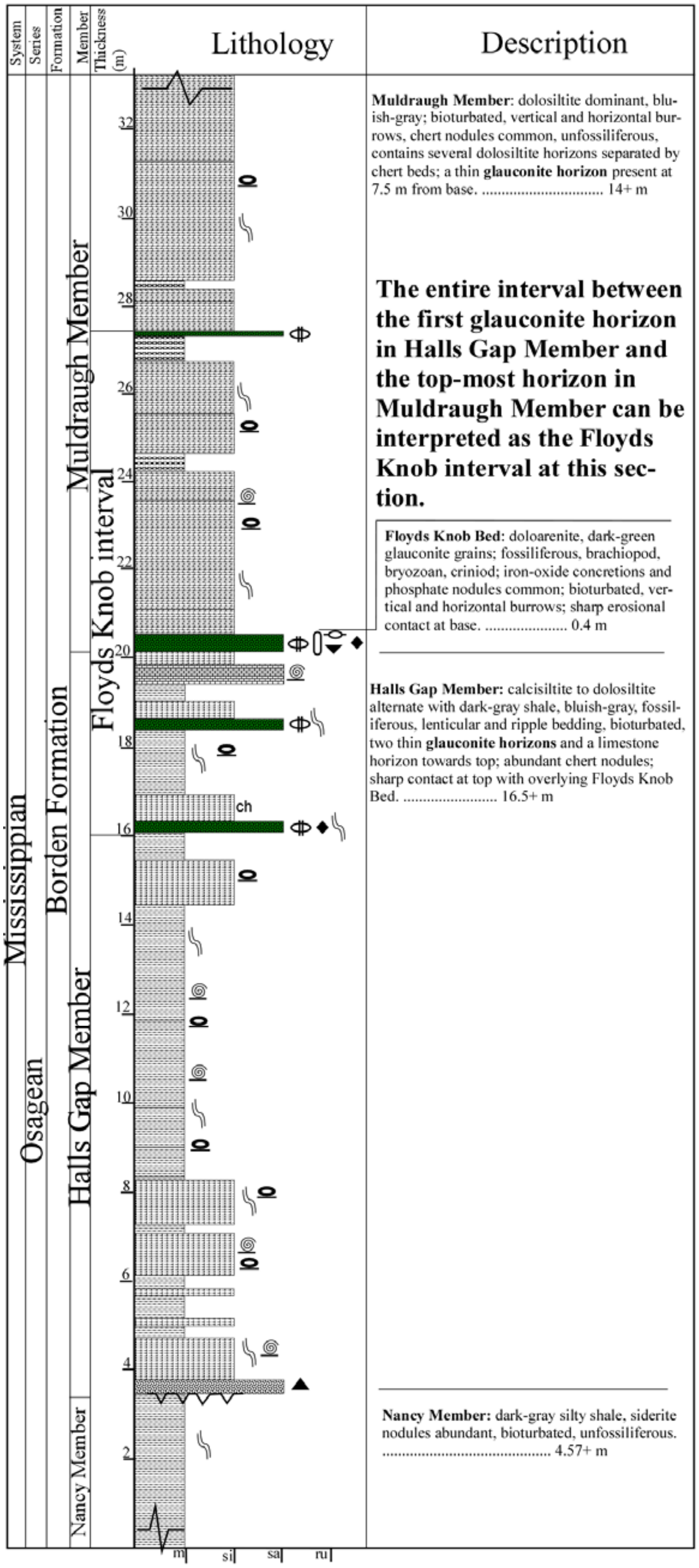



Figure FA20 – Measured stratigraphic section at the section L1.

**Liberty section-2**: Outcrop located along US-127, south of Liberty, Casey County, Phil quadrangle. 84°57'25.62"W, 37°13'11.04"N

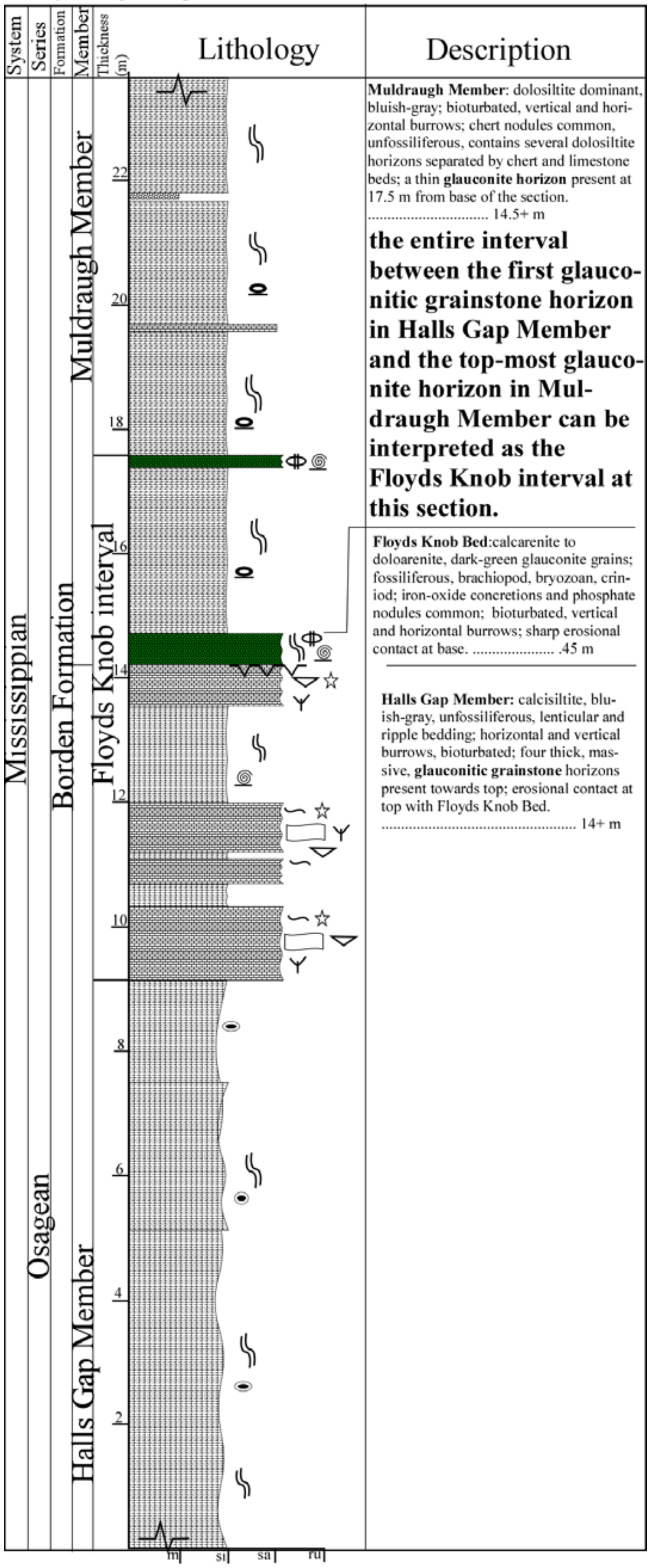



Figure FA21 – Measured stratigraphic section at the section L2.

**Cumberland Parkway section-1**: Outcrop located along Cumberland Parkway, west of Somerset, Pulaski County, Delmer quadrangle. 84°42'33.48"W, 37°5'45.12"N

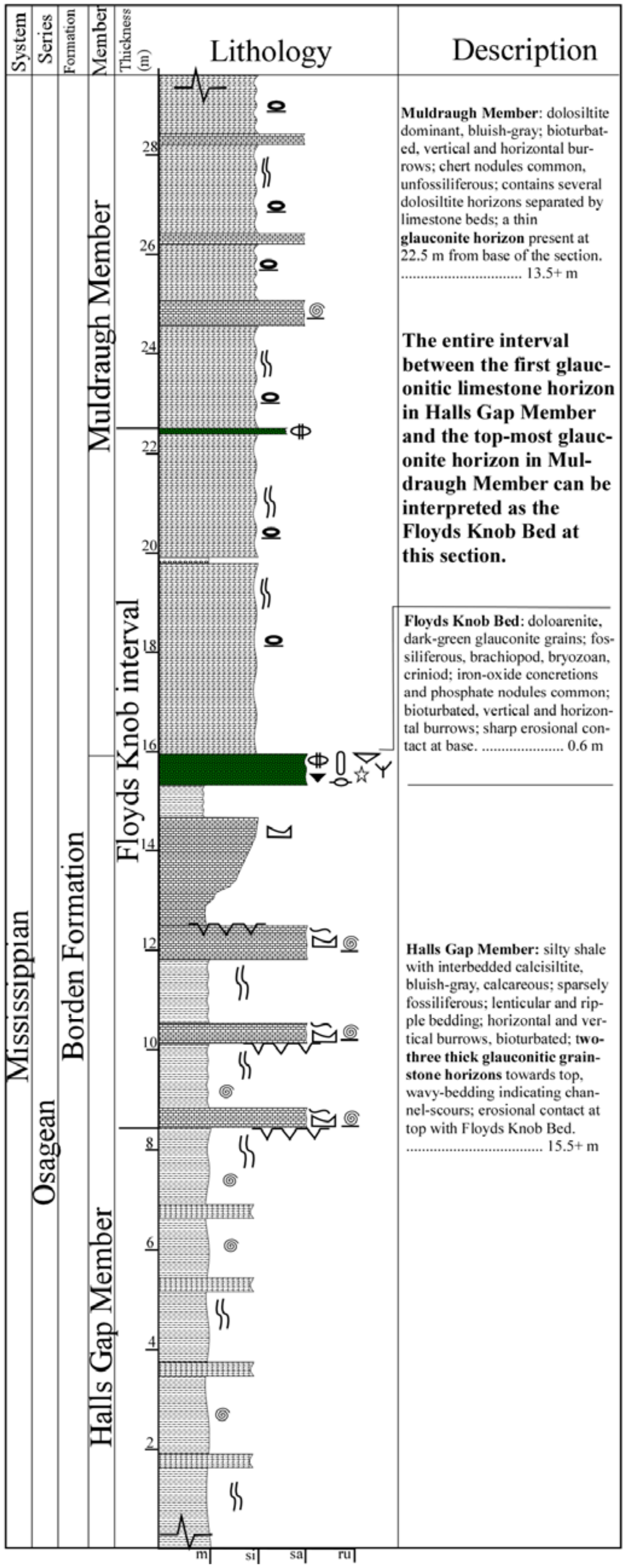



Figure FA22 – Measured stratigraphic section at the section S1.

**Cumberland Parkway section-2**: Outcrop along Cumberland Parkway, west of Somerset, Pulaski County, Eli quadrangle, 84°52'59.34"W, 37°5'22.26"N

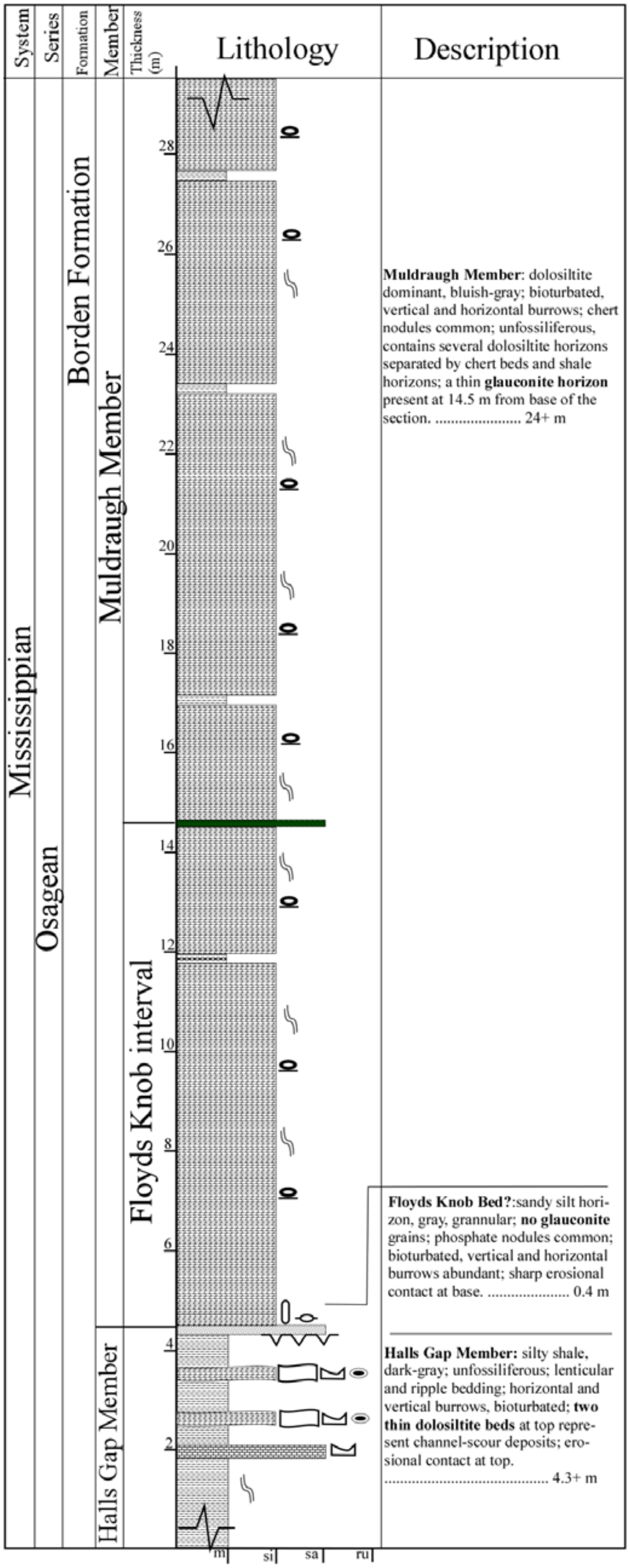



Figure FA23 – Measured stratigraphic section at the section S2.

**Lake Cumberland section-1**: Inside lake Cumberland, Russell County, Jabez quadrangle. 84°58'43.8"W, 36°55'3.36"N

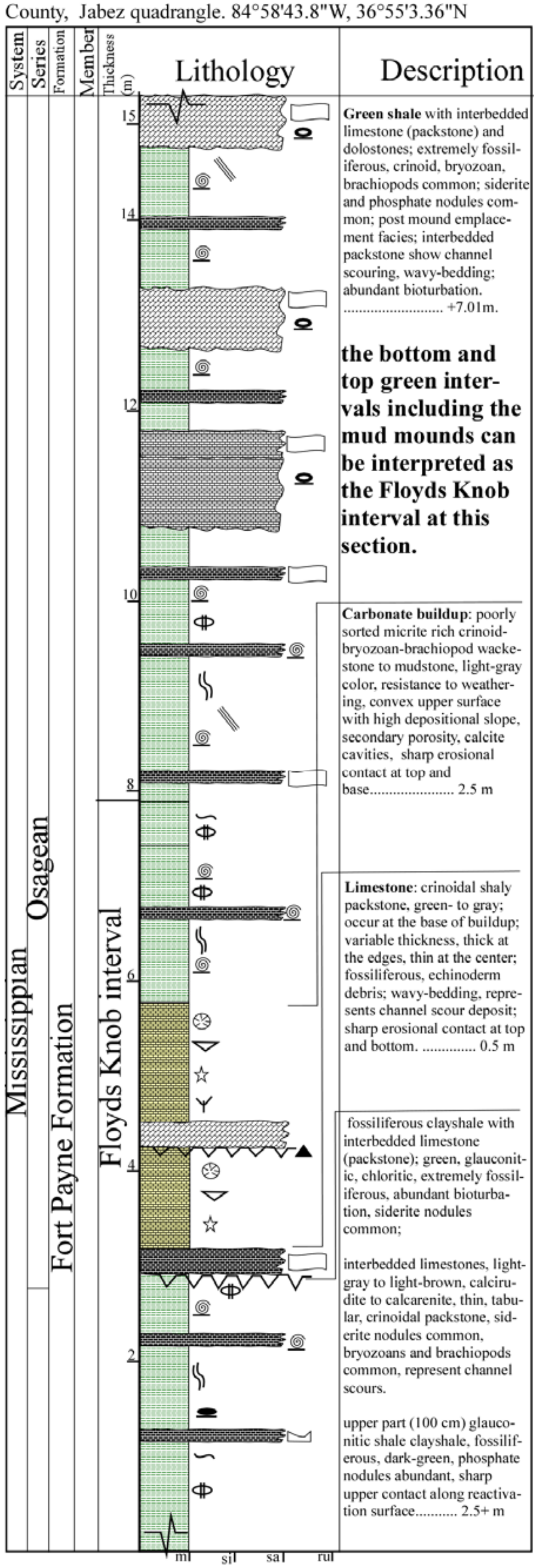



Figure FA24 – Measured stratigraphic section at the section LC1.

**Lake Cumberland section-2**: Inside lake Cumberland, Russell County, Jabez quadrangle. 84°58'2.28"W, 36°55'18.36"N

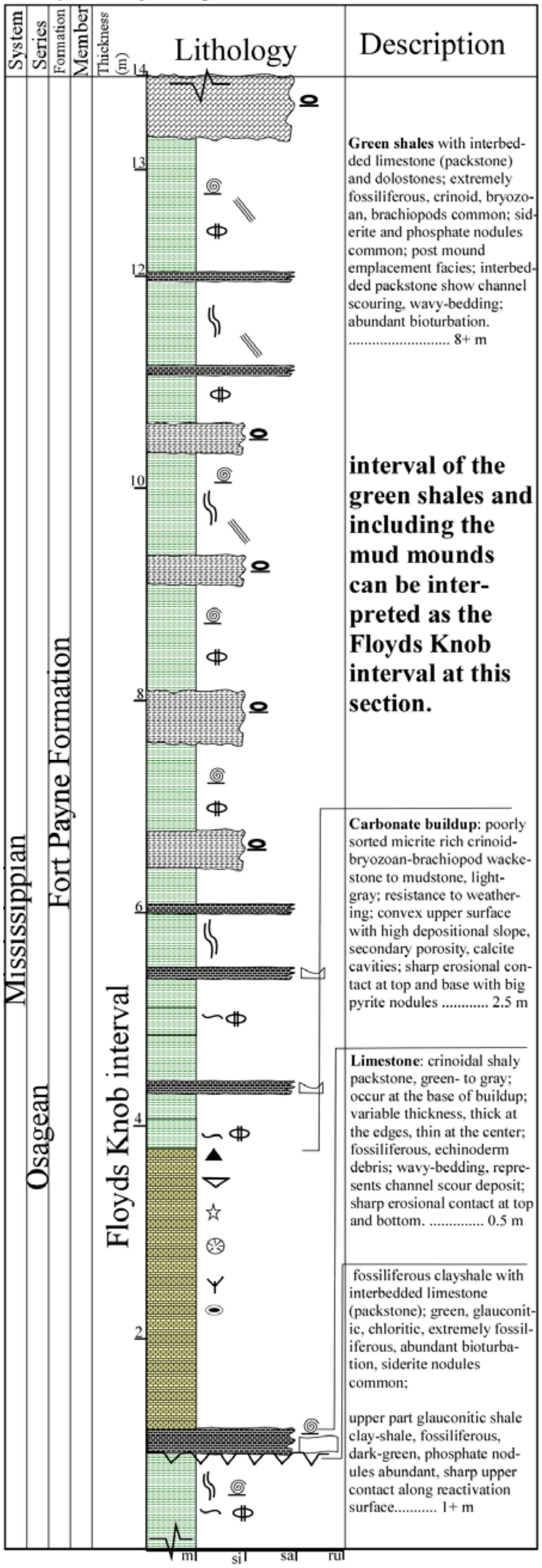



Figure FA25 – Measured stratigraphic section at the section LC2.

**Lake Cumberland section-3**: Inside lake Cumberland, Russell County, Jabez quadrangle. 84°57'44.52"W, 36°55'48.66"N

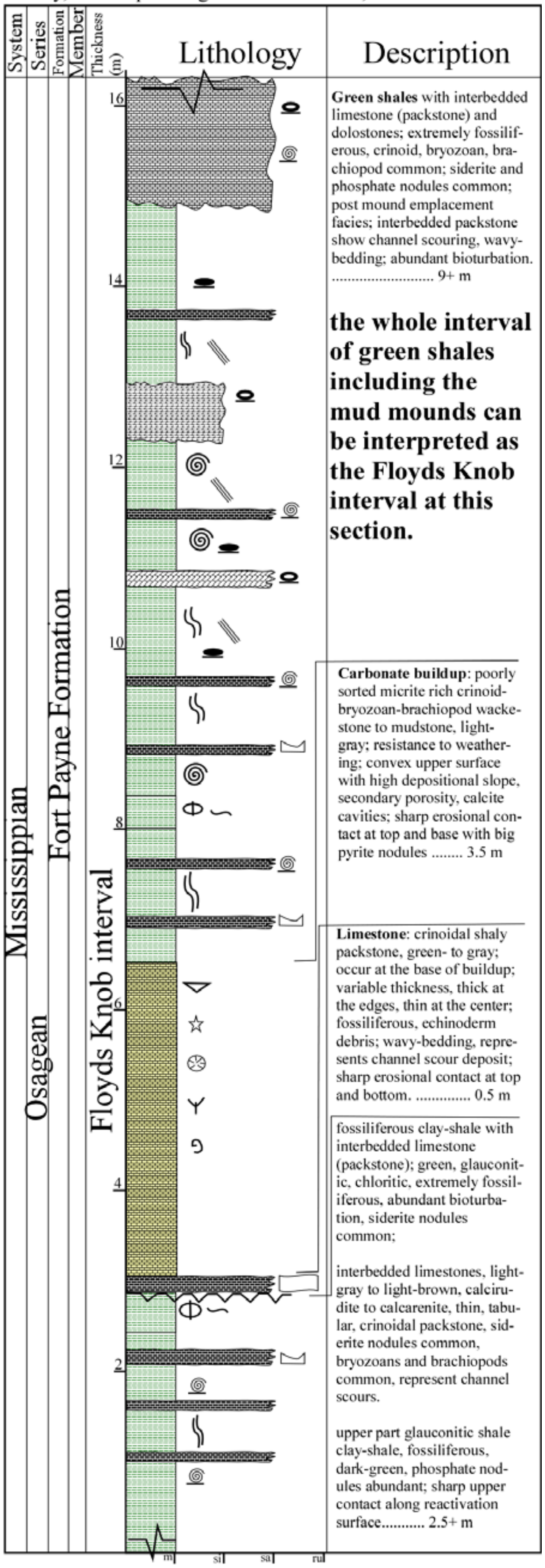



Figure FA26 – Measured stratigraphic section at the section LC3.

**Lake Cumberland section-4**: Inside lake Cumberland, Wayne County, Mill Springs quadrangle. 84°51'4.08"W, 36°58'21.06"N

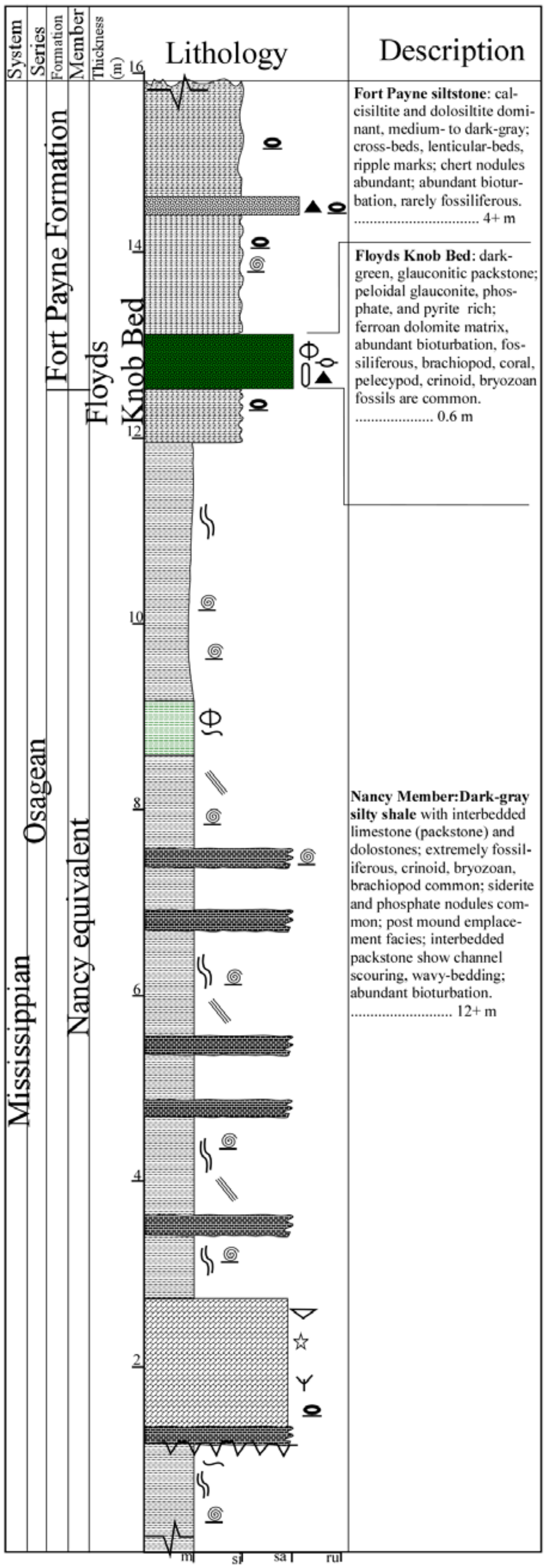



Figure FA27 – Measured stratigraphic section at the section LC4.

**Wolf-Creek Dam section**: Located at the parking structure, Russell County, Cumberland City quadrangle. 85°7'44.7"W, 36°52'9.36"N

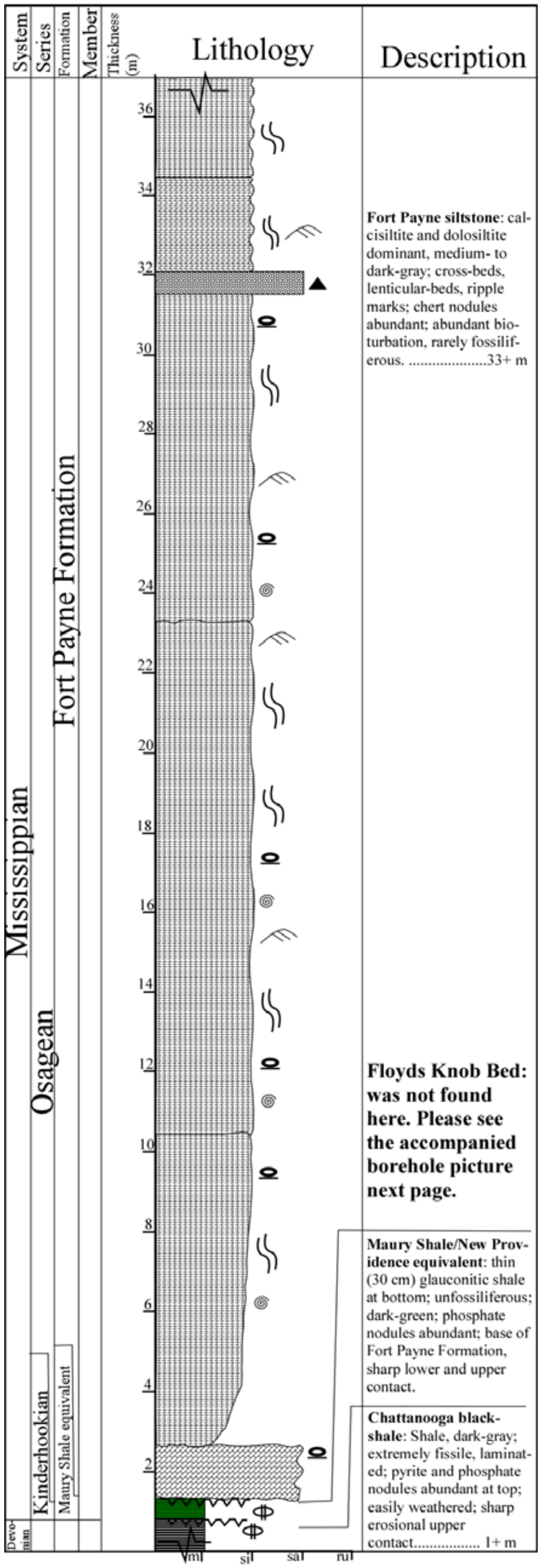
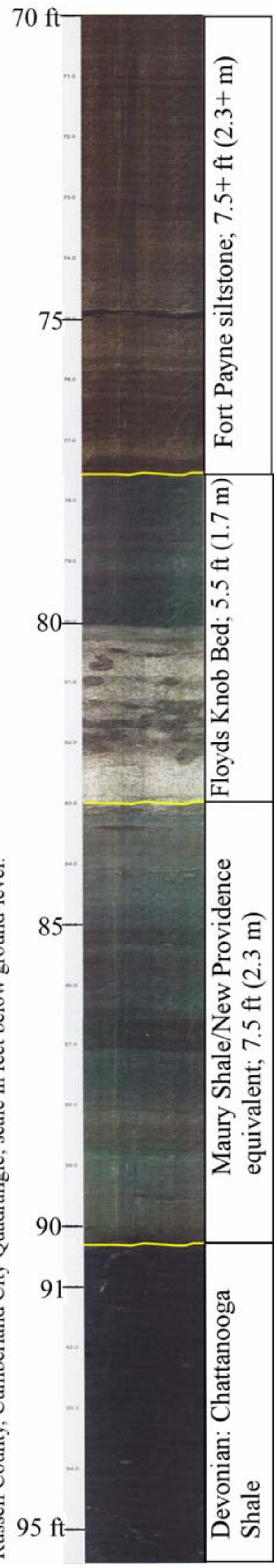



Figure FA28 – Measured stratigraphic section at the section WD.




**Composite borehole image:** Fort Payne Formation, Wolf Creek dam parking structure; Russell County, Cumberland City Quadrangle; scale in feet below ground-level.

Figure FA29 – Borehole image for figure FA28.

**Section Swanpond Road**: Outcrop located along Swanpond Road, Russell County, Wolf Creek Dam quadrangle. 85°9'43.74"W, 36°52'34.44"N

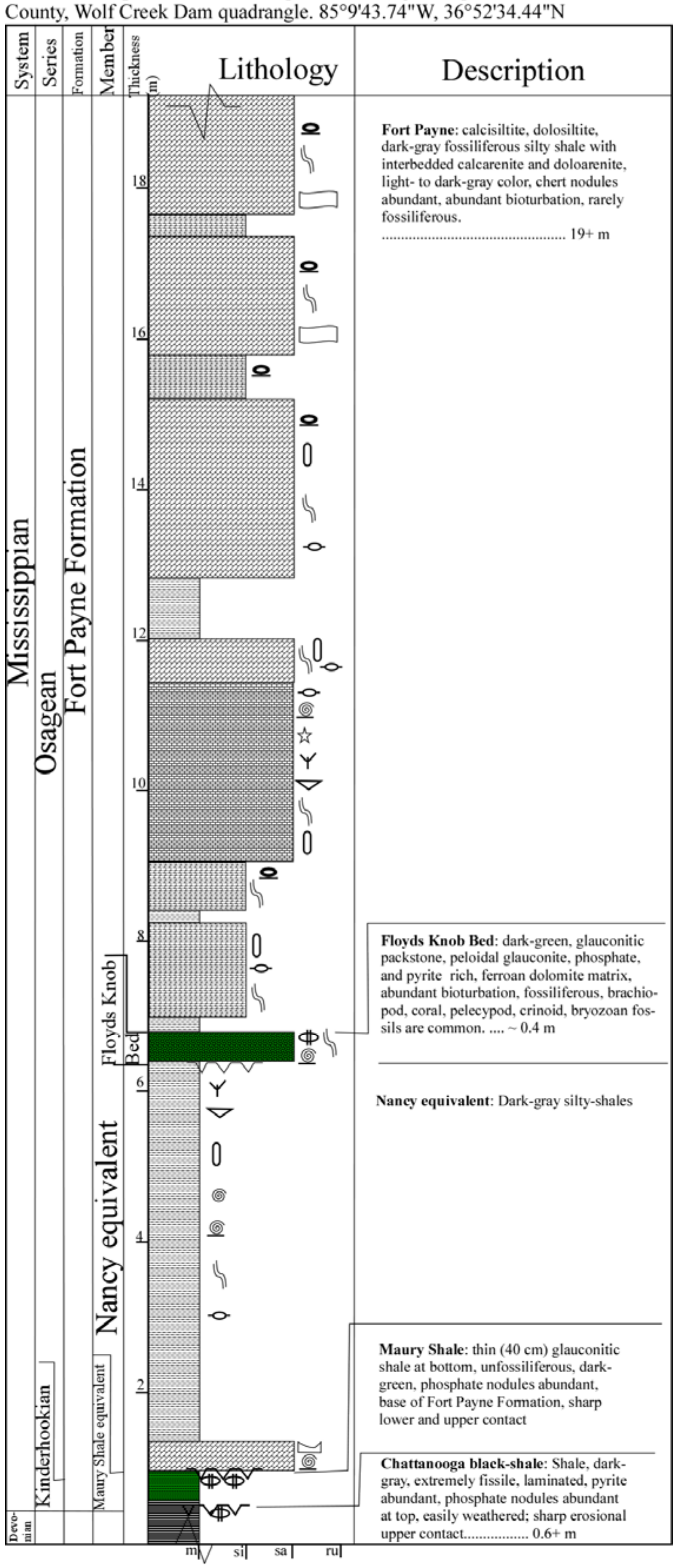



Figure FA30 – Measured stratigraphic section at the section SR.

**Mantown Road Section**: Outcrop located along Mantown Road, Clinton County, Wolf Creek Dam quadrangle. 85°12'15.78"W, 36°51'11.16"N

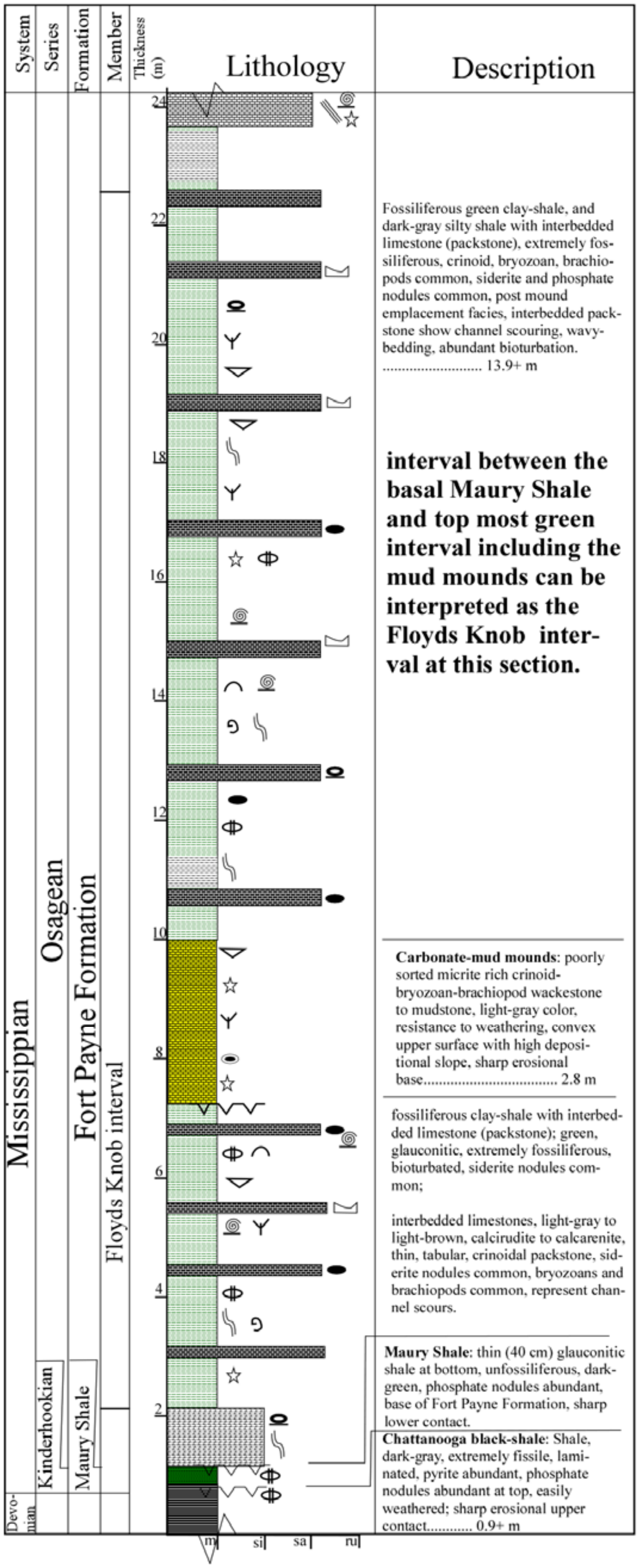



Figure FA31 – Measured stratigraphic section at the section MR.

**Section 61N-1**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°25'22.38"W, 36°53'24.36"N

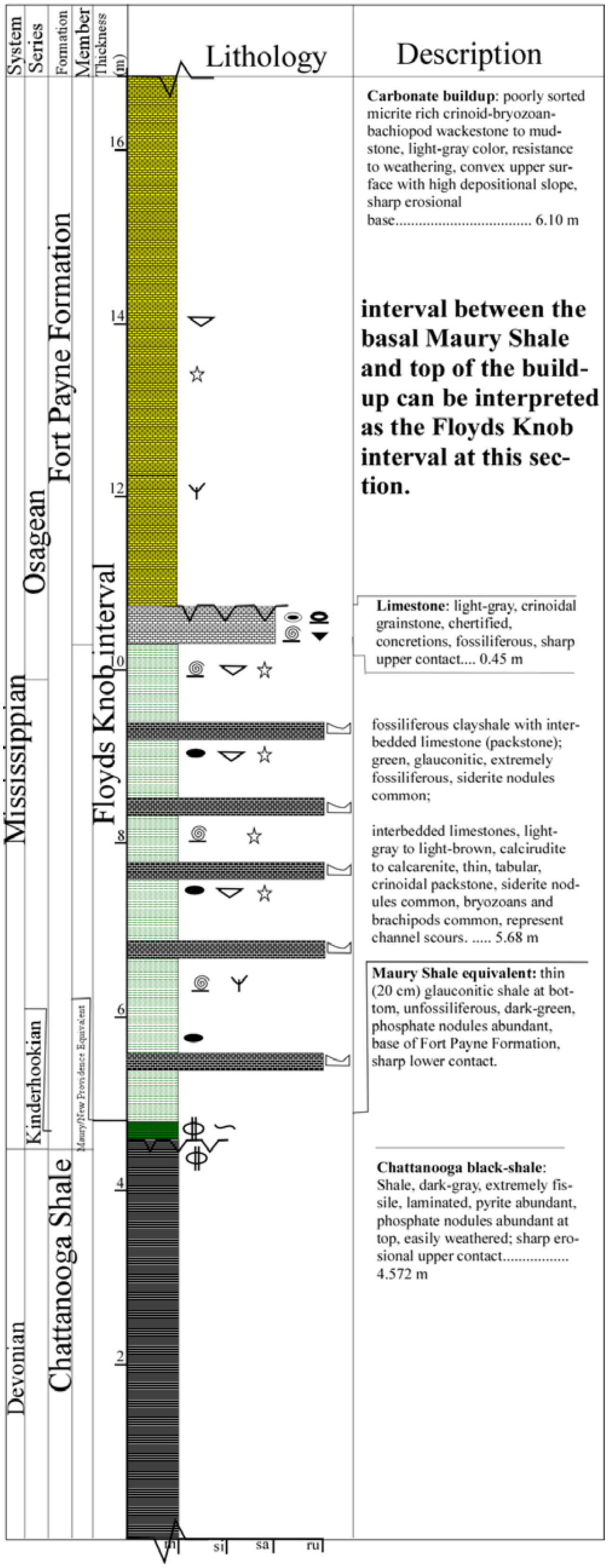



Figure FA32 – Measured stratigraphic section at the section BN1.

**Section 61N-2**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°25'41.88"W, 36°53'47.82"N

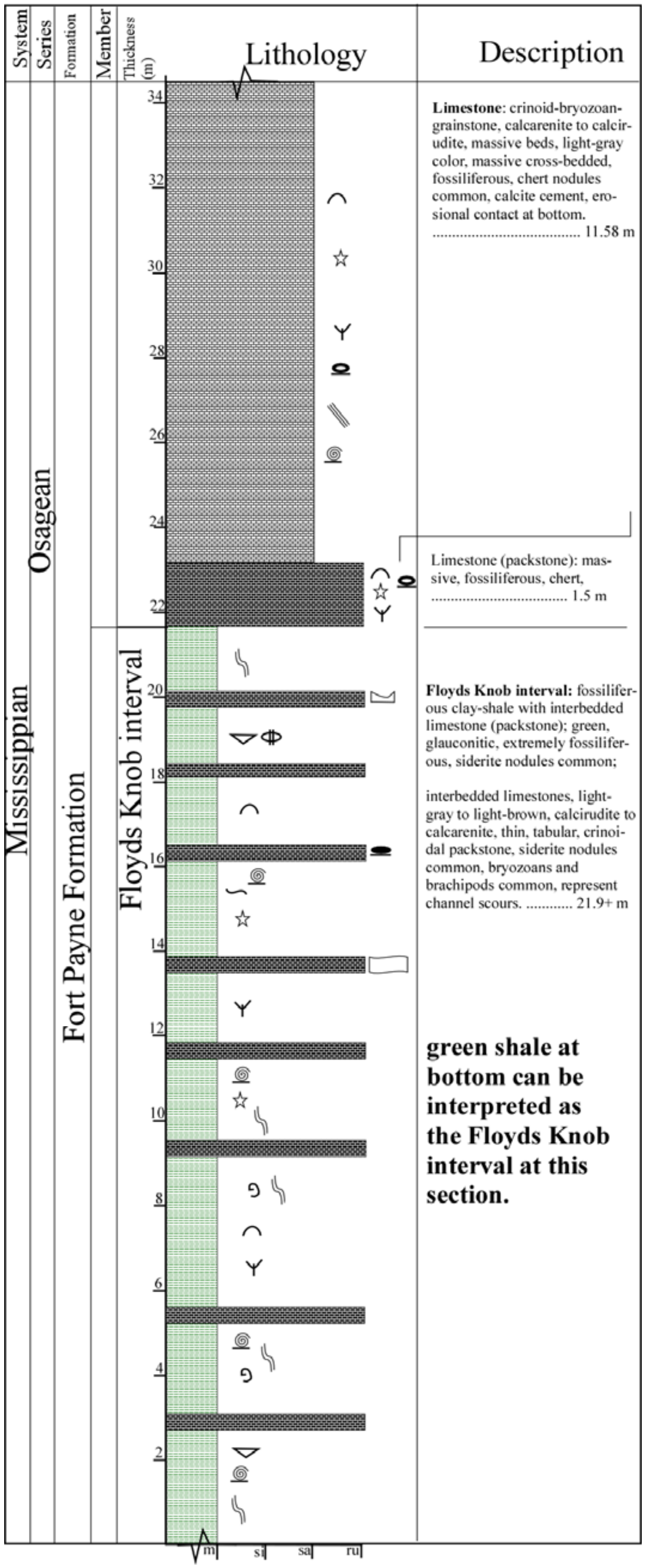



Figure FA33 – Measured stratigraphic section at the section BN2.

**Section 61N-3**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°25'46.74"W, 36°54'0.6"N

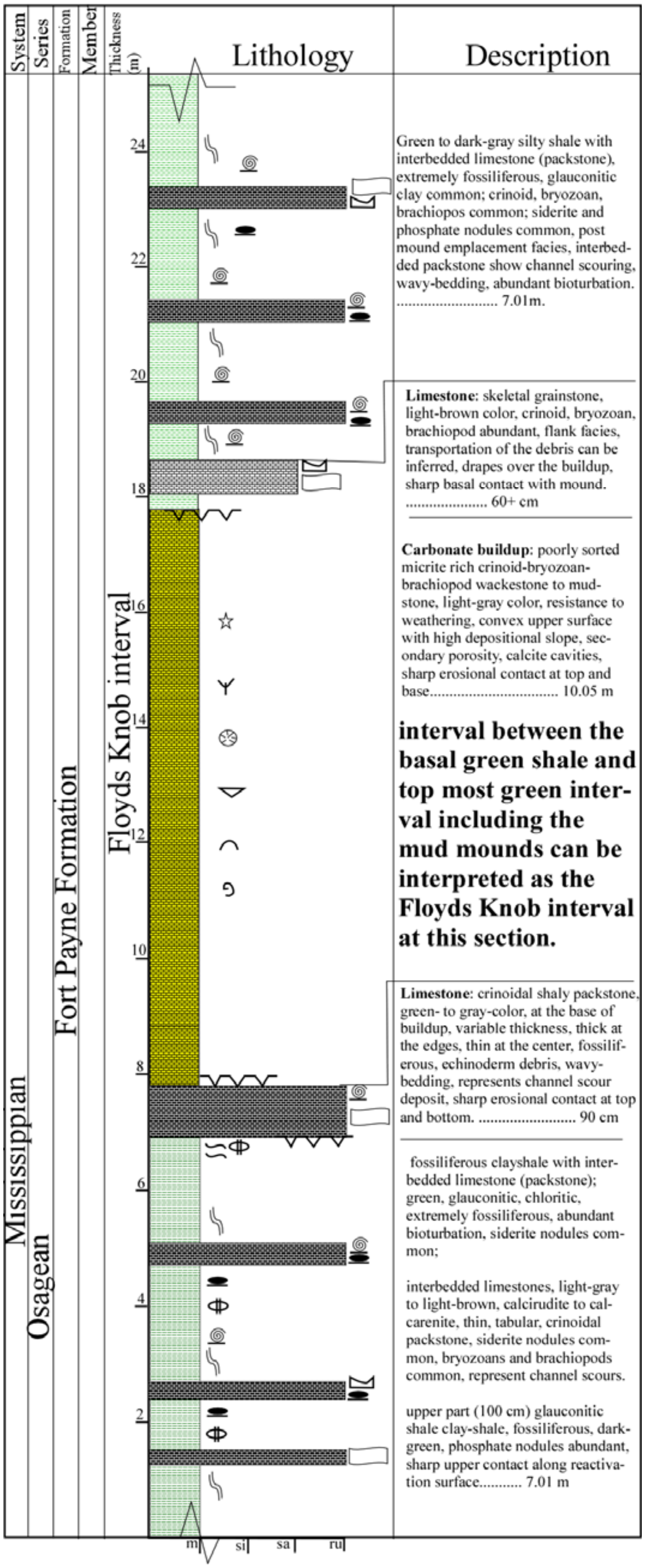



Figure FA34 – Measured stratigraphic section at the section BN3.

**Section 61N-4**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°25'54.36"W, 36°54'7.02"N

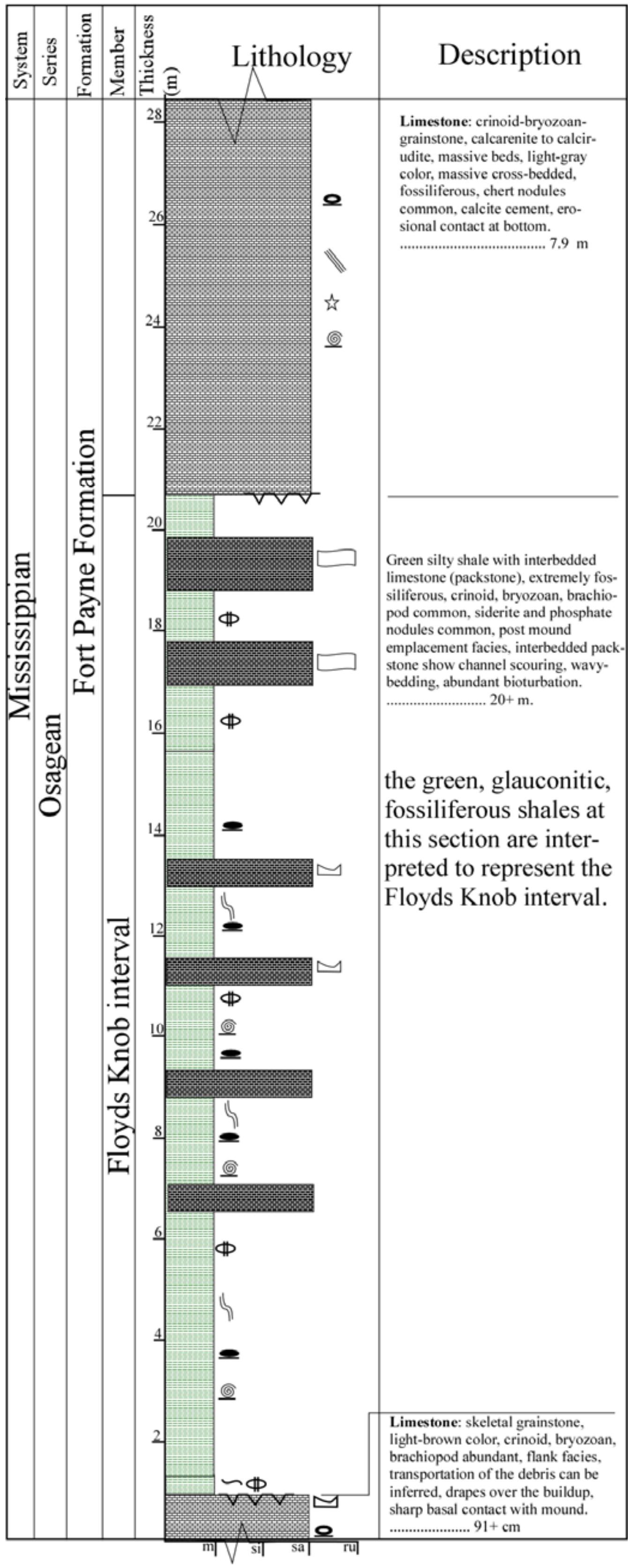



Figure FA35 – Measured stratigraphic section at the section BN4.

**Section 61N-5**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°26'16.14"W, 36°54'17.46"N

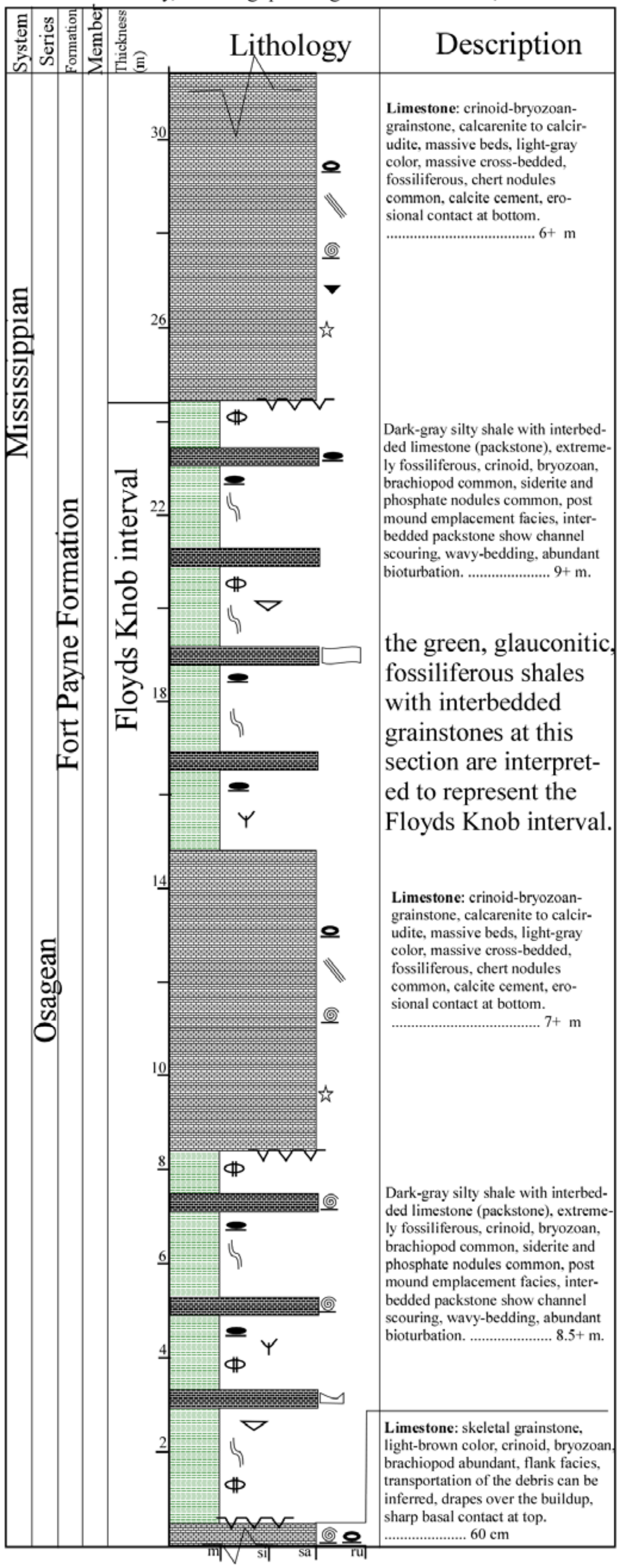



Figure FA36 – Measured stratigraphic section at the section BN5.

**Section 61S**: Outcrop located along KY-61S, south of Burkesville, Cumberland County, Frouge quadrangle. 85°21'59.94"W, 36°43'14.7"N

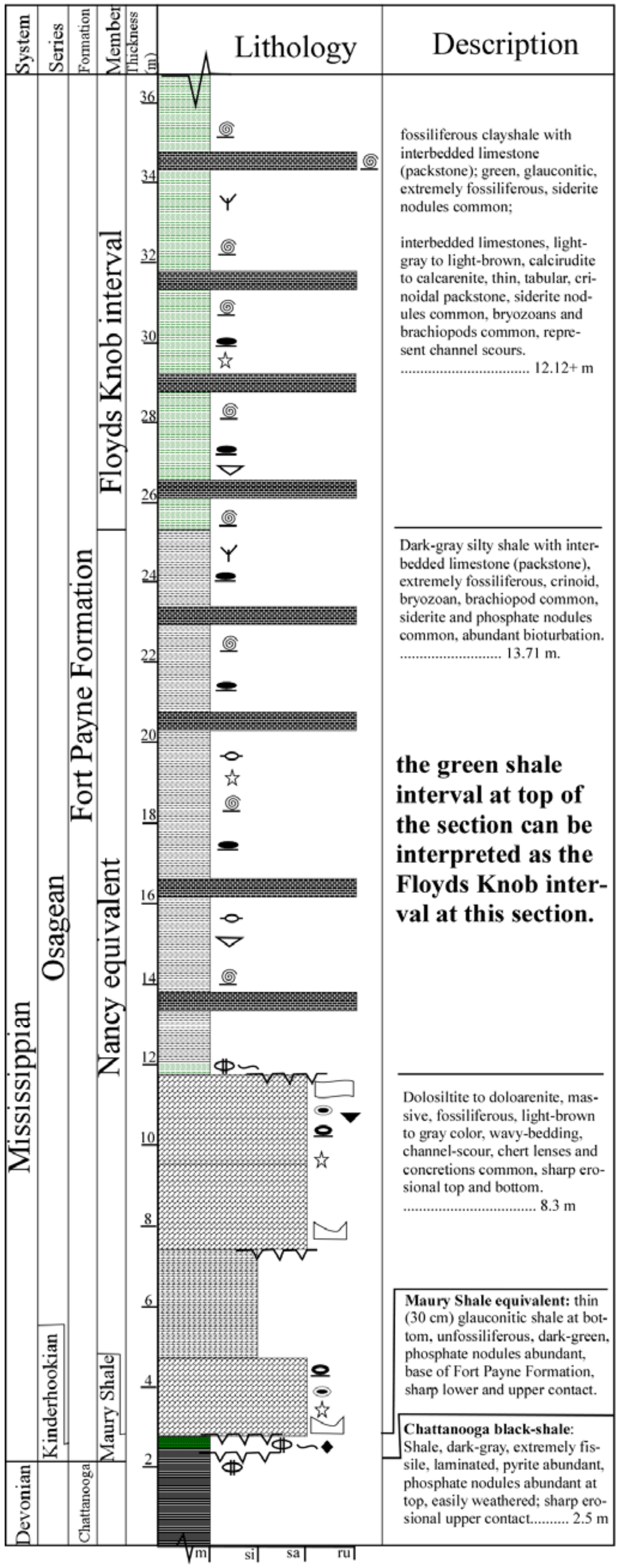



Figure FA37 – Measured stratigraphic section at the section BS.

**Section 90W**: Outcrop located along KY-90W, west of Burkesville, Cumberland County, Waterview quadrangle. 85°22'55.86"W, 36°47'59.04"N

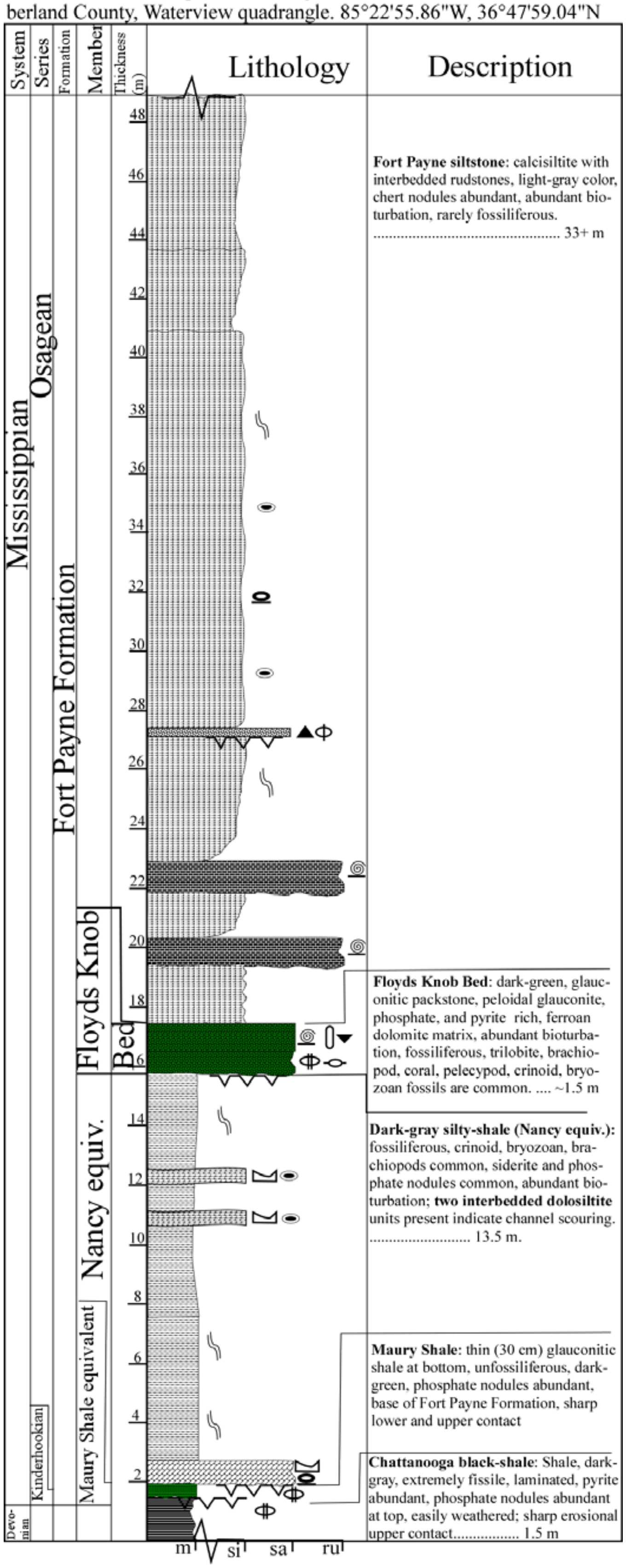



Figure FA38 – Measured stratigraphic section at the section BW

**Section 61N-6**: Outcrop located along KY-61N, north of Burkesville, Cumberland County, Breeding quadrangle. 85°26'36.3"W, 36°54'53.76"N

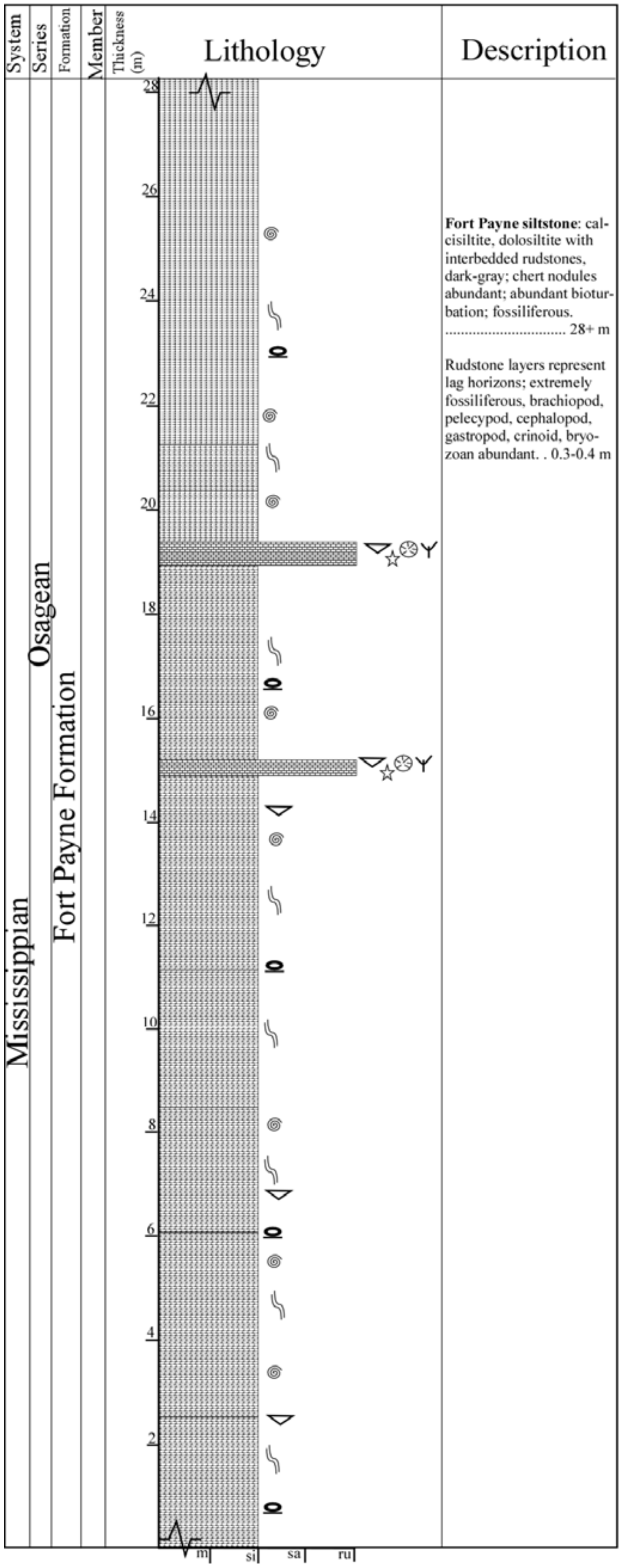



Figure FA39 – Measured stratigraphic section at the section BN6.

**Core C-505 section**: Fort Payne core, Russell County, Jamestown quadrangle. 85°5'48.919"W, 36°54'52.088"N

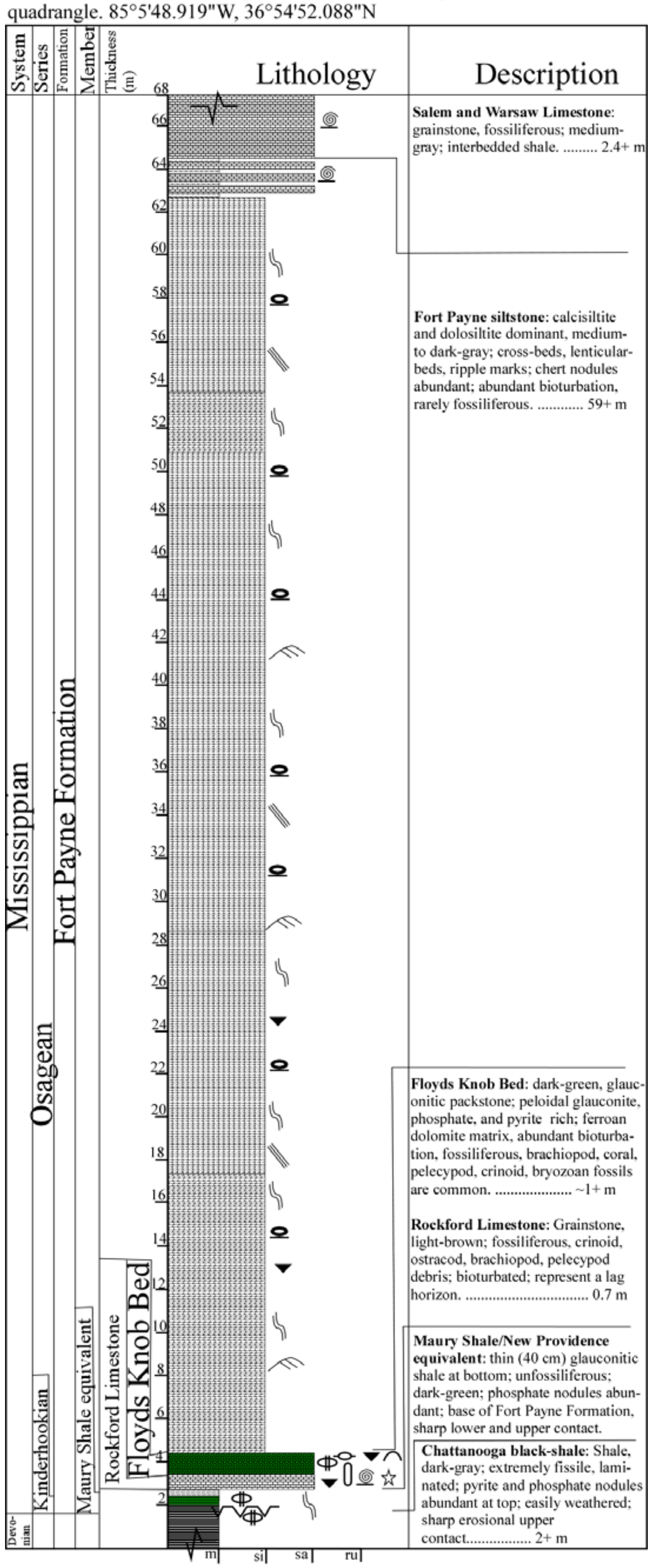



Figure FA40 – Measured stratigraphic section at the section C5.

**Pound Gap section**: Outcrop located at Pound Gap road, Letcher County
82°38'37.73"W, 37°9'25.1"N

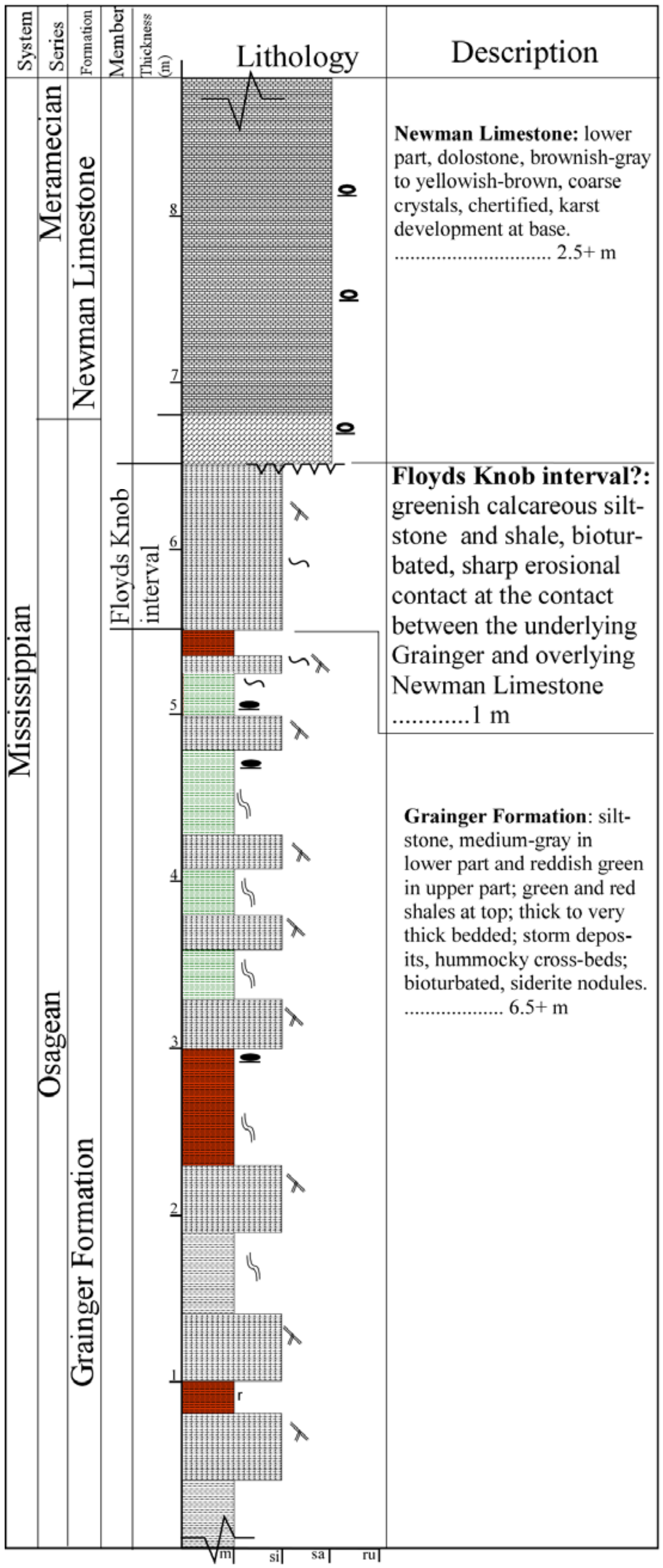



Figure FA41 – Measured stratigraphic section at the section PG.

**Cumberland Tunnel section**: Outcrop located inside Cumberland Tunnel (adapted and modified from Dean and Moshier, 1989), Claiborne County (VA), 83°40'36.96"W, 36°36'21.01"N

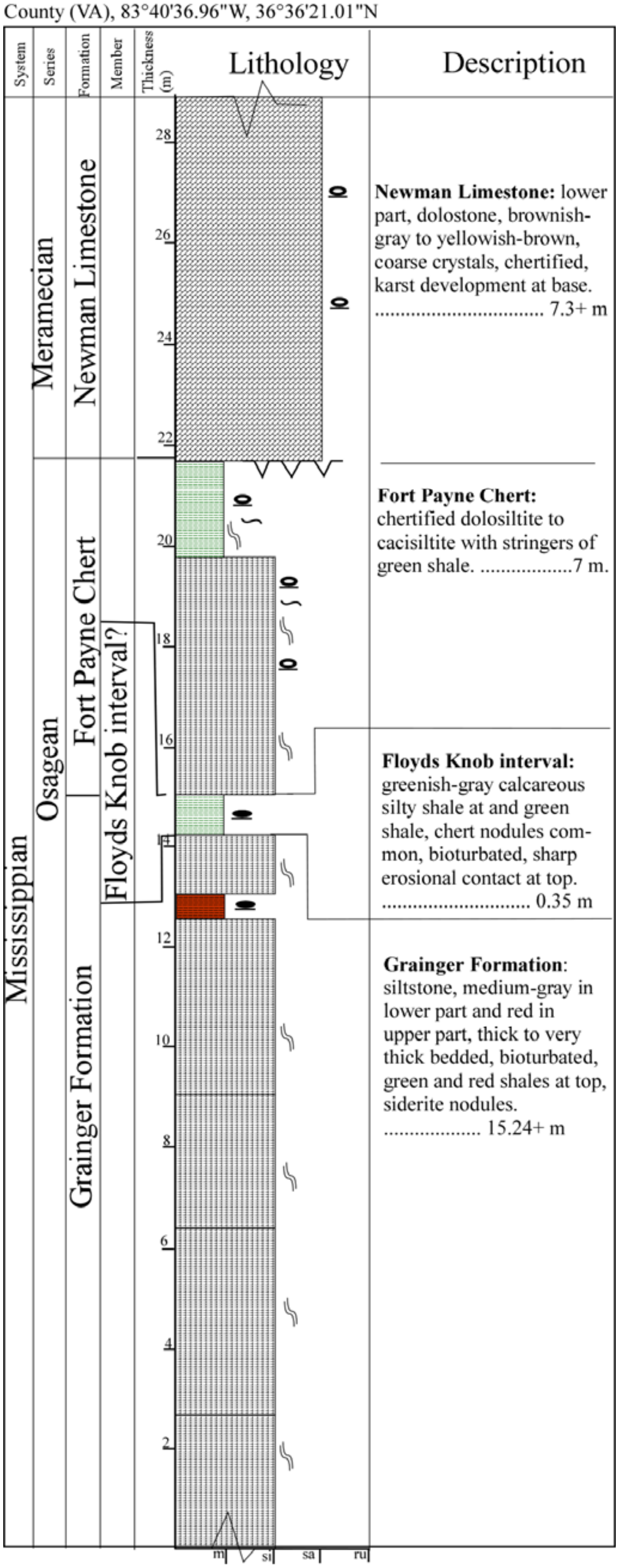



Figure FA42 – Measured stratigraphic section at the section CG.

**Jellico Mountain section**: Outcrop located along Interstate-75N, Campbell County (TN), 84°8'9.96"W, 36°33'12.25"N

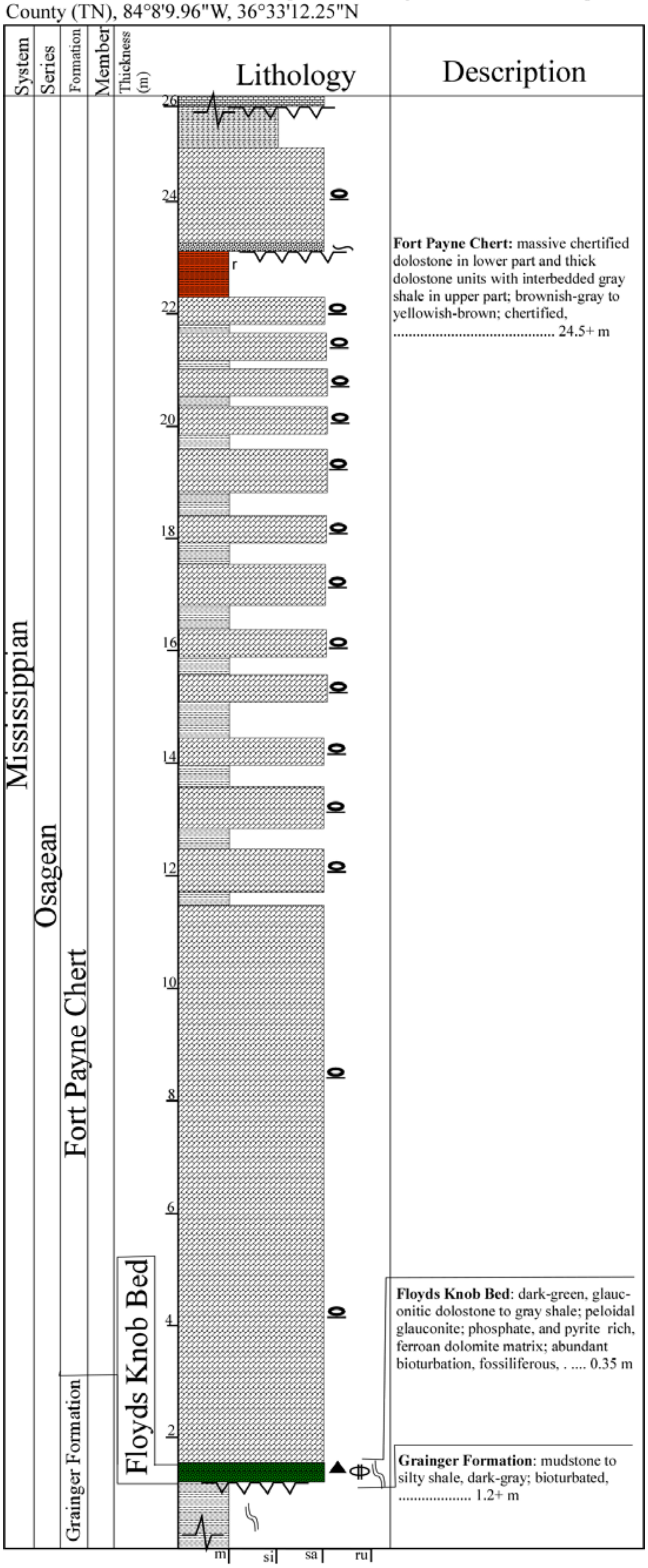



Figure FA43 – Measured stratigraphic section at the section JM.

# APPENDIX 2

($^{40}Ar/^{39}Ar$ analyses Spectra)

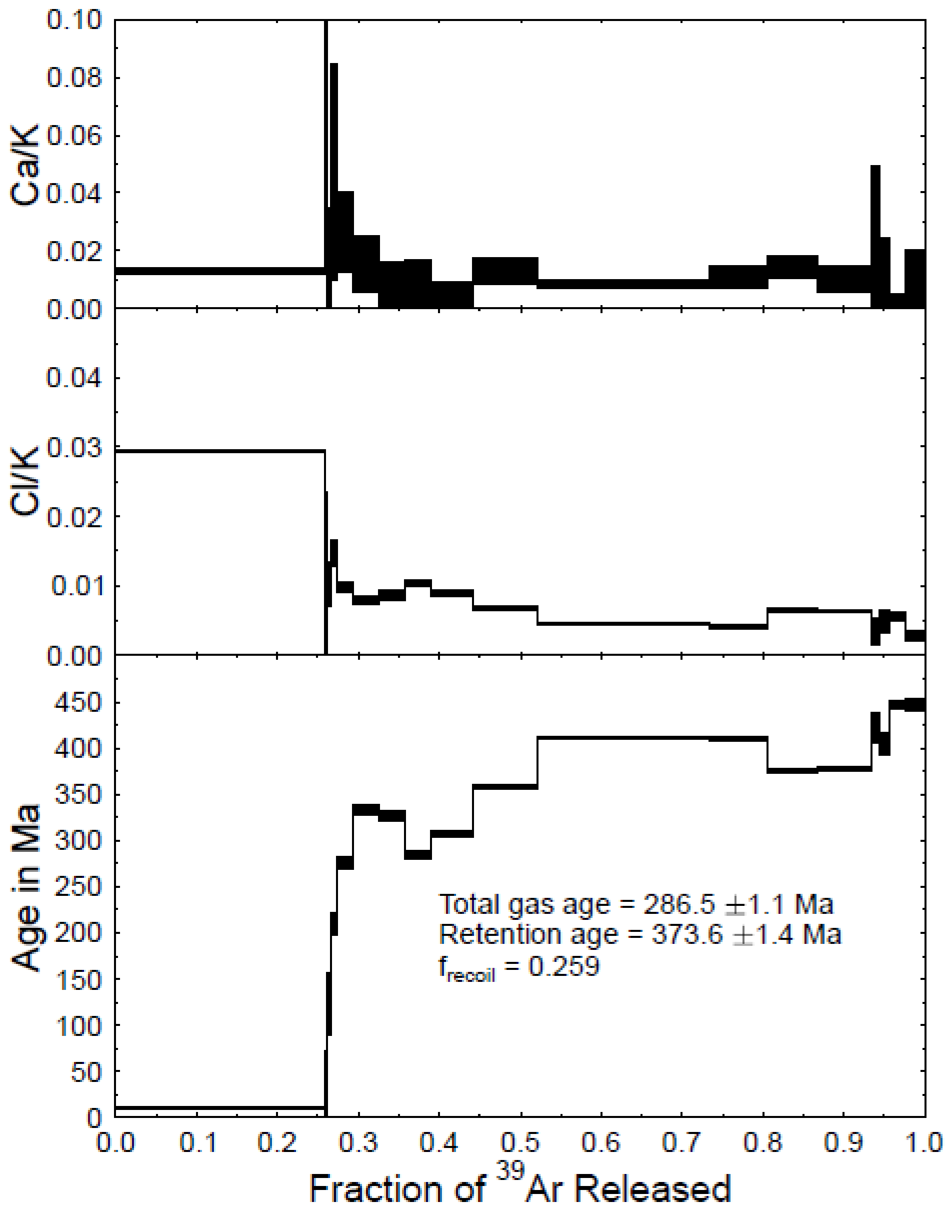



Figure FA44 – Ar-Ar spectrum for the sample L1-1.

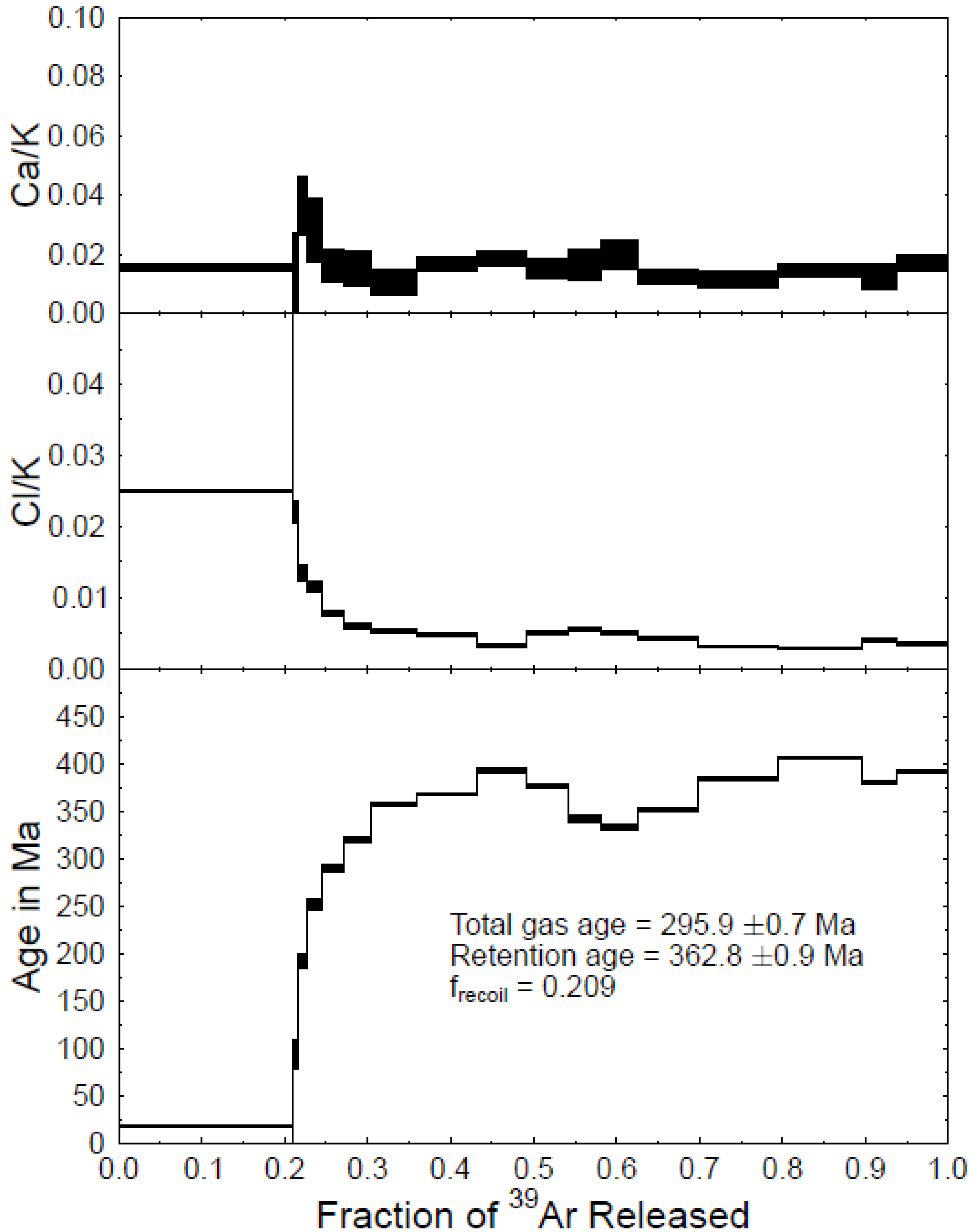



Figure FA45 – Ar-Ar spectrum for the sample L1-2.

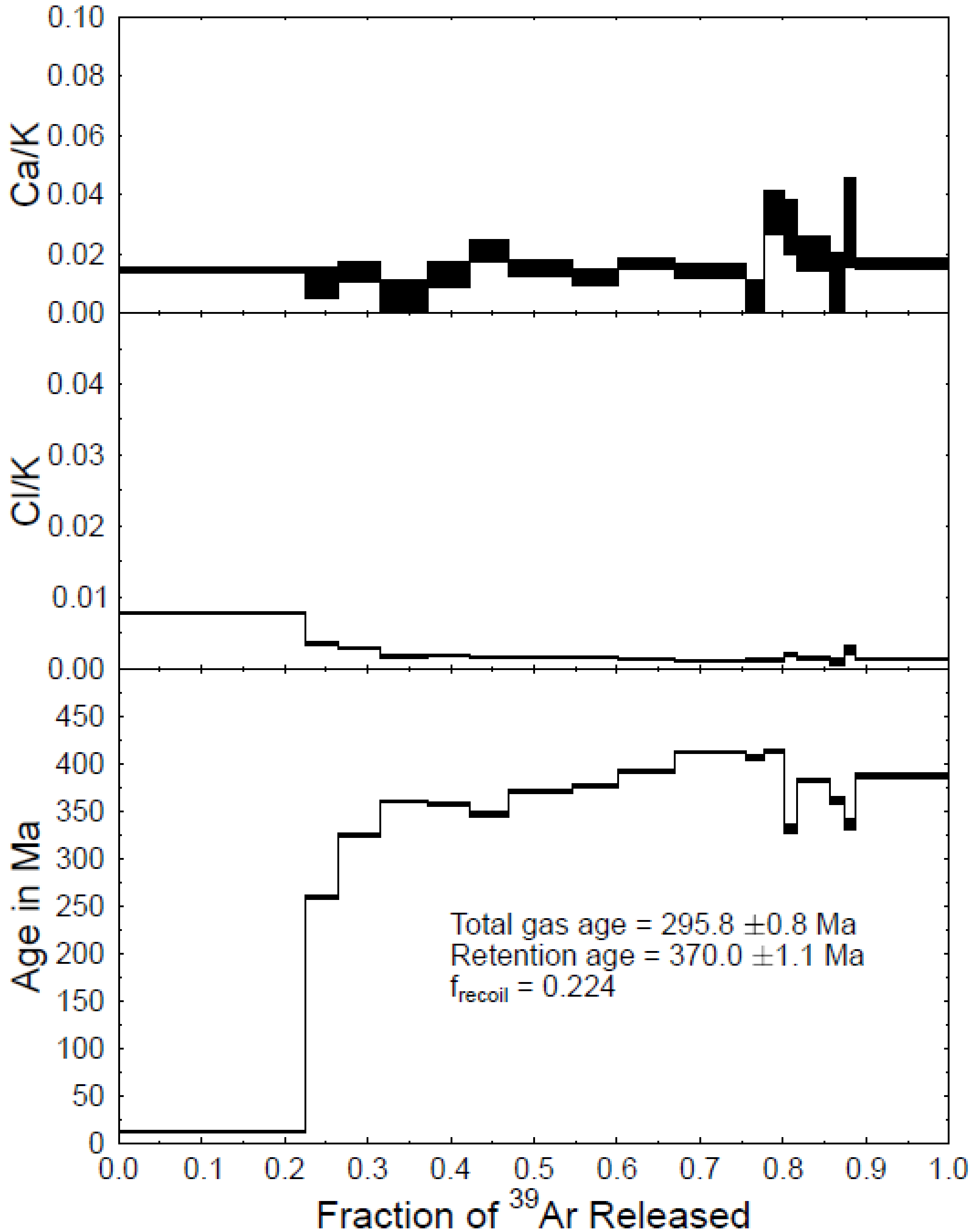



Figure FA46 – Ar-Ar spectrum for the sample BH-2.

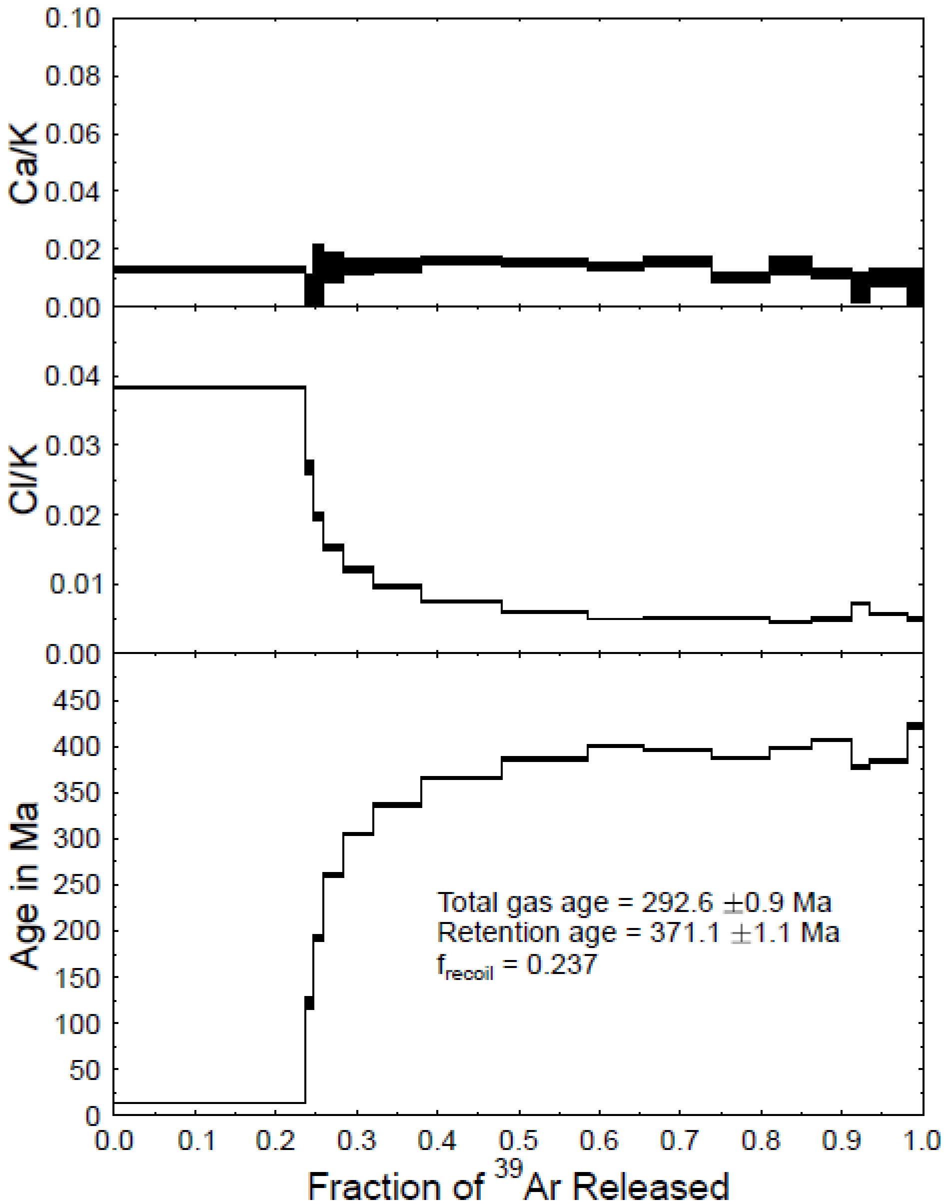



Figure FA47 – Ar-Ar spectrum for the sample BH-3.

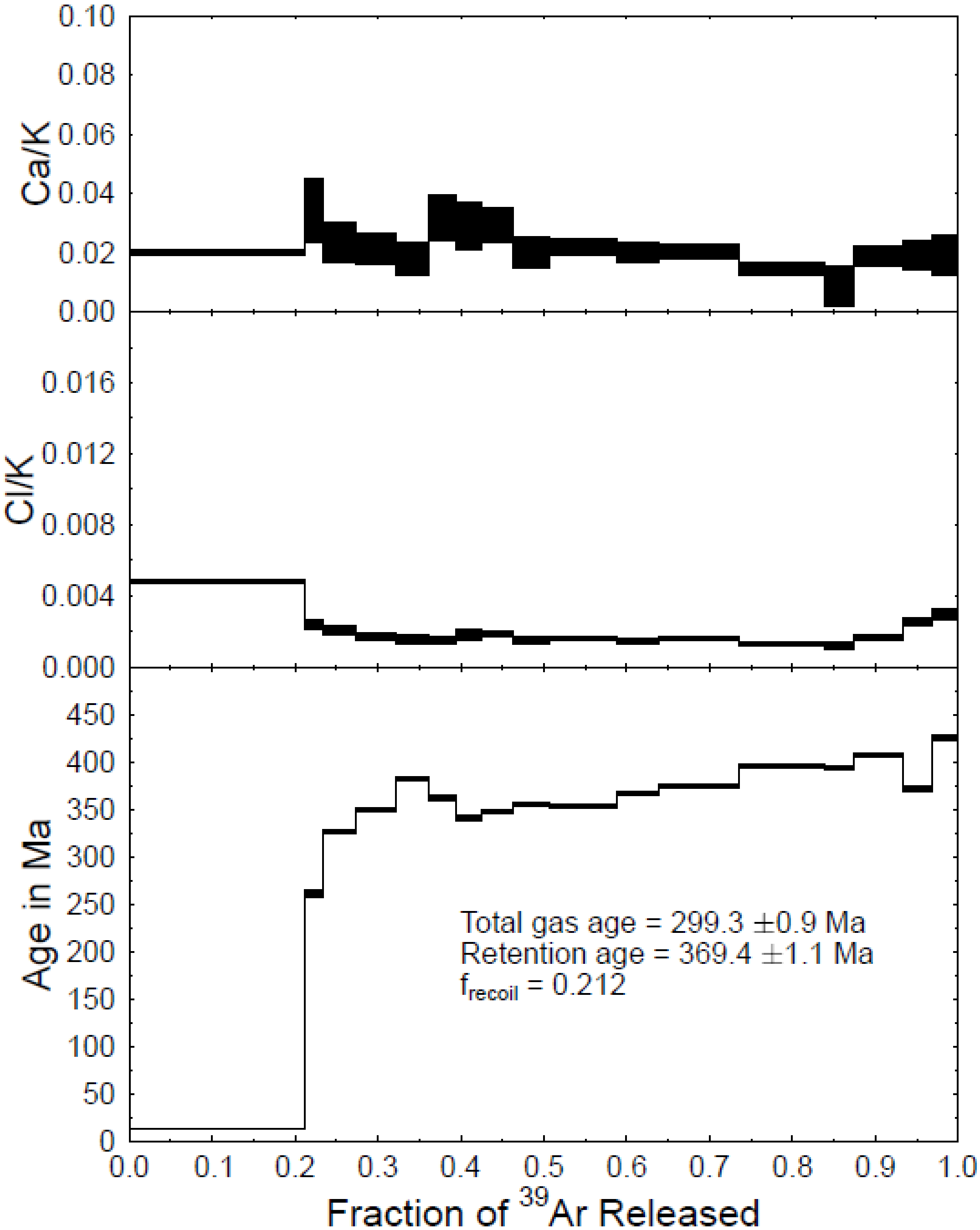



Figure FA48 – Ar-Ar spectrum for the sample OH3-1

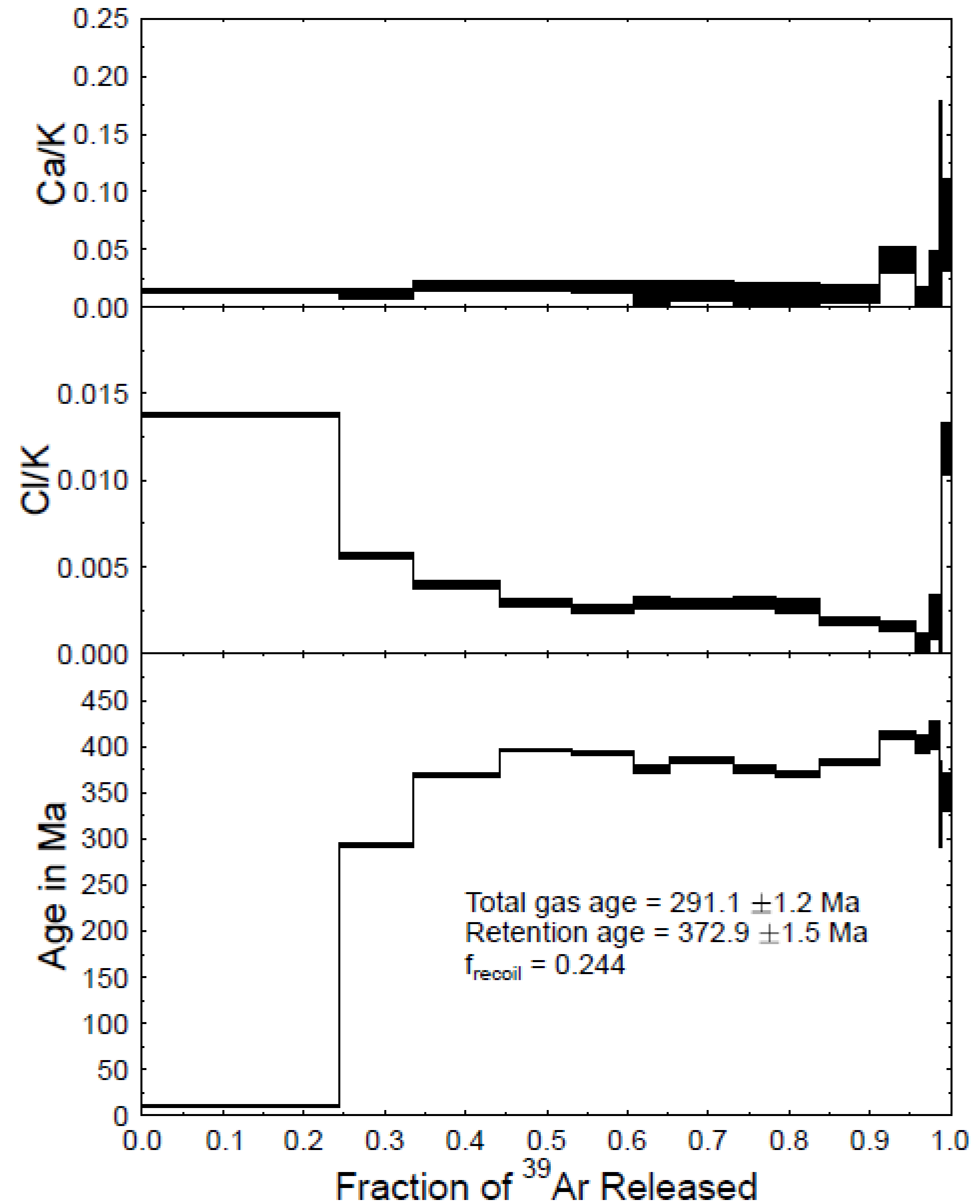



Figure FA49 – Ar-Ar spectrum for the sample OH3-2.

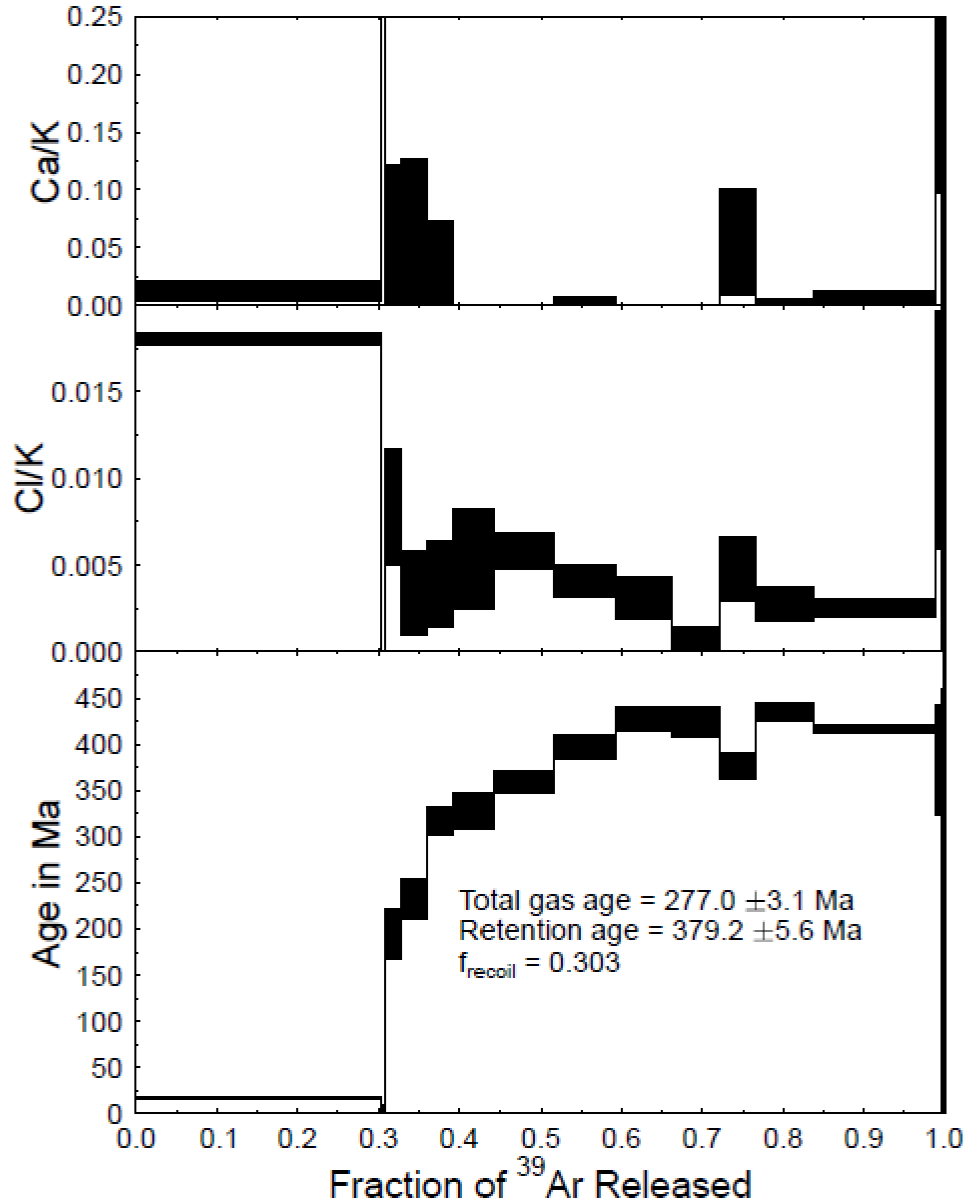



Figure FA50 – Ar-Ar spectrum for the sample OH3-3.

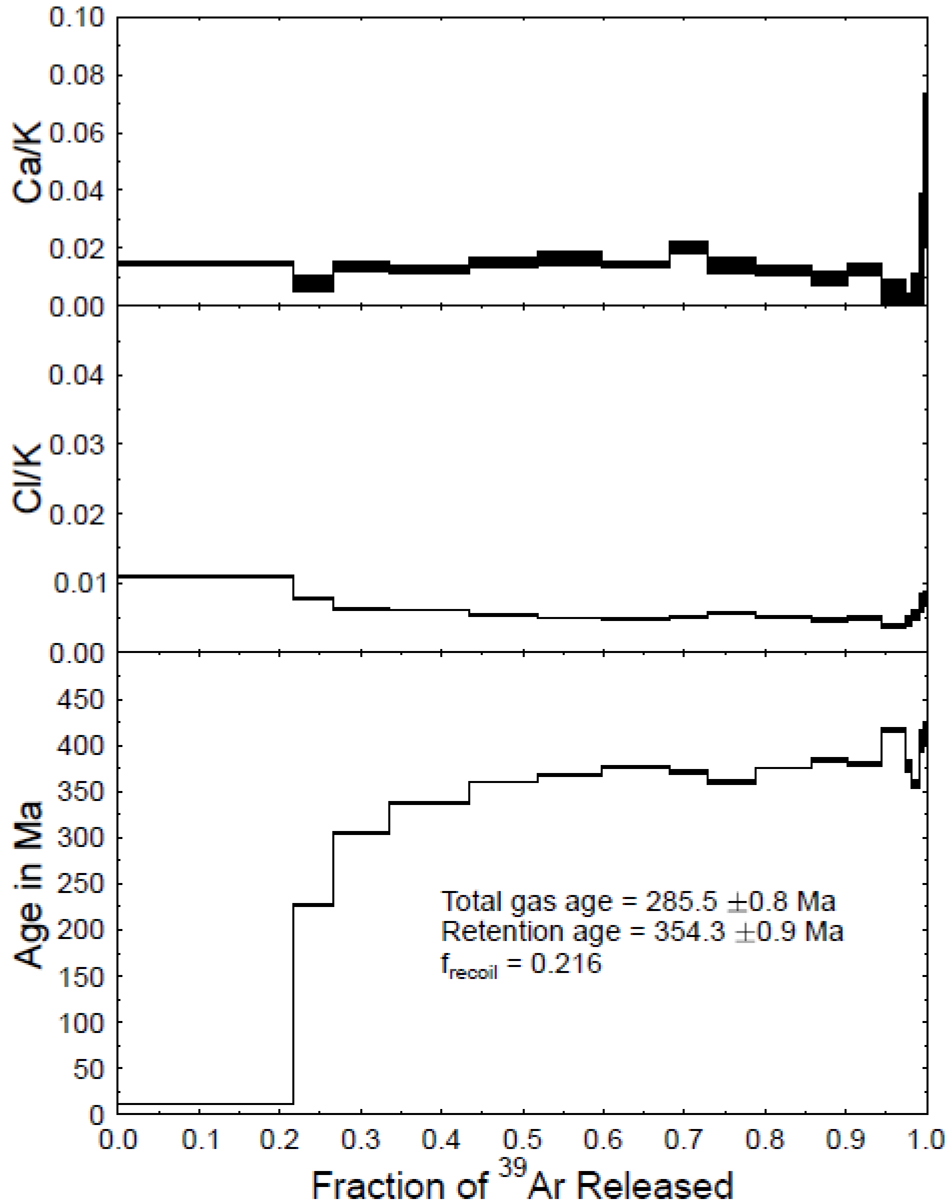



Figure FA51 – Ar-Ar spectrum for the sample BP-1.

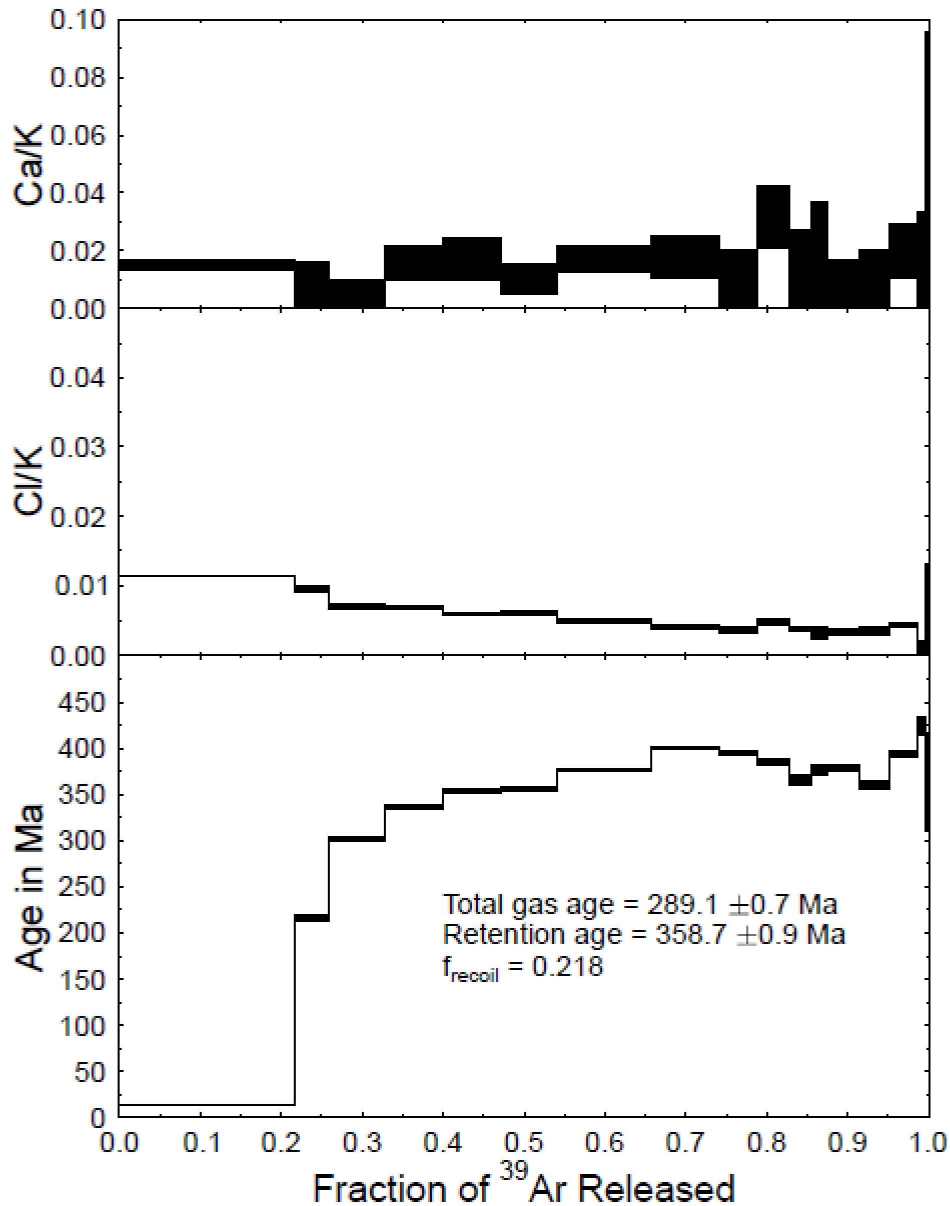



Figure FA52 – Ar-Ar spectrum for the sample BP-2.

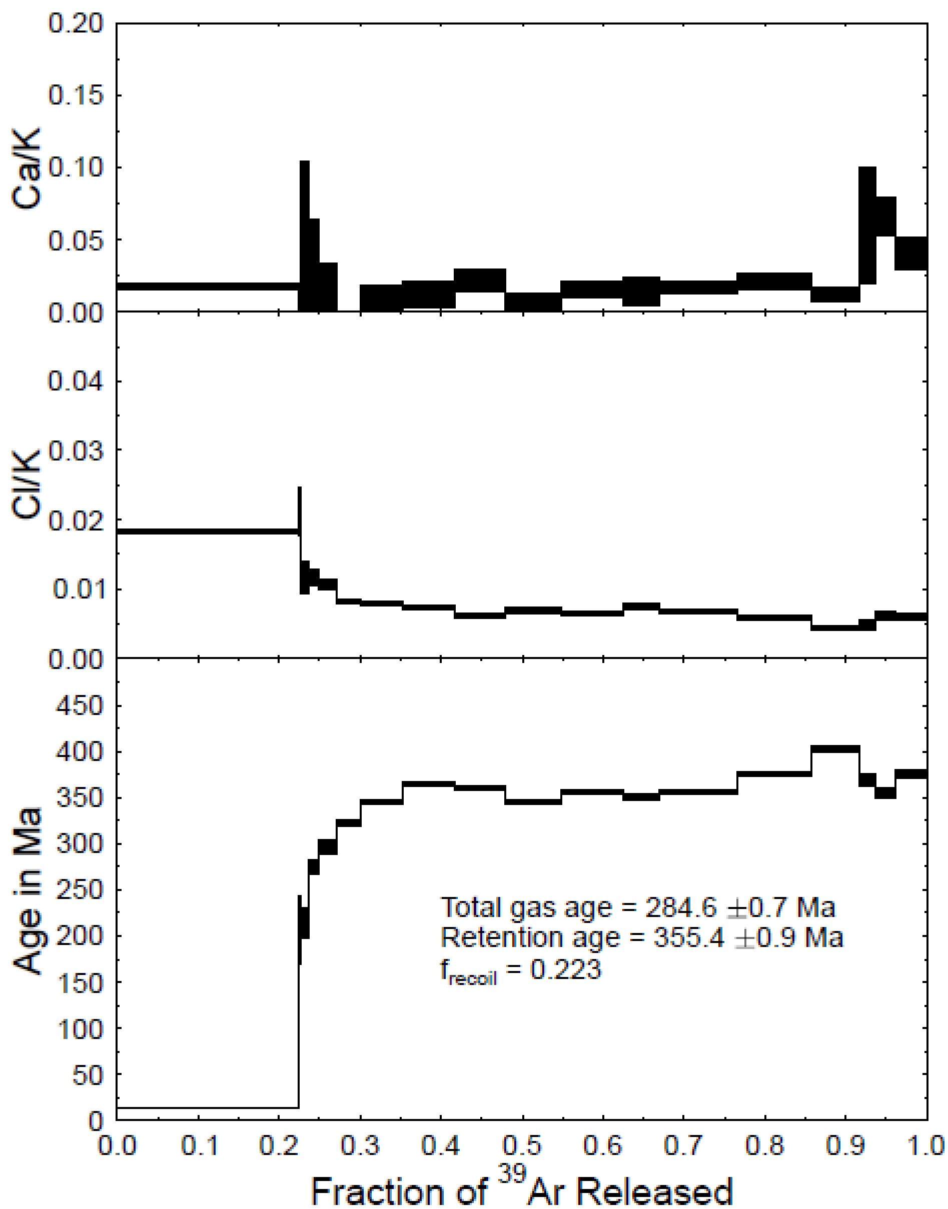



Figure FA53 – Ar-Ar spectrum for the sample BP-3.

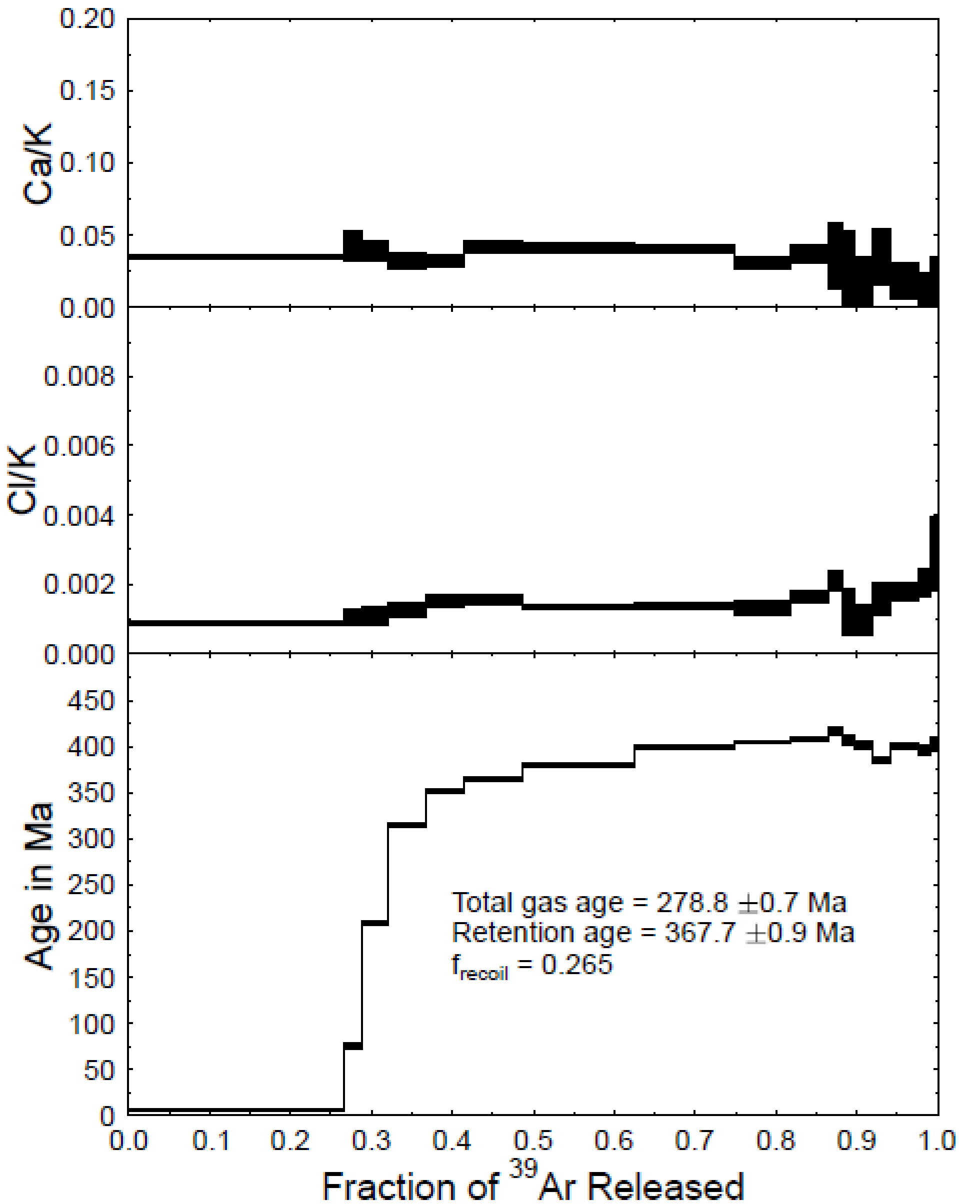



Figure FA54 – Ar-Ar spectrum for the sample BS (Maury Shale).

## REFERENCES


Albani, A., Fürsich, F. T., Colin, J., Meunier, A., Hochuli, P., Martin-Closas, C., Mazin, J., and Bruyat, J. B., 2004, Palaeoenvironmental reconstruction of the basal Cretaceous vertebrate bearing beds in the Northern part of the Aquitaine Basin (SW France): Sedimentological and geochemical evidence: Facies, v. 50, no. 2, p. 195-215.

Albarede, F., 1982, The $^{39}Ar/^{40}Ar$ technique of dating: In CNRS, Paris, France. Wiley-Interscience Publication, p. 181-197.

Algeo, T.J., Berner, R.A., Maynard, J.D., and Scheckler, S.U., 1995, Late Devonian oceanic anoxic events and biotic crisis: "Rooted" in the evolution of vascular land plants? GSA Today, v. 5, p. 45-66.

Amireh, B. S., Jarrar, G., Henjes-Kunst, F., and Schneider, W., 1998, K-Ar dating, X-Ray diffractometry, optical and scanning electron microscopy of glauconies from the early Cretaceous Kurnub Group of Jordan: Geological Journal, v. 33, p. 49-65.

Ammerman, M.L., and Keller, G.R., 1979, Delineation of Rome Trough in Eastern Kentucky by gravity and deep drilling data: American Association of Petroleum Geologists Bulletin, v. 63, no, 3, p. 341-353.

Amorosi, A., 1995, Glaucony and sequence stratigraphy: A conceptual framework of distribution in siliciclastic sequences: Journal of Sedimentary Research, v. B65, p. 419-425.

Amorosi, A., 1997, Detecting compositional, spatial, and temporal attributes of glaucony: a tool for provenance research: Sedimentary Geology, v. 109, p. 135-153.

Amouric, M., and Parron, C., 1985, Structure and growth mechanism of glauconite as seen by high-resolution transmission electron microscopy: Clays and Clay Minerals, v. 33, no. 6, p. 473-482.

Anderson, A., Jonas, E.C., and Odum, H.T., 1958, Alteration of clay minerals by digestive processes of marine organisms: Science, v. 127, p. 190-191.

Anderson, W.H., 1989, Controls on mineralization and hydrocarbon accumulation in the Cambro-Ordovician of the Knox Group in south-central Kentucky: Lexington, University of Kentucky, M.S. Thesis, 93 p.

Anderson, W.H., 1991, Mineralization and hydrocarbon emplacement in the Cambrian-Ordovician Mascot Dolomite of the Knox Group in south-central Kentucky: Kentucky Geological Survey, Series 11, Report of Investigations 4, 31 p.

Andrews, W.M., 1997, Structural control on the origin and nature of the Brassfield Formation (Lower Silurian) west of the Cincinnati Arch, Kentucky: Lexington, University of Kentucky, MS Thesis, 120 p.

Arbenz, J. K., 1989, The Ouachita system, *in* Balley, A. W. and Palmer, A. R. eds., The geology of North America—An overview, Geological Society of America, The geology of North America, Boulder, Colorado, v. A, p. 371–396.

Arkle, T. JR., Beissel, D. R., Larese, R. E., Nuhfer, E. B., Patchen, D. G., Smosna, R. A., Gillespie, W. H., Lund, R., Norton, C. W., and Pfefferkorn, H. W., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—West Virginia and Maryland: U. S. Geological Survey Professional Paper 1110-D, 35p.

Artyushkov, E. V., 1987, Rifts and grabens: Tectonophysics, v. 133, p. 321-331.

Ausich, W.I., and Meyer, D.L., 1990, Origin and composition of carbonate buildups and associated facies in the Fort Payne Formation (Lower Mississippian, south-central Kentucky): An integrated sedimentologic and paleoecologic analysis: Geological Society of America Bulletin, v. 102, p. 129-146.

Ausich, W.I., and Meyer, D.L., 1992, Crinoidea Flexibilia (Echinodermata) from the Fort Payne Formation (Lower Mississippian; Kentucky and Tennessee), Journal of Paleontology, v. 65, p. 825-838.

Ausich, W.I., Goldstein, A., Yates, R., 2000, Crinoids from the Muldraugh Member of the Borden Formation in north-central Kentucky (Echinodermata, Lower Mississippian): Journal of Paleontology, v. 74, no.6, 2000, pp. 1072-1082.

Barnett, S.F., and Ettensohn, F.R., 1992a, Portwood Member of the New Albany Shale and the Boyle Dolostone *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology. Layer-cake, facies, flexure, and eustasy: Ohio Geological Survey, Miscellaneous Report 5, p. 42-44.

Barnett, S.F., and Ettensohn, F.R., 1992b, The Carpenter Fork Graben and its implications, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology. Layer-cake, facies, flexure, and eustasy: Ohio Geological Survey, Miscellaneous Report 5, p. 44-45.

Bartlett, C.S., 1974, Anatomy of the Lower Mississippian delta in southwestern Virginia: Knoxville, University of Tennessee, Ph.D. Dissertation, 373 p.

Bates, R.L., and Jackson, J.A., 1984, Dictionary of Geological Terms: The American Geological Institute, Garden City, New York, Anchor Press/Doubleday, 571 p.

Baum, G.R., and Vail, P.R., 1988, Sequence stratigraphic concepts applied to Paleogene outcrops, Gulf and Atlantic basins, *in* Wilgus, C.K., Hastings, B. S., Ross, C.A., Posamentier, H.W., Van Wagoner, J., and Kendall, C.G., eds., Sea-level changes: An integrated approach, Society of Economic Paleontologists and Mineralogists, Special Publication 42, p. 309-327.

Beaumont, C., 1981, Foreland basins: Geophysical Journal of the Royal Astronomical Society, v. 65, p. 291–329.

Beaumont, C., G. M. Quinlan, and J. Hamilton, 1987, The Alleghanian orogeny and its relationship to the evolution of the eastern interior of North America, *in* C. Beaumont and A. J. Tankard, eds., Sedimentary basins and basin-forming mechanisms: Canadian Society of Petroleum Geologists Memoir 12, p. 425–445.

Beaumont, C., Quinlin, G.M., and Hamilton, J., 1988, Orogeny and stratigraphy: numerical models of the Paleozoic in the Eastern Interior of North America: Tectonics, v. 7. p. 389-416.

Bement, W.O., Elias, R.J., Goodman, W.R., Bacon, R., Yu, H., and Potter, P.E., 1981, Mississippian and Pennsylvanian section on Interstate 75 south of Jellico, Campbell County, Tennessee: Tennessee Division of Geology Report of Investigation 38, p. 1-42.

Benson, D. J., Lithofacies and depositional environments of Osagean–Meramecian platform carbonates southern Indiana, central and eastern Kentucky: Cincinnati, University of Cincinnati, Ph. D. dissertation, 215 p.

Berner, R.A., 1994, GEOCARB II: a revised model of atmospheric $CO_2$ over Phanerozoic time: American Journal of Science, v. 294, p. 56-91.

Bethke, C. M., W. J. Harrison, C. Upson, and S. P. Altaner, 1988, Supercomputer analysis of sedimentary basins: Science, v. 239, p. 261–267.

Bjerstedt, T.W., and Kammer, T.W., 1988, Genetic stratigraphy and depositional systems of the Upper Devonian-Lower Mississippian Price-Rockwell deltaic complex in the Central Appalachians, U.S.A.: Sedimentary Geology, v. 54, p. 265-301.

Black, D.F.B., 1989, Tectonic evolution in central and eastern Kentucky: A multidisciplinary study of surface and subsurface structure: United States Geological Survey Open-File Report 89-106, 151 p.

Borella, P.E., and Osbourne, R.H., 1978, Late-middle and early-Late Ordovician history of the Cincinnati arch province, central Kentucky to central Tennessee: Geological Society of America Bulletin, v. 89, no. 10, p. 1559-1573.

Bornhold, B.D., and Giresse, P., 1984, Glauconitic sediments on the continental shelf off Vancouver Island, British Columbia, Canada: Journal of Sedimentary Petrology, v. 55, p. 653-664.

Brand, U., 1989, Biochemistry of the Late Paleozoic North America brachiopods and secular variations of seawater composition: Biochemistry, v. 7, p. 159-193.

Brannon, J. C., F. A. Podosek, and R. K. McLimans, 1992, Alleghenian age of the Upper Mississippi Valley zinc-lead deposit determined by Rb-Sr dating of sphalerites: Nature, v. 356, p. 509–511.

Brereton, N. R., Hooker, P. J., Miller, J. A., 1976, Some conventional potassium-argon and $^{40}Ar/^{39}Ar$ age studies of glauconite: Geological Magazine, v. 113, p. 329-340.

Brezinski, D. K., 1999, The Rise and Fall of Late Paleozoic Trilobites of the United States: Journal of Paleontology, v. 73, no. 2, p. 164-175.

Bruckschen, P., and Veizer, J., 1997, Oxygen and carbon isotopic composition of Dinantian brachiopods: Paleoenvironmental implications for the Lower Carboniferous of western Europe: Paleogeography, Paleoclimatology, and Paleoecology, v. 132, p. 243-264.

Bruckschen, P., Bruhn, F., Veiver, J., and Buhl, D., 1995, $^{87}Sr/^{86}Sr$ isotopic evolution of Lower Carboniferous seawater: Dinantion of western Europe: Sedimentary Geology, v. 100, p. 63-81.

Butts, C., 1922, The Mississippian series of eastern Kentucky: Kentucky Geological Survey, Series 6, v. 7, 88 p.

Butts, C., 1940, Geology of the Appalachian valley in Virginia: Virginia Geological Survey Bulletin 52, 568 p.

Caputo, M. V., and Crowell, J. C., 1985, Migration of glacial centers across Gondwana during Paleozoic Era: Geological Society of America Bulletin, v. 96, p. 1020–1036.

Cecil, C. B., and DuLong, F. T., 2003, Precipitation models for sediment supply in warm climates, in Cecil, C. B. and Edgar, N. T. eds., Climate controls on stratigraphy, SEPM (Special Publication 77), Tulsa, p. 21–27.

Cecil, C. B., Brezinski, D., and DuLong, F., 2004, The Paleozoic record of changes in global climate and sea level: central Appalachian basin, *in* Southworth, S. and Burton, W. eds., Geology of the National Capital Region—field trip guidebook, U.S. Geological Survey Circular 1264, p. 77–135.

Chafetz, H. S., and Reid, A., 2000, Syndepositional shallow-water precipitation of glauconitic minerals: Sedimentary Geology, v. 136, p. 29-42.

Chaplin, J. R., 1985, Early Mississippian deltaic sedimentation in northeastern Kentucky, *in* Haban, S. M., eds., Carboniferous of eastern Kentucky (field excursion no. 6, Sixth Gondwana Symposium): Columbus, Ohio, Ohio State University, p. 26-30.

Chaplin, J.R., 1980, Stratigraphy, trace fossil associations, and depositional environments in the Borden Formation (Mississippian), Northeastern Kentucky: Annual Field Conference Guidebook, Geological Society of Kentucky, Kentucky Geological Survey, Lexington, 114 p.

Chesley, J. T., A. N. Halliday, T. K. Kyser, and P. G. Spry, 1994, Direct dating of Mississippi Valley–type mineralization—use of Sm-Nd in fluorite: Economic Geology, v. 89, p. 1192–1199.

Chesnut, D.R., Jr., 1991, Timing of Alleghanian tectonics determined by central Appalachian foreland basin analysis: Southeastern Geology, v. 31, no. 4, p. 203-221.

Childs, C., Watterson, J. and Walsh, J. J., 1995, Fault overlap zones within developing normal fault systems: Journal of the Geological Society (London), v. 152, p. 535–550.

Claypool, G.E., Holser, W.T., Kaplan, I.R., Sukai, H., and Zak, I., 1980, The age curves of sulfur and oxygen isotopes in marine sulfate and mutual interpretation: Chemical Geology, v. 28, p. 199-260.

Conant L. C. and Swanson V. E., 1961, Chattanooga Shale and related rocks of central Tennessee and nearby areas: U.S. Geological Survey Professional Paper 357, 91 p.

Conrad, J. E., Hein, J. R., Chaudhuri, A. K., Deb, S. P., Mukhopadhaya, J., Deb, G. K., and Beukes, N. J., 2011, Constraints on the development of Proterozoic basins in central India from $^{40}Ar/^{39}Ar$ analysis of authigenic glauconitic minerals: Geological society of America Bulletin, v. 123, no. 1-2, p. 158-167.

Contreras, J., Scholz, C.H., King, G.C.P., 1997, A general model of rift basin evolution: constraints of first order stratigraphic observations: Journal of Geophysical Research, v. 102, p. 7673-7690.

Cooper, B.N., 1961, Grand Appalachian Excursion: Blacksburg, Virginia Polytechnic Institute Geological Guidebook no. 1, p. 62-63.

Coskren, T. D., 1981, Structure and stratigraphy of the Pine Mountain Thrust Sheet, *in* T. G. Roberts ed., G.S.A. Cincinnati' 1981 Field Trip Guidebooks II: Economic Geology, Structure; Field Trip no. 19, Falls Church, American Geological Institute, p. 363-382.

Craig, L.C., and Varnes, K.L., 1979, History of the Mississippian System-An interpretative summary, *in* Craig, L.C., Connor, C.W., and others, Paleotectonic investigations of the Mississippian System in the United States: United States Geological Survey Professional Paper 1010 pt. 2, p. 371-406.

Currie, M.T., 1981, Subsurface stratigraphy and depositional environments of the "Corniferous" (Silurian-Devonian) of eastern Kentucky: Lexington, University of Kentucky, M.S. Thesis, 108 p.

Currie, M.T., and MacQuown, W.C., 1984, Subsurface stratigraphy of the Corniferous (Silurian–Devonian) of eastern Kentucky, *in* Luther, M.K., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association 45$^{th}$ Annual Meeting, June 10$^{th}$-12$^{th}$, Kentucky Geological Survey, Series 11, Special Publication 11, p. 1-21.

Davydov, V. I., Wardlaw, B. R., and Gradstein, F. M 2004, The Carboniferous period, *in* Gradstein, F. M., Ogg, J. G., and Smith, A. J. eds., A Geologic Time Scale 2004, by: Cambridge University Press, Cambridge, U. K. p. 222–248.

De Witt, W., Jr., and Mcgrew, L.W., 1979, The Appalachian Basin Region, *in* Craig, L.C., Connor, C.W., and others, Paleotectonic Investigations of the Mississippian System in the United States, Part I: Introduction and regional analyses of the Mississippian System: U.S. Geological Survey, Professional Paper 1010, p. 13-48.

De Witt, W., Jr., Sable, E.G., and Cohee, G.V., 1979, Evaporite deposits in Mississippian rocks of the eastern United States, *in* Craig, L.C., Connor, C.W., and others, Paleotectonic investigations of the Mississippian System in the United States: United States Geological Survey Professional Paper 1010 pt. 2, p. 431-439.

Dean, C. S., and Moshier, S. O., 1989, Cumberland Mountain: The inside story, the geology of Cumberland Gap as interpreted from the Federal Highway Administration pilot bore, Guidebook, Annual Field Conference, Geological Society of Kentucky, Lexington. Kentucky Geological Survey, 43 p.

Denison, R.E., Koepnick, R.B., Burke, W.H., Hetherington, E.A., and Fletcher, A., 1994, Construction of Mississippian, Pennsylvanian, and Permian seawater $^{87}Sr/^{86}Sr$ curve: Chemical Geology (Isotope Geoscience Section), v. 112, p. 145-167.

Dennison, J.M., Wheeler, W.H., 1975. Stratigraphy of Precambrian through Cretaceous strata of probable fluvial origin in southeastern United States and their potential as uranium host rocks. Southeastern Geology, Special Publication 5.

Dever, G.R., Jr., 1990, Tectonically influenced deposition and erosion in Mississippian limestones in south-central Kentucky, *in* Dever, G.R., Jr., Greb, S.F., Moody, J.R., Chesnut, D.R., Kepferle, R.C., and Sargent, R.E., Tectonic implications of depositional and erosional feature in Carboniferous rocks of south-central Kentucky (Guidebook and for road log for Geological Society of Kentucky Field Conference): Kentucky Geological Survey, Series 11, p. 1-18.

Dever, G.R., Jr., 1995, Tectonic implication of erosional and depositional features in upper Meramecian and lower Chesterian (Mississippian) rocks of south-central and east-central Kentucky: Lexington, University of Kentucky, Ph.D. Dissertation, 157 p.

Dever, G.R., Jr., 1999, Tectonic implication of erosional and depositional features in upper Meramecian and lower Chesterian (Mississippian) rocks of south-central and east-central Kentucky: Kentucky Geological Survey Bulletin 5, Series 11, 65 p.

Dever, G.R., Jr., and Moody, J.R., 2002, Bronston and Burnside members—Subdivision of the St. Louis Limestone in south-central Kentucky: Kentucky Geological Survey, Information Circular, Series, 11.

Dever, G.R., Jr., Ettensohn, F.R., and Haney, D.C., 1984, Relationship between the Kentucky River Fault System and Paleozoic sedimentation in eastern Kentucky [abs.]: Geological Society of America Abstracts with Programs, v. 16, no. 3, p. 133.

Dever, G.R., Jr., Greb, S.F., Moody, J.R., Chesnut, D.R., Jr., Kepferle, R.C., and Sergeant, R.E., 1990, Tectonic implications of depositional and erosional features in Carboniferous rocks of south-central Kentucky: Kentucky Geological Survey, Annual Field Conference of the Geological Society of Kentucky, 53 p.

Diaz, E., Issacson, P.E., Lema, J.C., Christenson, K.L., Vavrdova, M., and Antelo, B., 1993, Significance of a Late Devonian (Famennian) glacial marine diamictite, northern Altiplano, Bolivia, *in* Archangelsky, S., eds., Douzieme Congres International de la Stratigraphie et Geologie du Carbonifere et Permian: Comptes Rendus XII ICC-P, Buenos Aires, v. 1, p. 293-304.

Dickens, J.M., 1996, Problems of a Late Paleozoic glaciation in Australia and subsequent climate in the Permian: Paleogeography, Paleoclimatology, and Paleoecology, v. 125, p. 185-197.

Dickinson, W. R., 1974, Plate tectonics and sedimentation, *in* Dickinson, W. R. ed., Tectonics and sedimentation, SEPM Special Publication 22, Tulsa, p. 1–27.

Dickinson, W. R., Soreghan, G. S., and Giles, K. A., 1994, Glacio-eustatic origin of Permo-Carboniferous stratigraphic cycles: evidence from the southern Cordilleran foreland region, *in* Dennison, J. M. and Ettensohn, F. R. eds., Tectonic and eustatic controls on sedimentary cycles, SEPM Concepts in Sedimentology and Paleontology 4, p. 25–34.

Dillman, S.B., 1980, Subsurface geology of the Upper Devonian and Lower Mississippian black-shale sequence in eastern Kentucky: Lexington, University of Kentucky, M.S. Thesis, 72 p.

Dong, H., Hall, C. M., Peacor, D. R. and Halliday, A. N. 1995, Mechanisms of argon retention in clays revealed by laser $^{40}Ar$–$^{39}Ar$ dating: Science, v. 267, p. 355–359.

Drahovzal, J. A. and Noger, M.C., 1995, Preliminary map of the structure of the Precambrian surface in eastern Kentucky: Kentucky Geological Survey, ser. 11, Map and Chart Series 8, 9 p., scale 1:500,000.

Drahovzal, J.A., Harris, D.C., Wickstrom, K.C., Walker, D., Baranoski, M.T., Keith, B., and Furer, L.C., 1992, The east continent rift basin: A new discovery: Ohio Geological Survey Information Circular 57, 24 p.

Drake, A. A., Jr., Sinha, A.K., Laird, J., and Guy, R.E., 1989, The Taconic orogen: *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geol. Soc. Am., Geology of North America, F-2, 101-177.

Duplay, J., and Buatier, M., 1990, The problem of differentiation of glauconite and Celadonite: Geochemistry of the Earth's surface and of mineral formation, 2$^{nd}$ International Symposium, France, p. 264-266.

Elliott, W. C., and J. L. Aronson, 1993, The timing and extent of illite formation in Ordovician K-bentonites at the Cincinnati arch, the Nashville dome and north-eastern Illinois basin: Basin Research, v. 5, p. 125–135.

Englund, K.J., 1964, Geology of the Middlesboro South Quadrangle, Kentucky-Tennessee-Virginia: United States Geological Survey, Geologic quadrangle map, 301, Scale 1:24,000.

Englund, K.J., Henry, T.W., and Cecil, C.B., 1981, Upper Mississippian and Lower Pennsylvanian depositional environments, southwestern Virginia and southern West Virginia, *in* Roberts, T.G., ed., GSA Cincinnati '81, Field Trip Guidebooks, v. 1: Stratigraphy, Sedimentology: American Geological Institute, p. 171-175.

Ettensohn, F. R., 1985a, The Catskill Delta complex and the Acadian orogeny: a model, *in* Woodrow, D. L. and Sevon, W. D. eds., The Catskill Delta, Geological Society of America (Special Paper 201), Boulder, Colorado, p. 39–49.

Ettensohn, F. R., 1985b, Controls on development of Catskill Delta complex basin-facies, *in* Woodrow, D. L. and Sevon, W. D. eds., The Catskill Delta, Geological Society of America (Special Paper 201), Boulder, Colorado, p. 65–75.

Ettensohn, F. R., 2008, The Appalachian Foreland Basin in Eastern United States, i*n* Hsü, K.J., eds. Sedimentary Basins of the World, v. 5, The Sedimentary Basins of the United States and Canada. The Netherlands: Elsevier, p. 105-179.

Ettensohn, F. R., Lierman, R. T., and Mason, C. E., 2009, Upper Devonian—Lower Mississippian clastic rocks in northeastern Kentucky: Evidence for Acadian alpine glaciation and models for source-rock and reservoir-rock development in the eastern United States: American Institute of Professional Geologists, Kentucky Section spring field trip, 52 p.

Ettensohn, F.R., 1975, Stratigraphic and paleoenvironmental aspects of upper Mississippian rocks (upper Newman Group), east-central Kentucky: Urbana, University of Illinois, Ph.D. Dissertation, 320 p.

Ettensohn, F.R., 1977, Effects of synsedimentary tectonic activity on the upper Newman Limestone and Pennington Formation, *in* Dever, G.R., Jr., Hoge, H.P., Hester, N.C., and Ettensohn, F.R., eds., Stratigraphic evidence for late Paleozoic tectonism in northeastern Kentucky (Guidebook and road log for field trip held in conjunction with the fifth annual meeting of the eastern section of the American Association of Petroleum Geologists and the 1977 field conference of the Geological Society of Kentucky): Kentucky Geological Survey, Series 10, p. 18-29.

Ettensohn, F.R., 1979, Generalized description of Carboniferous stratigraphy, structure, and depositional environments in east-central Kentucky, *in* Ettensohn, F.R., and Dever, G.R., Jr., eds., Carboniferous geology from the Appalachian Basin to the Illinois Basin through eastern Ohio and Kentucky (field trip No. 4, IX

International Congress of Carboniferous Stratigraphy and Geology): Lexington, University of Kentucky, p. 64-77.

Ettensohn, F.R., 1980, An alternative to the barrier-shoreline model for deposition of Mississippian and Pennsylvanian rocks in northeastern Kentucky: Geological Society of America Bulletin, v. 91, no. 3, pt. I, p. 130-135; pt. II, p. 934-1056.

Ettensohn, F.R., 1981, Mississippian-Pennsylvanian boundary in northeastern Kentucky, in Roberts, T.G., ed., GSA Cincinnati '81 field trip guidebooks, v. 1: American Geological Institute, p. 195-257.

Ettensohn, F.R., 1990, The Mississippian System in the Appalachian Basin: A flexural relaxation response following the Acadian Orogeny [abs.]: Geological Society of America Abstracts with Programs, v. 22, no. 4, p. 13.

Ettensohn, F.R., 1992, General Silurian paleogeographic and tectonic framework for Kentucky, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology. Layer-cake, facies, flexure, and eustacy: Ohio Geological Survey Miscellaneous Report 5, p. 149-150.

Ettensohn, F.R., 1992, Kentucky River Fault Zone, the Lexington Limestone and the Clays Ferry Formation near the southeastern margin of the Tanglewood buildup, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology. Layer-cake, facies, flexure, and eustacy: Ohio Geological Survey Miscellaneous Report 5, p. 66-68.

Ettensohn, F.R., 1992, Silurian-Devonian contact and transgressive black shales at the base of the Ohio Shale, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology. Layer-cake, facies, flexure, and eustacy: Ohio Geological Survey Miscellaneous Report 5, p. 74-76.

Ettensohn, F.R., 1992, The Mississippian-Pennsylvanian systemic boundary on the Waverly Arch apical island, *in* Cecil, C.B., and Eble, C.F., Paleoclimate controls on Carboniferous sedimentation and cyclic stratigraphy in the Appalachian Basin: United States Geological Survey Open-File Report 92-546, p.76-81.

Ettensohn, F.R., 1993, Possible flexural controls on the origins of extensive, ooid-rich, carbonate environments in the Mississippian of the United States, *in* Keith, B.D., and Zuppann, C.W., eds., Mississippian oolites and recent analogs: American Association of Petroleum Geologists Studies in Geology 35, p. 13-30.

Ettensohn, F.R., 1994, Tectonic control on formation and cyclicity of major Appalachian unconformities and associated stratigraphic sequences, *in* Dennison, J.M., and Ettensohn, F.R., eds., Tectonic and eustatic controls on sedimentary cycles: Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology, v. 4, p. 217-242.

Ettensohn, F.R., 1998, Compressional tectonic controls on epicontinental black-shale deposition: Devonian-Mississippian examples from North America in Schieber, J., Zimmerle, W., and Sethi, P.S., eds., Shales and mudstones, v. 1: Stuttgart, E. Schweizerbartsche Verlagsbuchhandlung, p. 109-128.

Ettensohn, F.R., 2004, Modeling the nature and development of major Paleozoic clastic wedges in the Appalachian Basin, U.S.A.: Journal of Geodynamics, v. 37, 657-681.

Ettensohn, F.R., Amig, B.C., Pashin, J.C., Greb, S.F., Harris, M.Q., Black, J.C., Cantrell, D.J., Smith, C.A., McMahan, T.M., Axon, A.G., and McHargue, G.J., 1986, Paleoecology and paleoenvironments of the bryozoan-rich Sulphur Well Member, Lexington Limestone (Middle Ordovician), central Kentucky: Southeastern Geology, v. 26, no. 4, p. 199-219.

Ettensohn, F.R., and Elam, T.D., 1985, Defining the nature and location of a Late Devonian-Early Mississippian pycnocline in eastern Kentucky: Geological Society of America Bulletin, v. 96, no. 10, p. 1313-1321.

Ettensohn, F.R., and Pashin, J.C., 1993, Mississippian stratigraphy of the Black Warrior Basin and adjacent parts of the Appalachian Basin: Evidence for flexural interaction between two foreland basins, *in* Pashin, J.C., ed., New perspectives on the Mississippian System of Alabama: A guidebook for the 30th annual field trip of the Alabama Geological Society, November 11-13, 1993: Alabama Geological Society, p. 29-40.

Ettensohn, F.R., and Peppers, R.A., 1979, Palynology and biostratigraphy of Pennington shales and coals (Chesterian) at selected sites in northeastern Kentucky: Journal of Paleontology, v. 53, no. 2, p. 453-474.

Ettensohn, F.R., Ed., 1992, Changing interpretations of Kentucky geology. Layer-cake facies, flexure, and eustasy: Geological Society of America, Annual Meeting, Miscellaneous Report no. 5, Field Trip 15, 184 p.

Ettensohn, F.R., Greb, S.F., Chesnut, D.R., Jr., Harris, D.C., Mason, C.E., Eble, C.F., Howell, P.D., Watson, A.E., and Johnson, W.K., 2002, Mississippian stratigraphy, depositional environments, and tectonic framework of the central Appalachian basin, eastern Kentucky, USA, *in* Hills, L.V., Henderson, C.M., and Bamber, E.W., eds., Carboniferous and Permian of the World, Canadian Society of Petroleum Geologists Memoir 19, p. 22-40.

Ettensohn, F.R., Johnson, W.K., Stewart, A., Solis, M., and White, T., 2004, Stratigraphy and depositional environments of the Middle and Upper Mississippian Slade and Paragon formations, Bighill exposure, east-central Kentucky, *in* The Bighill exposure, KSPG and Kentucky Section of the AIPG 2004 Joint Field Trip, p. 18-43.

Ettensohn, F.R., Miller, M.L., Dillman, S.B., Elam, T.D., Geller, K.L., Swager, D.R., Markowitz, G., Woock, R.D., and Barron, L.S., 1988, Characterization and implications of the Devonian-Mississippian black shale sequence, eastern and central Kentucky, U.S.A.: Pycnoclines, transgression, regression, and tectonism, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the world, Proceedings of the Second International Symposium on the Devonian System, Calgary, Canada: Canadian Society of Petroleum Geologists Memoir 14, v. 2, p. 323-345.

Evernden, J.F., Curtis, G.H., Kistler, R.W. and Obradovich, J., 1960, Argon diffusion in glauconite, microcline, sanidine, leucite and phlogopite: American Journal of Science, v. 38, p. 583-604.

Fischer, A. G., 1984, Two Phanerozoic supercycles, *in* Berggren, W. A. and Van Couvering, J. A. eds., Catastrophes and earth history, Princeton University Press, Princeton, NJ, p. 129–150.

Foland, K.A., Hubacher, F.A., and Arehart, G.B., 1992, $^{40}Ar/^{39}Ar$ dating of very fine-grained samples: An encapsulated-vial procedure to overcome the problem of $^{39}Ar$ recoil loss: Chemical Geology, v. 102, p. 269-276.

Foland, K.A., Linder, J.S., Laskowski, T.E. and Grant, N.K., 1984, $^{40}Ar/^{39}Ar$ dating of glauconites: Measured Ar recoil loss from well-crystallized specimens: Isotope Geosciences, v. 2, p. 241-264.

Frakes, L.A., Francis, J.E., and Syktus, J.I., 1992, Climate models of the Phanerozoic: The history of the Earth's climate over the past 600 million years: Cambridge, U.K., Cambridge University Press, 274 p.

Freeman, L.B., 1951, Regional aspects of Silurian and Devonian subsurface stratigraphy in Kentucky: American Association of Petroleum Geologists Bulletin, v. 35, no. 1, p.1-61.

Frey, R.W., and Seilacher, A., 1980, Uniformity in marine invertebrate ichnology: Lethaia, v. 13, p. 183–207.

Friedman, G. M., 1987, Vertical movements of the crust: case histories from the northern Appalachian basin: Geology, v. 15, p. 1130–1133.

Garven, G., S. Ge, M. A. Person, and D. A. Sverjensky, 1993, Genesis of stratabound ore deposits in the midcontinent basins of North America—I, the role of regional groundwater flow: American Journal of Science, v. 293, p. 497–568.

Garzanti, E., and Sciunnach, D., 1997, Early Carboniferous onset of Gondwanian glaciation and Neo-tethyan rifting in South Tibet: Earth and Planetary Science Letters, v. 148, p. 359-365.

Gauthier, M., 1988, The stratigraphy, petrology, and depositional environment of the Wildie Member of the Borden Formation (Mississippian) in southeast-central Kentucky: Richmond, Eastern Kentucky University, M.S. Thesis, 117 p.

Gawthorpe, R. L. and Leeder, M. R., 2000, Tectono-sedimentary evolution of active extensional basins: Basin Research, v. 12, p. 195–218.

Gawthorpe, R. L., and Hurst, J. M., 1993, Transfer zones in extensional basins: their structural style and influence on drainage development and stratigraphy: Journal of the Geological Society (London), v. 150, p. 1137–1152.

Gawthorpe, R.L., Fraser, A.J., Collier, R.E.L., 1994, Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin-fills. Marine Petroleum Geology, v. 11, p. 642–658.

Goodman, G. R., 1975, The conodont fauna of the Floyds Knob Member, Borden Formation: Cincinnati, University of Cincinnati, M.S. thesis, 289 p.

Gopalan, K., 2008, Conjunctive K–Ca and Rb–Sr dating of glauconies: Chemical Geology, v. 247, p. 119–123.

Gordon, L.A., and Ettensohn, F.R., 1984, Stratigraphy, depositional environments, and regional dolomitization of the Brassfield Formation (Llandoverian) in east-central Kentucky: Southeastern Geology, v. 25, no. 2, p. 101-115.

Grant, N.K., Loskowski, T.E., and Foland, K.A., 1984, Rb–Sr and K–Ar ages of Paleozoic glauconites from Ohio–Indiana and Missouri, USA: Chemical Geology (Isotope Geosciences), v. 2, p. 217–239.

Greb, S. F., Potter, P. E., Meyer, D. L., and Ausich, W. I., 2008;  Mud mounds, paleoslumps, crinoids, and more: the Geology of the Fort Payne Formation at Lake Cumberland, south-central Kentucky: Field trip guidebook for the Kentucky Chapter AIPG, 46 p.

Greb, S.L., and Dever, G.R., Jr., 2002, Critical evaluations of possible seismites: Examples from the Carboniferous of the Appalachian basin, *in* Ettensohn, F.R., Rast, N., and Brett, C.E., eds., Ancient Seismites: Geological Society of America Special Paper 359, p. 109-125.

Green, A.G., Milkereit, B., Davidson, A., Spencer, C., Hutchinson, D.R., Cannon, W.F., Lee, M.W., Agena, W.F., Berhrendt, J.C., and Hinze, W.J., 1988, Crustal structure of the Grenville front and adjacent terranes:  Geology, v. 16, p. 788–792.

Grossman, E.L., Mii, H.S., and Yancy, T.E., 1993, Stable isotopes in Late Pennsylvanian brachiopods from the United States: Implications for Carboniferous paleooceanography: Geological Society of America Bulletin, v. 105, p. 1284-1296.

Grossnickle, E.A., 1985, Tempestites and deposition interpretations of the Middle Ordovician Curdsville Limestone of central Kentucky: Lexington, University of Kentucky, M.S. Thesis, 107 p.

Gualteri, J.L., 1967, Geologic map of the Brodhead Quadrangle, East-Central Kentucky: United States Geological Survey, Geological quadrangle map, GQ-662, Scale 1:24000.

Halliday, A.N., 1978, $^{40}Ar/^{39}Ar$ stepheating studies of clay concentrations from Irish orebodies: Geochimica et Cosmochimica Acta, v. 42, p. 1851-1858.

Ham, H.E., and Wilson, J.L., 1967, Paleozoic epeirogeny and orogeny in the central United States: American Journal of Science, v. 265, p. 332-407.

Hannan, A. E, 1975, A sedimentary and petrographic study of the Fort Payne Formation, Lower Mississippian (Osage), in south-central Kentucky: Cincinnati, Ohio, University of Cincinnati MS thesis, 111 p.

Haq, B. U., and Schutter, S. R., 2008, A chronology of Paleozoic sea-level changes: Science, v. 322, no. 5898, p. 64-68.

Harris L. D., 1978, The eastern interior aulacogen and its relation to Devonian shale-gas production, i*n* Second Eastern Gas Shales Symposium Preprints, v. 2, p. 55-72. U.S. Department of Energy, Morgantown Energy Technology Center, METC/SP-78/6.

Harris, D. C., and Drahovzal, J. A., 1996, Cambrian hydrocarbon potential indicated in Kentucky's Rome Trough, Kentucky Geological Survey Information Circular 54, Lexington, 11 p.

Harris, D.C., and Sparks, T.N., 2000, Regional subsurface geologic cross section of the Mississippian System, Appalachian Basin, eastern Kentucky: Kentucky Geological Survey, maps and charts series, 14 sheets.

Hassanipak, A. A., and Wampler, J. M., 1996, Radiogenic argon released by stepwise heating of glauconite and illite: The influence of composition and particle size: Clays and Clay Minerals, v. 44, no. 6, p. 717-716.

Hasson, K.O., 1972, Lithostratigraphy of the Grainger Formation (Mississippian), northeast Tennessee: Knoxville, University of Tennessee, PhD Dissertation, 143 p.

Hasson, K.O., 1986, Mississippian facies of the Newman Ridge area, Hancock County, Tennessee: *in* Geological Society of America Centennial Field Guide—Southeastern Section, 1986, p. 127-130.

Hearn, P. P., Sutter, J. F., and Belkin, H. E., 1987, Evidence for Late-Paleozoic brine migration in Cambrian carbonate rocks of the central and southern Appalachians: Implications for Mississippi Valley-type sulfide mineralization: Geochimica et Cosmochimica Acta, v. 51, p. 1323-1334.

Heckel, P. H., and Witzke, B. J., 1979, The Devonian world paleogeography determined from distribution of carbonate and related lithic paleoclimatic indicators, *in* House, M. R., Scrutton, C. T., and Bassett, M. G. eds., The Devonian System, The Palaeontological Association Special Papers in Palaeontology, no. 23, pp. 99–123.

Heller, S.A., 1980, A hydrologic study of the Greenbrier Limestone karst of central Greenbrier County, West Virginia: Morgantown, University of West Virginia, PhD Dissertation, 167 p.

Hess, J.C. and Lippolt, H.J., 1986, Kinetics of Ar isotopes during neutron irradiation: $^{39}$Ar loss from minerals as a source of error in $^{40}$Ar/$^{39}$Ar dating: Chemical Geology (Isotope Geoscience Section), v. 59, p. 223-236.

Hoffman, P. F., and Grotzinger, J. P., 1993, Orographic precipitation, erosional unloading, and tectonic style: Geology, v. 21, pp. 195–198.

Holser, W.T., 1984, Gradual and abrupt shifts in ocean chemistry during Phanerozoic time, *in* Holland, H.D., and Trendall, A.F., eds., Patterns of change in Earth evolution, Dahlem Konferenzen: New York, Springer-Verlag, p. 123-143.

Howell, P.D., and Mason, C.E., 1998, Stops 18-20; the Grainger Formation at Pound Gap, Kentucky, *in* Geology of the Pound Gap roadcut, Letcher County, Kentucky: Kentucky Society of Professional Geologists, Lexington, KY, p. 83-89.

Hugget, J.M., 2005, Glauconites: Minerals, p. 542-548.

Hugget, J.M., and Gale, A.S., 1997, Petrology and paleoenvironmental significance of glaucony in the Eocene succession at Whitecliff Bay, Hampshire Basin, UK: Journal of the Geological Society, London, v. 154, p. 897-912.
International Symposium, France, p. 264-266.

Jarvis, G. T., 1983, An extensional model of graben subsidence—the first stage of basin evolution: Sedimentary Geology, v. 40, p. 13-31.

Jeffery, D. L., 1997, Tectonic control on sea-floor relief and the localization of Lower Mississippian Waulsortian mounds, New Mexico: Geology, v. 25, no. 11, p. 1011-1014.

Jewell, H.R., and Ettensohn, F.R., 2004, An ancient seismite response to Taconian farfield forces: The Cane Run Bed, Upper Ordovician (Trenton) Lexington Limestone, central Kentucky, Journal of Geodynamics, 37, 487-511.

Kammer, T. W, Ausich, W. I., and Goldstein, A., 2007, *Gilmocrinus Kentuckyensis N.* SP. from the late Osagean (Mississippian) Muldraugh Member of the Borden Formation in Kentucky: A European immigrant originally derived from North America?: Journal of Paleontology, v. 81, no. 1, p. 209–212.

Kammer, T.W. and Cox, K. D., 1985, Paleoecology of a delta slope community from the Lower Mississippian Borden Formation in central Kentucky: Southeastern Geology, 26:39-46.

Kammer, T.W., 1984, Crinoids from the New Providence Shale Member of the Borden Formation (Mississippian) in Kentucky and Indiana: Journal of Paleontology, v. 58, p. 115-130.

Kammer, T.W., Brenckle, P.L., Carter, J.L., and Ausich, W.I., 1990, Redefinition of the Osagean–Meramecian boundary in the Mississippian stratotype region: Palaios, v. 5, p. 441-431.

Karner, G. D., and Watts, A. B., 1983, Gravity anomalies and flexure of the lithosphere at mountain ranges: Journal of Geophysical Research, v. 88(B12), p. 10449–10477.

Kearby, J.K., 1971, The Cowbell Member of the Borden Formation (Lower Mississippian) of northeastern Kentucky: A delta front deposit: Lexington, University of Kentucky, M.S. Thesis, 89 p.

Keller, G. R., Ammerman, M. L., and Bland, A. E., 1981, A geophysical and tectonic study of east-central Kentucky with emphasis on the Rome Trough, in Luther, M. K., ed., Proceedings, Kentucky Oil and Gas Association 49$^{th}$ and 40$^{th}$ Annual Meetings, Technical Sessions, 1975 and 1976: Kentucky Geological Survey, Series 11, Special Publication 4, p. 41-48.

Keller, G. R., and Greenberg, J. K., 1982, Evidence for a major late Precambrian tectonic event (rifting?) in the eastern midcontinent region, United States: Tectonics, v. 1, p. 1213-1223.

Kelly, J.C., and Webb, J.A., 1999, The genesis of glaucony in the Oligo-Miocene Torquay Group, southeastern Australia: petrographic and geochemical evidence: Sedimentary Geology, v. 125, p. 99-114.

Kepferle, R. C., 1971, Members of the Borden Formation (Mississippian) in north-central Kentucky: U. S. Geological Survey Bulletin 1354-B, p. B1-B18.

Kepferle, R.C., 1977, Stratigraphy, petrology, and depositional environments of the Kenwood Siltstone Member of the Borden Formation (Mississippian), Kentucky and Indiana: United States Geological Survey Professional Paper 1007, 49 p.

Kepferle, R.C., 1978, Prodelta turbidite apron in Borden Formation (Mississippian), Kentucky and Indiana, *in* Stanley, D.J., and Kelling, G., eds., Sedimentation in submarine canyons, fans, and trenches: Stroudsburg, Pennsylvania, Dowden, Hutchinson, and Ross, p. 224-238.

Kepferle, R.C., 1986, Devonian System, *in* McDowell, R.C., ed., The geology of Kentucky-A text to accompany the “Geologic Map of Kentucky”: United States Geological Survey Professional Paper 1151-H, p. H15-H19.

Kepferle, R.C., and Lewis, R.Q., Sr., 1975, Knifley Sandstone and Cane Valley Limestone: two new members of the Fort Payne Formation (Lower Mississippian), *in* Cohee, G.V., and Wright, W.B., eds., Changes in stratigraphic nomenclature by the U.S. Geological Survey 1974: U.S. Geology Survey Bulletin 1394A, p. A63-A70.

Kepferle, R.C., Pryor, W.A., Maynard, J.B., and Harrell, J., 1980, Jabez Sandstone Member-A new member of the Fort Payne Formation (Mississippian) in south-central Kentucky: U.S. Geological Survey, Bulletin 1502-A, p. A104-A109.

Khetani, A.B., and Read, J.F., 2002, Sequence stratigraphic development of a Mississippian clinoformal ramp on an abandoned delta, Kentucky: Journal of Sedimentary Research, v. 72, p. 657-672.

Kitamura, A., 1998, Glaucony and carbonate grains as indicators of the condensed section: Omma Formation, Japan: Sedimentary Geology, v. 122, p. 151-163.

Klein, H. M., 1974, The Beaver Creek Limestone sediment gravity flow fan deposits, Fort Payne Formation, Lower Mississippian (Osagean), south-central Kentucky, USA: Cincinnati, University of Cincinnati, M.S. thesis, 121 p.

Kolata, D. R., and W. W. Olive, 1991, Zuni and Tejas sequences, Late Cretaceous through Holocene Series, *in* Leighton, M. W., Kolata, D. R., Oltz, D. F., and Eidel, J. J., eds., Interior cratonic basins: American Association of Petroleum Geologists Memoir 51, p. 165–168.

Kolata, D.R., Huff, W.D., and Bergström, S.M., 2001, The Ordovician Sebree Trough: an oceanic passage to the midcontinent United States: Geological Society of America Bulletin., 113, 1067-1078.

Krause, R.A., and Meyer, D.L., 2004, Sequence stratigraphy and depositional dynamics of carbonate buildups and associated facies from the Lower Mississippian Fort Payne Formation of southern Kentucky, U.S.A.: Journal of Sedimentary Research, v. 74, p 831-844.

Krause, R.A., Meyer, D.L., and Ausich, W.I., 2002, Carbonate buildups in the Fort Payne Formation (Lower Mississippian), Cumberland County, Kentucky, *in* Ettensohn, F.R., and Smath, M.L., eds., Guidebook for geology field trips in Kentucky and adjacent areas: Lexington, Kentucky, University of Kentucky, 2002 Joint Meeting of the North-Central Section and Southeastern Section of the Geological Society of America: p. 1-13.

Kronen, J.D., Jr., and Glenn, C.R., 2000. Pristine to reworked verdine: keys to sequence stratigraphy in mixed carbonate-siliciclastic forereef sediments (Great Barrier Reef), *in* Glenn, C.R., Prévôt-Lucas, L., and Lucas, J., eds., Marine Authigenesis: from Global to Microbial. SEPM Special Publication, no. 66, p. 387–403.

Kuczynski, J.C., and Hicks, M.C., 1978, A study of Mississippian red beds of Hancock County, Tennessee: Johnson City, East Tennessee State University, B.S. Thesis, 23 p.

Lane, N.G. and Dubar, J.R., 1983, Progradation of the Borden Delta: New evidence from crinoids: Journal of Paleontology, v. 57, no. 1, p. 112-123.

Lasemi, Z., Norby, E.D., Utgaard, J.E., Ferry, W.R., Cuffey, R.J., and Dever, G.R., Jr., 2003, Mississippian carbonate buildups and development of cool-water-like carbonate platforms in the Illinois Basin, Midcontinent, USA, *in* Ahr, W.M., Harris, D.M., Morgan, W.A., and Sommerville, J.D., eds., Permo-Carboniferous carbonate platforms and reefs: Society of Economic Paleontologists and Mineralogists Special Publication 78 and American Association of Petroleum Geologists Memoir 83, p. 69-95.

Layer, P. W., Hall, C. M. and York, D., 1987, The derivation of $^{40}Ar/^{39}Ar$ age spectra of single grains of hornblende and biotite by laser step-heating: Geophysical Research Letters, v. 14, p. 757-760.

Lee, K.G., Ausich, K.I., and Kammer, T.W., 2005, Crinoids from the Nada Member of the Borden Formation (Lower Mississippian) in eastern Kentucky: Journal of Paleontology, 79, 2, p. 337-355.

Lees, A., and Miller, J., 1985, Facies variation in Waulsortian buildups. Part 2: Mid-Dinatian buildups from Europe and North America: Geological Journal, v. 20, p.159-180.

Leslie, S.A., Ausich, W.I., and Meyer, D.L., 1996, Lower Mississippian sedimentation dynamics and conodont biostratigraphy (lowermost Fort Payne Formation) along the southeastern margin of the Eastern Interior Seaway: Southeastern Geology, v. 36, p. 27–35.

Lewis, R.Q., Sr., and Potter, P.E., 1978, Surface rocks in the western Lake Cumberland area, Clinton, Russell and Wayne Counties, Kentucky: Annual Field Conference of the Geological Society of Kentucky: Kentucky Geological Survey Lexington, Kentucky, 41 p.

Lidiak, E.G., and Zietz, I., 1976, Interpretation of aeromagnetic anomalies between latitude 37°N and 38°N in eastern and central United States: Geological Society of America Special Paper 167, 37 p.

Lierman, R.T., and Mason, C., 2004, Stratigraphy and depositional setting of the Borden Formation (Lower Mississippian) at Bighill, Kentucky, *in* The Bighill exposure, KSPG and Kentucky Section of the AIPG 2004 Joint Field Trip, p. 4-14.

Lierman, R.T., Mason, C.E., Pashin, J.C., and Ettensohn, F.R., 1992, Cleveland Shale-through lower Borden sequence (Devonian-Mississippian) and implications, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky Geology-Layer cake, facies, flexure, and eustasy: Ohio Geological Survey Miscellaneous Report 5, p. 77-84.

Lineback, J. A., 1966, Deep-water sediments adjacent to the Borden Siltstone (Mississippian) Delta in southern Illinois: Illinois State Geological Survey Circular, v. 401, 48 p.

Lineback, J.A., and Cluff, R.M., 1985, Ullin-Fort Payne, a Mississippian shallow to deep water carbonate transition in a cratonic basin., *in* Crevello, P.D., and Harris, P.M., eds., Deep-water carbonates buildups, turbidites, debris flows and chalks; a core workshop: Society of Economic Paleontologists and Mineralogists Core Workshop, v. 6, p. 1-26.

Lumsden, D.N., 1988, Origin of the Fort Payne Formation (Lower Mississippian), Tennessee: Southeastern Geology, v. 28, no. 3, p. 167-180.

MacGill, P.L., 1973, The stratigraphy and sedimentary petrology of the Renfro Member of the Borden Formation: Richmond, Eastern Kentucky University, M.S. Thesis, 52 p.

MacQuown W, C., and Perkins, J. H., 1982, Stratigraphy and petrology of petroleum-producing Waulsortian-type mounds in Fort Payne Formation (Lower Mississippian) of North–Central Tennessee: American Association of Petroleum Geologists, v. 66, p.1055-1075.

MacQuown, W.C., and Pear, J.L., 1983, Regional and local geologic factors control Big Lime stratigraphy and exploration for petroleum in eastern Kentucky, *in* Luther, M.K., eds., Proceedings of the technical sessions, Kentucky Oil and Gas Association 44$^{th}$ annual meeting, June 11-13, 1980: Kentucky Geological Survey, Series 11, Special Publication 9, p. 1-20.

Mason, C.E., and Lierman, R.T., 1992, Henley Bed (Farmers Member) of the Borden Formation (Lower Mississippian) along Kentucky state route 546 in northern Kentucky, *in* Ettensohn, F.R., eds., Changing interpretations of Kentucky geology.Layer cake, facies, flexure, and eustasy: Ohio Geological Survey Miscellaneous Report 5, p. 135-138.

Matchen, D.L., and Kammer, T.W., 1994, Sequence stratigraphy of the Lower Mississippian Price and Borden Formations in southern West Virginia and eastern Kentucky: Southeastern Geology, v. 34, p. 25-41.

McClay, K. R., 1990, Extensional fault systems in sedimentary basins: a review of analogue model studies: Marine and Petroleum Geology, v. 7, p. 206-233.

McFarlan, A.C., 1943, Geology of Kentucky: Lexington, University of Kentucky, 531 p.

McGuire, W.H., and Howell, P., 1963, Oil and gas possibilities of the Cambrian and Lower Ordovician in Kentucky: Lexington, Kentucky, Spindletop Research Center, 241 p.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25-32.

McLaughlin, P.I., and Brett, C.E., 2004, Eustatic and tectonic control of marine seismites; examples from the Upper Ordovician of Kentucky, USA: Sedimentary Geology, 168, 165-192.

McRae, S. G., 1972, Glauconite: Earth Science Reviews, v. 8, p. 397-440.

Meckel, L. D., 1970, Paleozoic alluvial deposition in the central Appalachians: a summary, *in* Fisher, G. W., Pettijohn, F. S., Reed, J. C., and Weaver, K. N. eds., Studies of Appalachian geology: Interscience Publishers, New York, p. 49–67.

Merrihue, C. and Turner, G., 1966, Potassium-argon dating by activation with fast neutrons: Journal of Geophysical Research, v. 71, p. 2852-2857.

Merschat, A. J, and Hatcher, R. D., Jr., 2007, The Cat Square terrane: Possible Siluro-Devonian remnant ocean basin in the Inner Piedmont, southern Appalachians, USA, *in* Hatcher, R. D., Jr., Carlson, M. P., McBride, J. H., and Martinenz Catalan, J. R., eds., 4-D framework of continental crust: Geological society of America Memoir 200, p. 553-565.

Meyer, D. L., Ausich, W. I., and Potter, P. E., 1992, Mississippian clinoform: lithologic and paleoecologic diversity amid slopes, slides and mounds: Palaios, v. 7, p. 335-336.

Meyer, D.I., Ausich, W.I., Bohl, D.T., Norris, W.A., and Potter, P.E., 1995, Carbonate mud-mounds in the Fort Payne Formation (lower Carboniferous), Cumberland Saddle Region, Kentucky and Tennessee, U.S.A.: International Association of Sedimentologists Special Publications, v. 23, p. 273-287.

Mii, H. S., Grossman, E.L., and Yancey, T.E., 1999, Carboniferous isotope stratigraphies of North America: Implications for Carboniferous paleoceanography and Mississippian glaciation: Geological Society of America Bulletin, v. 111, p. 960-973.

Mii, H., Grossman, E.L., Yancey, T.E., Chuvashov, B., and Egorov A., 2001, Isotope records of brachiopod shells from the Russian Platform: evidence for the onset of mid-Carboniferous glaciation: Chemical Geology, v. 175, p. 133-147.

Milici, R.C., Play Mfp: The Lower Mississippian Fort Payne carbonate mound play, *in* Roen, J.B., and Walker, B.J., eds., Atlas of Major Appalachian Gas Plays: West Virginia Geological and Economical Survey, p. 51-55.

Mitra, S., 1988, Three-dimensional geometry and kinematic evolution of the Pine Mountain thrust system, southern Appalachians: Geological Society of America Bulletin, v. 100, p. 72-95.

Morton, J.P., and Long, L.E., 1980, Rb–Sr dating of Palaeozoic glauconites from the Llano region, central Texas: Geochim. Cosmochim. Acta, v. 44, p. 663–672.

Nicoll, R.S. and Rexroad, C.B., 1975, Stratigraphy and conodont paleontology of the Sanders Group (Mississippian) in Indiana and adjacent Kentucky: Indiana Geological Survey Bulletin, v. 51, 36 p.

Odin G. S., and Masse, J. P., 1988, The verdine facies from the Senegalese continental shelf, *in* Odin, G. S., ed., Green marine clays: Oolitic ironstone facies, verdine facies, glaucony facies and celadonite-bearing facies – A comparative study: Developments in Sedimentology 45, Elsevier, Amsterdam, p. 83-104.

Odin, G. S., 1988. The verdine facies from the lagoon off New-Caledonia, *in* Odin G. S., ed., Green marine clays. Developments in Sedimentology, Amsterdam: Elsevier, p. 57-81.

Odin, G. S., and Dodson, M. H., 1982, Zero isotopic age of glauconies, *in* Odin G. S., ed., Numerical Dating in Stratigraphy: John Wiley and Sons, Chichester, p. 277-305.

Odin, G. S., and Fullagar, P. D., 1988, Geological significance of the Glaucony Facies, *in* Odin G. S., ed., Green Marine Clay, Elsevier, Amsterdam, p. 295-332.

Odin, G. S., and Hunziker, J. C. 1982, Radiometric dating of the Albian-Cenomanian boundary, *in* Odin G. S., ed., Numerical Dating in Stratigraphy. John Wiley and Sons, Chichester, 537-556.

Odin, G. S., and Letolle, R., 1980, Glauconitization and phosphatization environments; a tentative comparison, i*n* Marine Phosphorites; Geochemistry, Occurrence, Genesis: SEPM, Special Publication 29, p. 227-237.

Odin, G. S., and Morton, A. C., 1988, Authigenic green particles from marine environments, *in* Chilingarian, G. V., and Wolf, K. H., eds., Diagenesis II. Developments in Sedimentology 43, Elsevier, Amsterdam, p. 213-264.

Odin, G. S., and Sen Gupta, B. K., 1988, Geological significance of the verdine facies, *in* Odin, G. S., ed., Green marine clays: Oolitic ironstone facies, verdine facies, glaucony facies and celadonite-bearing facies – A comparative study: Developments in Sedimentology 45, Elsevier, Amsterdam, p. 205-220.

Odin, G. S., Bailey, S. W., Amouric, M., Frohlic, F., and Waychunas, G., 1998, Mineralogy of the verdine facies, *in* Odin, G. S., ed., Green marine clays: Oolitic ironstone facies, verdine facies, glaucony facies and celadonite-bearing facies – A comparative study: Developments in Sedimentology 45, Elsevier, Amsterdam, p. 159-204.

Odin, G.S., and Matter, A., 1981, De glauconiarum origine: Sedimentology, v. 28, p. 611-641.

Oliver, J., 1986, Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena: Geology, v. 14, p. 99-102.

Pashin, J.C., and Ettensohn, F.R., 1987, An eperic shelf-to-basin transition: Bedford-Berea sequence, northeastern Kentucky and south-central Ohio: American Journal of Science, v. 287, no. 9, p. 893-926.

Pashin, J.C., and Ettensohn, F.R., 1992, Lowstand deposition in a foreland basin: Bedford-Berea sequence (Upper Devonian) eastern Kentucky and West Virginia, *in* Ettensohn, F.R., ed., Changing interpretations of Kentucky geology. Layer cake, facies, flexure, and eustasy: Ohio Geological Survey Miscellaneous Report 5, p. 123-144.

Patchen, D. G., Avary, K. L., and Erwin, R. B., 1985, Southern Appalachian region: American Association of Petroleum Geologists COSUNA Chart SAP, Tulsa.

Peacock, D.C.P., and Sanderson, D. J., 1995, Pull-aparts, shear fractures and pressure solution: Tectonophysics, v. 241, p. 1-13.

Pemberton, S.G., MacEachern, J.A., and Frey, R.W., 1992, Trace fossils facies models: environmental and allostratigraphic significance *in* Walker, R.G., James, N.P., eds., Facies Models Response to Sea Level Change: Geological Association Canada, p. 47-72.

Peterson, W.L. and Kepferle, R.C., 1970, Deltaic deposits of the Borden Formation in Central Kentucky, in Geological Survey Research, 1970: United States Geological Survey Professional Paper 700-D, p. D49-D54.

Popp, B.N., Anderson, T.F., and Sandberg, P.A., 1986, Brachiopods as indicators of original isotopic compositions in some Paleozoic limestones: Geological Society of America Bulletin, v. 97, p. 1262-1269

Powell, D., and Saxena, M.N., 1971, Tillite horizons in the Chamba Himalayas of Himachal Pradesh, North India: Geological Society of London, v. 127, p. 595-598

Pratt, T.R., Culotta, R., Hauser, E., Nelson, D., Brown, L., Kaufman, S., Oliver, J., and Hinze, W., 1989, Major Proterozoic basement features of the eastern midcontinent of North America revealed by recent COCORP profiling: Geology, v. 17, p. 505–509.

Proust, J., and Hosu, A., 1996, Sequence stratigraphy and Paleogene tectonic evolution of the Transylvanian Basin (Romania, eastern Europe): Sedimentary Geology, v. 105, p. 117-140.

Pryor, W. A., and Sable, E. G., 1974, Carboniferous of the Eastern Interior Basin, *in* Briggs, B., ed., Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 281-314.

Pryor, W.A., 1975, Biogenic sedimentation and alternation of argillaceous sediments in shallow marine environments: Geological Society of America Bulletin, v. 86, p. 1244-1254.

Quinlan, G.M., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the Eastern Interior of North America: Canadian Journal of Earth Sciences, v. 21, p. 973-996.

Rao, V. P., Lamboy, M., and Dupeuble, P.A., 1993, Verdine and other associated authigenic (glaucony, phosphate) facies from the surficial sediments of the southwestern continental margin of India: Marine Geology, v. 111, p. 133-158.

Rao, V. P., Thamban, M., and Lamboy, M., 1995, Verdine and glaucony facies from surface sediments of the eastern continental margin of India: Marine Geology, v. 127, p. 105-113.

Rast, N., and Goodman, P. T., 1994, Tectonic and sedimentary consequences of Late Proterozoic and Mid-Paleozoic overthrusting in Kentucky and adjacent states: Northeastern Geology, v. 17, p. 2–9.

Raymond, A., Kelley, P.H., and Lutken, C.B., 1989, Polar glacier and life at the equator: The history of Dinination and Namurian (Carboniferous) climate: Geology, v. 17, p. 408-411.

Read, J.F., 1989, Controls on evolution of Cambrian-Ordovician passive margin, U.S. Appalachians: *in* Controls on carbonate platform and basin development, P.D. Crevello, J.L. Wilson, J.F. Sarg, and J.F. Read eds., SEPM Special Publication 44, p. 147-165.

Rexroad, C.B., and Scott, A.J., 1964, Conodont zones in the Rockford Limestone and lower part of the New Providence Shale (Mississippian) in Indiana: Indiana Geological Survey Bulletin 30, 54 p.

Rice, C.L., 1972, Geologic map of the Alcorn quadrangle, east-central Kentucky: United States Geological Survey, geologic quadrangle map, GQ-963, scale, 1:24,000.

Rice, C.L., Sable, E.G., Dever, G.R., Jr., and Ken, T.M., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States-Kentucky: United States Geological Professional Paper 1110-F, 32 p.

Richardson, C. K, and D. M. Pinckney, 1984, The chemical and thermal evolution of the fluids in the Cave-in-Rock Fluorspar district, Illinois: mineralogy, paragenesis, and fluid inclusions: Economic Geology, v. 79, p. 1833–1856.

Richardson, J. G., and Ausich, W. I., 2004, Miospore biostratigraphy of the Borden delta (Lower Mississippian; Osagean) in Kentucky and Indiana, USA: Palynology, v. 28, p. 159-174.

Rodgers, J., 1971, The Taconic Orogeny: Geological Society of America Bulletin, v. 82, p. 1141-1178.

Ross, C.A., and Ross, J.R.P., 1988, Late Paleozoic transgressive-regressive deposition, *in* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoneer, J., and Kendall, C.G. St. C., eds., Sea-level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, pp. 227-247.

Ruffell, A., and Wach, G., 1998, Firmgrounds – Key surfaces in the recognition of parasequences in the Aptian Lower Greensand Group, Isle of Wight (southern England): Sedimentology, v. 45, p. 91-107.

Sable, E.G., 1979, Eastern Interior Basin region, *in* Craig, L.C., and Connor, C.W., eds., Paleotectonic investigations of the Mississippian System in the United States: United States Geological Survey Professional Paper 1010, pt. 1, p. 59-106.

Sable, E.G., and Dever, G.R., Jr., 1990, Mississippian rocks in Kentucky: U.S. Geological Survey Professional Paper 1503, 125 p.

Samson, S.D., and Alexander, E.C., 1987, Calibration of the interlaboratory $^{40}Ar$-$^{39}Ar$ dating standard, Mmhb-1: Chemical Geology, v. 66, p. 27–34.

Sandberg, C. A., Mason, C. E., and Work, D. M., 2002, Position of the Kinderhookian—Osagean boundary in northeastern Kentucky and southern Ohio: Geological Society of America, Abstracts with Programs, v. 34, no. 2, p. 37.

Sanders, A.W., 1979, Petrology and stratigraphic relations of the Renfro Member of the Borden Formation (Mississippian) in southeast-central Kentucky: Richmond, Eastern Kentucky University, M.S. Thesis, 47 p.

Sanders, J.E., 1952, Geology of the Pressman Home area, Hawkins and Grainger Counties, Tennessee: New Haven, Yale University, PhD Dissertation, 253 p.

Sarg, J.F., 1988, Carbonate sequence stratigraphy, *in* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H., Van Wagoner, J., Kendall, C.G. eds., Sea-level changes: an integrated approach, Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 155-181.

Schlische, R. W., 1991, Half-graben filling models: implications for the evolution of continental extensional basins: Basin Research, v. 3, p. 123–141.

Schlische, R. W., 1992, Structural and stratigraphic development of the Newark extensional basin, eastern North America: implications for the growth of the basin and its bounding structures: Geological Society of America Bulletin, v. 104, p. 1246–1263.

Scotese, C. R., 1997, Quicktime computer animations, PALEOMAP Project, Arlington, Department of Geology, University of Texas at Arlington.

Scott, L.P., IV, 1978, Tectonic history of the Kentucky River Fault System in Eastern Kentucky during the Silurian and Devonian: Richmond, Eastern Kentucky University, M.S. Thesis, 64 p.

Sedimentation Seminar, 1972, Sedimentology of the Mississippian Knifley Sandstone and Cane Valley Limestone in south-central Kentucky: Kentucky Geological Survey Series X, Report of Investigation 13, 30 p.

Shaver, R. H., 1985, Midwestern Basin and Arches Region, Correlation of Stratigraphic Units of North America (COSUNA) project (folded chart): Tulsa, Oklahoma, American Association of Petroleum Geologists.

Shrake, D.L., 1991, The Middle Run Formation: A new stratigraphic unit in the subsurface of southwestern Ohio: Ohio Journal of Science, v. 91, p. 49–55.

Shumaker, R. C., 1986, Structural development of Paleozoic continental basins of eastern North America, in Proceedings of the Sixth International Conference on Basement tectonics, Salt Lake City, Basement tectonics Association, Inc., p. 82–95.

Silberman, J.D., 1972, Cambro-Ordovician structural and stratigraphic relationships of a portion of the Rome Trough, *in* Hutchison, D.W., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association 34$^{th}$ and 35$^{th}$ Annual Meeting, 1970 and 1971: Kentucky Geological Survey, Series 10, Special Publication 21, p. 35-45.

Smith, M. O., Noger, M. C., and Smith, G. E., 1967, Some aspects of the stratigraphy of the Pine Mountain front near Elkhorn City, Kentucky, with notes on pertinent structural features, Annual spring field conference, Geological Society of Kentucky: Lexington, Kentucky, Kentucky Geological Survey, 24 p.

Smith, P.E., Evensen, N.M., and York, D., 1993, First successful $^{40}Ar–^{39}Ar$ dating of glauconies: argon recoil in single grains of cryptocrystalline material: Geology, v. 21, p. 41–44.

Smith, P.E., Evensen, N.M., York, D., and Odin, G.S., 1998, Single grain $^{40}Ar–^{39}Ar$ ages of glauconies: implications for the geologic time scale and global sea level variations: Science, v. 279, p. 1517–1519.

Stapor, F., and Knox, L. W., 1995, Waulsortian-like bioherms of the Maury and Fort Payne Formations, Tennessee, *in* Driese, S.G., ed., Guidebook for field trip excursions, southeastern section, GSA (Trips prepared for the 44th Annual Meeting of the Southeastern Section of the Geological Society of America, Knoxville, Tennessee, April 1995), Department of Geological Sciences, University of Tennessee, Knoxville, 90 p.

Stark, T.J., 1997, The East Continent Rift Complex: Evidence and conclusions, *in* Ojakangas, R.W., Dickas, A.B., and Green, J.C., eds., Middle Proterozoic to Cambrian rifting, central North America: Geological Society of America Special Paper 312, p. 253–266.

Stearns, R. G., and A. L. Reesman, 1986, Cambrian to Holocene structural and burial history of Nashville Dome: American Association of Petroleum Geologists Bulletin, v. 70, p. 143–154.

Stewart, S. A., Ruffell, A. H., and Harvey, M. J., 1997, Relationship between basement-linked and gravity-driven fault systems in the UKCS salt basins: Marine and Petroleum Geology, v. 14, p. 581-604.

Stockdale, P. B., 1931, The Borden (Knobstone) rocks of southern Indiana: Indiana Department of Conservation, Division of Geology Publication 98, 330 p.

Stockdale, P. N., 1939, Lower Mississippian rocks of the east-central interior: Geological Society of America Special Paper 22, 248 p.

Stose, G. W. 1913. Geology of the salt and gypsum deposits of southwestern Virginia: Virginia Geological Survey Bulletin 8, Charlottesville, p. 51–73.

Sutton, E.M., 1981, Deep exploration in eastern Kentucky by the SCLAW Group during the early seventies, *in* Luther, M.K., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association 44th annual meeting, June 11-13, 1980: Kentucky Geological Survey, Series 11, Special Publication 3, p. 31-44.

Swan, D. H., Lineback, J. A., and Frund, E., 1965, The Borden siltstone (Mississippian) delta in southwestern Illinois: Illinois State Geological Survey Circular 386, Urbana, 20 p.

Tankard, A.J., 1986, Depositional response to foreland deformation in the Carboniferous of eastern Kentucky: American Association of Petroleum Geologists Bulletin, v. 70, no. 7, p. 853-868.

Taylor, C. D., E. L. Rowan, M. B. Goldhaber, and T. S. Hayes, 1992, A relationship between Hicks dome and temperature zonation in fluorite in the Illinois-Kentucky fluorspar district, a fluid inclusion study, *in* M. B. Goldhaber, and J. J. Eidel, eds., Mineral resources of the Illinois basin in the context of basin evolution: U.S. Geological Survey Open-File Report 92-1, p. 62–64.

Thaden, R.E., and Lewis, R.Q., Sr., 1962, Geology of the Jamestown Quadrangle, Kentucky: U.S. Geological Survey, 7.5-minute quadrangle map, GQ-182.

Thaden, R.E., and Lewis, R.Q., Sr., 1966, Geologic map of the Jabez Quadrangle, Russell and Wayne Counties, Kentucky: U.S. Geological Survey, 7.5-minute quadrangle map, GQ-483.

Thamban, M., and Rao, V.P., 2000, Distribution and composition of verdine and glaucony facies from the sediments of the western continental margin of India, *in* Glenn, C.R., Prevot-Lucas, L., and Lucas, J., eds., Marine authigenesis: From global to microbial: Society of Economic Paleontologists and Mineralogists Special Publication 66, p. 233-244.

Thomas, G.R., 1960, Geology of recent deep drilling in eastern Kentucky, *in* McGrain, Preston, and Crawford, T.J., eds., Proceeding of the technical session, Kentucky Oil and Gas Association 24th annual meeting, June 3, 1960: Kentucky Geological Survey, Series 10, Special Publication 3, p. 10-28.

Thomas, W. A., 1977, Evolution of Appalachian–Ouachita salients and recesses from reentrants and promontories on the continental margin: American Journal of Science, v. 277, pp. 1233–1278.

Thomas, W.A., 1989, The Appalachia-Ouachita orogen beneath the Gulf Coastal Plain between the outcrops in the Appalachian and Ouachita mountains, *in* Hatcher, R.D., Jr., Thomas, W.A., and Veile, G.W., The Appalachian-Ouachita orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, p. 537-553.

Thomas, W.A., 1991, The Appalachia-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, no. 3, p. 415-431.

Thomson, G.R., and Hower, J., 1975, The mineralogy of glauconite: Clays and Clay Minerals, v. 23, p. 289-300.

Triplehorn, D.M., 1966, Morphology, internal structure, and origin of glauconite pellets: Sedimentology, v. 6, p. 247-266.

Trudgill, B., and J. Cartwright, 1994, Relay-ramp forms and normal fault linkages, Canyonlands National Park, Utah: Geological Society of America Bulletin, v. 106, p. 1143–1157.

Turner G., and Cadogan, P.H., 1974, Possible effects of $^{39}Ar$ recoil in $^{40}Ar$-$^{39}Ar$ dating: Lunar Science Conference, Proceedings, New York, Pergamon Press, v. 5, p. 1601–1615.

Udgata, D. B.P. and Ettensohn F. R., 2008, Significance of green-mineral or verdine facies from Upper Ordovician and Middle Mississippian rocks in the western Appalachian Basin, east-central Kentucky: Geological Society of America Abstracts with Programs, v. 40, no. 6, p. 480.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990, Siliciclastic sequence stratigraphy in well logs, cores, and outcrops; concepts for high-resolution correlation of time and facies: American Association of Petroleum Geologists Methods in Exploration Series 7, 55 p.

Van Wei, W. A., 1971, The petrology of the Floyds Knob glauconite: Cincinnati, University of Cincinnati, M.S. thesis, 90 p.

Vanover, J. D., Dean, C. S., and Perkins, R. D., 1989, Pilot bore traverse, *in* C. S. Dean and S. O. Moshier eds., Cumberland Mountain: The inside story: Guidebook, Annual field conference, Geological Society of Kentucky, Lexington, Kentucky Geological Survey, p. 24-30.

Veevers, J.J., and Powell, C.M., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica: Geological Society of America Bulletin, v. 98, p. 475-487.

Walker, D., Hamilton-Smith, T., and Drahovzal, J.A., 1991, The Rome Trough and evolution of the Iapetan margin [abs.]: American Association of Petroleum Geologists Bulletin, v. 75, no. 8, p. 1391.

Walker, D., Hamilton-Smith, T., Noger, M.C., and Drahovzal, J.A., 1992, Structure and stratigraphy of the Rome Trough [abs.]: American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1288-1289.

Warne, A.G., 1990, Regional stratigraphic analysis of the Lower Mississippian Maccrady Formation of the Central Appalachians: Chapel Hill, University of North Carolina, PhD Dissertation, 493 p.

Webb, E.J., 1969, Geologic history of the Cambrian System in the Appalachian Basin, in Rose, W.D., ed., Proceedings of the technical sessions, Kentucky Oil and Gas Association 33rd annual meeting, June 5-6, 1969: Kentucky Geological Survey, Series 10, Special Publication 18, p. 7-15

Webb, E.J., 1980, Cambrian sedimentation and structural evolution of the Rome Trough in Kentucky: Cincinnati, University of Cincinnati, PhD Dissertation, 98 p.

Weir, G.W., 1970, Borden Formation (Mississippian) in southeast-central Kentucky, *in* Guidebook for field trips, 18th annual meeting, Southeastern Section, Geological Society of America: Kentucky Geological Survey, Series 10, p. 29-48.

Weir, G.W., Gualtieri, J.L., and Schlanger, S.O., 1966, Borden Formation (Mississippian) in south- and south-central Kentucky: United States Geological Survey Bulletin 1224-F, 38 p.

Weir, G.W., Peterson, W.L., and Swadley, W.C., 1984, Lithostratigraphy of Upper Ordovician strata exposed in Kentucky: United States Geological Survey Professional Paper 1151-E, 121 p.

Weller, J. M., Williams, J. S., Bell, W. A., Dunbar, C. O., Laudon, L. R., Moore, R. C., Stockdale, P. B., Warren, P. S., Caster, K. E., Cooper, C. I., Willaerd, B., Corries, C., Malott, C. A., Price, P. H., and Sutton, A. H., 1948, Correlation of Mississippian Formations of North America: Geological Society of America publications, v. 59, p. 91-196.

Whitehead, N.H., III, 1976, The stratigraphy, sedimentology, and conodont paleontology of the Floyd's Knob Bed and Edwardsville Member of the Muldraugh Formation (Valmeyeran), southern Indiana and north-central Kentucky: Urbana, University of Illinois, M.S. Thesis, 443 p.

Whitehead, N.H., III, 1978, Lithostratigraphy, depositional environments, and conodont biostratigraphy of the Muldraugh Formation (Mississippian) in southern Indiana and north-central Kentucky: Southeastern Geology, v. 19, p. 83-109.

Wilhelm, D. B., 2008, From clastic to carbonates: Tectonic and eustatic controls on the transition from the Borden delta to the Slade carbonate platform: Lexington, University of Kentucky, M.S. thesis, 286p.

Wilpolt, R.H., and Marden, D.W., 1959, Geology and oil and gas possibilities of Upper Mississippian rocks of southwestern Virginia, southern West Virginia, and eastern Kentucky: United States Geological Survey Bulletin, 1072-K, p. 587-656.

Woodward, H.P., 1961, Preliminary subsurface of study of south eastern Appalachian Interior Plateau: American Association of Petroleum Geologists Bulletin, v. 45, no. 10, p. 16341655.

Woodward, S.C., 1983, Paleocurrents of the Mississippian Ste. Genevieve Limestone and equivalents in the eastern United States: Cincinnati, University of Cincinnati, M.S. Thesis, 276 p.

Work, D.M., and Mason C.E., 2003, Mississippian (Middle Osagean) ammonoids from the Nada Member of the Borden Formation, Kentucky: Journal of Paleontology, 77, p. 593-596.

## Vita

**Author's Name:** Devi Bhagabati Prasad Udgata

**Place of Birth:** Cuttack, Odisha, India

**Year of Birth:** 1980

**Education:**

- Ph. D. in Geology, expected, 2011, University of Kentucky, Lexington, KY.
- M. S. in Geology, 2007, Auburn University, Auburn, AL.
- M.Sc. (Technology) in Applied Geology, 2001, Indian School of Mines, Dhanbad, India.
- B. Sc. in Geology (Honors with distinction), 1998, Utkal University, Odisha, India.

**Work Experiences:**

- Summer Intern, 2009, Hess Corporation, Houston, TX.
- Teaching Assistant, 2007–2010, University of Kentucky, KY.
- Teaching Assistant, 2005–2007, Auburn University, AL.

**Awards:**

- 2010 Outstanding Teaching Assistant Award, Department of Earth and Environmental Sciences, University of Kentucky.
- Geological Society of America (GSA) Research Grant-in-aid 2009.
- 2$^{nd}$ best paper presentation award at the Annual Kentucky Academy of Science meeting, 2007, Louisville, KY.
- 3$^{rd}$ best poster award at the eastern AAPG conference 2007, Lexington, KY.
- Gulf Coast Association of Geological Societies (GCAGS) Research Grant-in-aid, 2006.
- Geological Society of America (GSA) Research Grant-in-aid 2006.
- Best essay award for "Fossil Fuel- finite or infinite source?" at 2$^{nd}$ APG (Association of Petroleum Geologists) conference, Khajuraho, India, October 2004.
- Council of Scientific and Industrial Research (CSIR) research fellowship, Government of India, 2002.
- Indian School of Mines-University Grants Commission scholarship, 1998-2001.

**Society Memberships:**

- Member, Geological Society of America.
- Member, American Association of Petroleum Geologists.
- Sigma Gamma Epsilon, the Earth Science Honorary.
- Member, Houston Geological Society, Houston, TX.