MIOSPORE BIOSTRATIGRAPHY,
SEQUENCE STRATIGRAPHY, AND GLACIO-EUSTATIC RESPONSE
OF THE BORDEN DELTA
(OSAGEAN; TOURNAISIAN-VISEAN)
OF KENTUCKY AND INDIANA,
U.S.A.

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
The Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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*****

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The Borden Delta (Osagean; Tournaisian-Visean) represents a classic siliciclastic basin filling succession. Historically, the Borden Delta was thought to be deposited in response to tectonic activity centered around a peripheral bulge associated with the newly formed Acadian Highlands in the east. As the highlands eroded, the sediments were transported and deposited in the basin. This report proposes that the sea level fluctuations recorded in the Borden Delta rocks were formed in response to Gondwanan glaciations. Lithologic data from South America and chemostratigraphic data from numerous localities globally support this idea.

The rocks in the study area were subdivided into three Primary Depositional Centers (PDC-I, II, III) based on lithologic and stratigraphic characteristics. The rocks in PDC-I (northeastern Kentucky) were deposited during the lowstand systems tract and the transgressive systems tract of the Vanceburg Sequence. Palynologically, the rocks in PDC-I belong to the PC Biozone of Higgs et al. (1988).

The rocks in PDC-II (south-central Kentucky) represent parts of two different third order sequences (Vanceburg and Cumberland Sequences). In the eastern part of PDC-II, the Borden succession is represented only by the Nancy Member. With the
continued deltaic processes, the Borden Delta migrated out of the area, leaving space for the deposition of the Cumberland Sequence during the Visean sea level rise, consisting of the Fort Payne Formation (west) and the Muldraugh Member (east). Palynologically, the eastern part of PDC-II contains the PC Biozone – CM Biozone boundary. This boundary is also coeval with the Tn3b-Tn3c boundary (middle Osagean).

The Borden Delta in PDC-III is vastly different than the other parts of the study area. The Borden rocks in PDC-III are represented by parts of two third order sequences, the New Providence Sequence and the Millport Knob Sequence. Most of the sediments in this part of the Borden succession were deposited during a sea level rise in the early Visean. Palynologically, the Borden rocks in PDC-III are do not correlate with the previously established biozones of western Europe. The rocks in PDC-III are part of the *Scopfites claviger* Assemblage, the *Tumulispora* sp. B Assemblage, the *Tricidarisporites* sp. A – *Dictylotriletes* sp. B Assemblage, and the Pu Biozone (western Europe).
Dedicated to my parents and to

Sara, my wife
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Finally, a thank you to my wife, for putting up with the long days and short temper associated with the completion of this project. Without you Sara, this project would have not been completed.
VITA

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succession of southeastern Indiana, U.S.A. Abstracts with Programs, Geological
Society of America Annual Meeting,. V. 34, no. 6.


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FIELD OF STUDY

Major Field of Study: Geological Sciences
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CHAPTER 1

INTRODUCTION

The Mississippian System (353 – 312 Ma) represents an important time in the history of the planet. Ecologically, the Mississippian System included the establishment of the modern terrestrial ecosystem, the first floral provincialism on a global scale, and the re-establishment of marine faunal niches after the Frasnian – Famennian crisis (Behrensmeyer et al., 1992).

During the Early Mississippian, the study area (Kentucky and Indiana) was located approximately 10°S to 15°S latitude (Figure 1). North America was dominated by carbonate deposition throughout most of the Mississippian (Gutschick and Sandberg, 1983) except in parts of eastern North America adjacent to the Acadian Highlands (Figure 2). The central part of the craton was dominated by a massive carbonate platform centered around the transcontinental arch, and western North America was undergoing active tectonism as a result of the Antler Orogeny. Today, remnants of the massive
Figure 1. Paleogeographic reconstruction of the Early Mississippian
The black dot indicates the location of the study area.
(from McKerrow and Scotese, 1990)
Study Area

Figure 2. North American depositional environments during the Early Mississippian (Tournaisian).
(modified from Gutschick and Sandberg, 1983)
carbonate platform that dominated the central North American craton during the Early Mississippian can be observed in the Madison Limestone of the Wyoming and Montana, the Redwall Limestone in the Grand Canyon, the Chappel Limestone of west Texas, and the Mississippian stratotype along the Mississippi River. The only areas of clastic deposition near the craton were the flysch deposits associated with the Antler Orogeny in the west, and in the east, the Borden Delta was being constructed from erosion of the newly formed Acadian Highlands.

Tectonically, the Mississippian was a time of relative quiescence. The Mississippian (Lower Carboniferous) rocks in the eastern part of North America were deposited between the Acadian Orogeny (Middle – Late Devonian) and the Alleghanian Orogeny (Late Carboniferous; Pennsylvanian). The western part of North America was active with the Antler Orogeny, and the tectonism associated with the Ouachita Region was in its very early stages.

Historically, it has been proposed that a post-Acadian ‘relaxation phase’, which included load emplacement and bulge migration, was responsible for the deposition of the early Borden clastics and the mixed carbonate – siliciclastic succession deposited during late-Borden time in eastern North America (Ettensohn, and Pashin, 1993). This report will propose new factors that controlled the deposition of the Borden Delta.

The Early Mississippian was a time of terrestrial ecosystem stabilization. The landscape was dominated by simple plants, mostly pteridosperms and mid-size tree lycopsids. The landscape was markedly different from the Late Devonian, which was dominated by shade-producing *Archeopteris* forests, and the lower, wetter areas were
blanketed with *Rhacophyton*. By the onset of the Early Carboniferous, *Archeopteris* and *Rhacopyhton* were extinct, leaving the landscape to be dominated by *Archeocalamites, Triphyllopteris, Neurocardiocarpus*, and *Rhodeopteridium* (Behrensmeyer et al., 1992). The shade-producing forests did not return to the landscape until the appearance of *Pitus* and other gymnosperms in the middle Visean (upper Osagean) (Behrensmeyer et al., 1992).

With the presence of terrestrial plants, environments usually not suitable for marine or marginal marine preservation of fossils can now be biostratigraphically analyzed. Not all early land plants were vascular and needed to be near water to reproduce. Early land plants (vascular and non-vascular) dropped spores for reproduction. Once dropped, these spores could be buried, wind-blown or transported by water. Many spores were transported and deposited in shallow marine or marginal marine settings where depositional energy or chemical environments (salinity and oxygen differences) would normally not allow preservation of organisms. Therefore, deposition of miospores is extremely important stratigraphic tool in areas such as the Borden Delta, a high-energy, relatively shallow water, deltaic setting.

**Statement of Problem.**

A detailed biostratigraphic correlation does not exist for the Lower Mississippian Borden Formation (delta) in Kentucky and Indiana. Although individual members of the Borden Formation locally can be very fossiliferous, a continuous biostratigraphic succession is not known. Most of the depositional environments in which the sediments
of the Borden Delta were deposited were not conducive to fossil preservation. A renewed interest in Paleozoic palynology (primarily miospores) has provided a basis to solve the biostratigraphic problems for this Lower Mississippian clastic succession in eastern North America. Miospores, being acid-resistant, are preserved in a number of depositional settings. The Lower Mississippian (Osagean; Tournaisian/Visean) clastic succession in Kentucky and Indiana was derived from the weathering of the subaerially exposed Acadian Highlands, thus providing an ideal setting for constructing a miospore biostratigraphic framework.

Recent advances in chemostratigraphy have provided insight into detailed global correlations, based primarily on $\delta^{13}C$ and $\delta^{18}O$ excursions. Recognition of these positive stable isotope excursions and their correlations with glacial events have renewed an interest in Paleozoic sea levels and paleoclimates. Lower Mississippian carbonates of the Arrow Canyon (NV) section have one of the largest $\delta^{13}C$ excursions in the Paleozoic (Figure 3) (Saltzman, 2003) and the Borden succession (Lower Mississippian) in Kentucky and Indiana may have recorded the associated glacio-eustatic signals. Glacial deposits in Gondwana also provide evidence for this glacial event during the Lower Mississippian (Tournaisian) (Caputo and Crowell, 1985). These new views of the sedimentologic history of the Borden Delta will be discussed in detail below.

Objectives.

In this study, I will (1) describe the miospore biostratigraphy of the Borden Formation in Kentucky and Indiana; (2) apply sequence stratigraphic concepts to the
Figure 3. Carbon stable isotope record for the Carboniferous of Arrow Canyon, Nevada, U.S.A. (from Saltzman, 2003)
time-transgressive units of the Borden (Delta) Formation; (3) analyze the glacial history of the Early Mississippian (Tournaisian) based on lithologic evidence and chemostratigraphic evidence; (4) propose the occurrence of glacial signals recorded in the Borden Formation of Kentucky and Indiana; and (5) combine the biostratigraphy with the sequence stratigraphy and chemostratigraphy in order to construct a detailed understanding of the depositional settings and spatial and temporal relations of the Lower Mississippian Borden Delta.
CHAPTER 2

HISTORY OF STUDY

Sedimentary and Stratigraphic Studies.

The research presented in this paper centers on the Lower Mississippian Borden Formation (Osagean; Tournaisian/Visean), which is located stratigraphically above the lowermost Mississippian fine-grained clastics (Kinderhookian; Tournaisian) and below the Middle Mississippian (Meramec; Visean) carbonates. Throughout the late 1800’s and 1900’s, the rocks of the Borden Formation and its equivalents have been the center of much stratigraphical work.

The original description of rocks of the “Mississippian Group” (Winchell, 1869), and soon thereafter, the strata of the Borden Formation and its equivalents were widely identified over most the east-central United States. W.W. Borden (1874) described rocks of the “Mississippian Group” in Indiana and Kentucky. These rocks were grouped into the New Providence Formation, which was originally part of the Knobstone Formation. In 1891, Williams described the Osagean Series. This series was named for the strata
exposed along the Osage River, near Osceola, St. Clair County, Missouri. Finally, Chamberlain and Salisbury (1906) proposed the Mississippian System, equivalent to the lower part of the Carboniferous, originally defined by Coneybeare and Phillips (1822).

A great amount of work on the Mississippian in the United States mid-continent was done during the early part of the 1900’s. Hyde (1927) described the Mississippian rocks in Ohio; (in ascending order) the Bedford Formation, the Berea Grit, the Sunbury Shale, the Cuyahoga Formation, and the Logan Formation. The rocks were collectively described as the “Waverly Rocks.” During the 1930’s, Stockdale reported on the Mississippian rocks in the Eastern Interior Basin, most of which were from southern Indiana. In 1932, Stockdale discussed stratigraphic problems involved in determining the geologic structures controlling the Lower Mississippian rocks in southern Indiana. Stockdale (1937) composed a correlation chart comparing the Lower Mississippian formations of the east-central interior, and Stockdale (1939) described the rocks of pre-New Providence age, the New Providence Formation, the Brodhead Formation, the Floyds Knob Formation, and the Muldraugh Formation.

The middle to late 1900’s witnessed a plethora of work on regional stratigraphic correlations and sedimentologic relationships of the Borden-aged rocks. Kepferle (1967) proposed stratigraphic and sedimentologic relationships for the turbidites in northeastern Kentucky. Moore and Clarke (1970) suggested that the Farmers Member in northeastern Kentucky was deposited by turbidity flows during the early Borden Delta progradation. Kepferle (1977) concluded that the sediments of the Kenwood Siltstone were a submarine canyon fill and were deposited with a flow direction to the west - southwest. Craig and
Connor (1979) reported on the stratigraphic relationships of the Mississippian rocks across the entire state of Kentucky. They proposed the spatial relationships of different members of the Borden from east to west. In 1990, Sable and Dever published an additional report on the Mississippian rocks throughout Kentucky. The stratigraphic relationships between the clastics and the carbonates in the northeastern part of the state were compared to those in the central part of the state. Sedimentological indicators, fossil data, and spatial relationships of the Mississippian rocks in Kentucky were all included in the report (Sable and Dever, 1990).

Tectonic Studies.

The tectonic framework of the Mississippian rocks in Kentucky and Indiana has not received as much attention as the stratigraphical and sedimentological aspects. Ettensohn and Dever (1979) reported on the structural trends in the Mississippian rocks in the Illinois Basin, across Indiana and into eastern Ohio and Kentucky. During the Osagean, most of the features in the Appalachian Basin had negative relief most of Indiana underwent subsidence throughout the Osagean. One positive element in Kentucky during the Osagean was the Waverly Arch, which was originally described by Woodward (1961). The Waverly Arch was a north – south trending arch located on the eastern edge of the Cincinnati Arch.

In 1979, deWitt and McGrew reported on the paleotectonics in the study area during the Early Mississippian and on the relationship of the depositional history of the Fort Payne Formation and its relationship to the late Osagean (Visean) transgression.
Ettensohn and Pashin (1993) described in detail the tectonic processes affecting the Lower and Middle Mississippian sedimentation in the Black Warrior and the southern Appalachian Basins.

**Paleoecological Studies.**

During the last part of the 1900’s (1970-1999), paleoecologic studies of the Borden rocks became increasingly more abundant and more important. Most of the work done on the paleoecological aspects of the Borden strata was centered around crinoids, possibly due to their vast abundance in the Mississippian carbonates (Borden equivalents). Lane (1973), Ausich et al. (1979) and Ausich (1983) described the Crawfordsville (Formation) crinoids and the associated fauna in Indiana, along with their relationships as a delta platform community. Ausich and Lane (1980) reported on delta platform communities of the Borden Delta in Indiana, and Ausich et al. (1979) and Lane and DuBar (1983) used changes in crinoid communities as evidence of delta progradation. Kammer (1985) described prodelta communities in the upper Osagean New Providence Shale of southern Indiana and north-central Kentucky. Two communities are present, the Coral Ridge and Button Mold Knob faunas. The Coral Ridge fauna lived in front of the delta on the basin floor. The environment was interpreted to have been dysaerobic, where deposit feeders thrived. The Button Mold Knob fauna is a younger fauna, which thrived in an aerobic environment at the base of the delta slope. Most of the organisms in the Button Mold Knob fauna were suspension feeders, and they lived at the mouth of submarine canyons where nutrient-rich sediments and well-oxygenated water flowed into
the basin. Li (2000) reported on the community paleoecology and evolution of platform communities of the Nada Member.

The sediments of the Borden Formation and its equivalents have been the subject of other faunal studies. Rexroad and Scott (1964) described the conodonts; Weller et al. (1948) and Matchen and Kammer (1994) discussed the brachiopods; Laudon (1973), Ausich and Lane (1982), and Kammer and Ausich (1996) described Mississippian crinoids; Ausich and Guenther (1996) discussed blastoids from the Cuyahoga Formation in Ohio; Ausich, Goldstein, and Yates (2000) described a new Upper Osagean crinoid fauna dominated by advanced cladids; Manger (1979) described Osagean ammonoids from eastern Kentucky; Rigby and Ausich (1981) described Lower Mississippian sponges from Indiana; and Conkin and Conkin (1979) described the foraminifera from the Henley Bed in eastern Kentucky. Powers and Ausich (1990) described epizoan associations of the Edwardsville Formation, including bryozoans, crinoids, and brachiopods. One of the more complete works on Borden paleoecology was reported by Lane (1973). This work gives a complete description of the paleontology and paleoecology of Crawfordsville fossil site (Indiana). Chaplin (1980) described the ichnofacies if the Borden Formation in northeastern Kentucky. This report identified three primary ichnofacies (Nereities, Zoophycus, and Cruziana-Skolithos), occurring from the basin-floor turbidites to the delta platform, respectively.

Biostratigraphic zonations for Mississippian strata have been proposed based on several fossil groups. Although the majority of Osagean rocks in Kentucky and Indiana are siliciclastic and yield few conodonts, the conodont zones are still important for
stratigraphic purposes. Collinson et al. (1971) divided the Osagean into four conodont zones. The base of the Osagean appears slightly above the base of the *Gnathodus semiglaber – Pseudopolygnathus multistriatus* conodont zone. The upper Osagean boundary corresponds with the top of the *Gnathodus texanus – Taphrognathus* conodont zone. Craig and Connors (1979) combined the four zones of Collinson et al. (1971) into two assemblage zones. The base of the Osagean corresponds with the base of the *Bactrognathus* Assemblage Zone. Stratigraphically above the *Bactrognathus* Assemblage Zone is the *Taphrognathus* Assemblage Zone.

The Mississippian has also been biostratigraphically zoned based on brachiopods. Weller (1926) classified the Osagean rocks as the *Spirifer grimesi – logani* Assemblage Zone, which is composed of eight brachiopod zones. According to Gordon (1970), the Osagean incorporates only one part of an ammonoid zone. The top half of the *Protocanites lyoni* ammonoid zone is in the lower part of the Osagean. The majority of this zone lies within the Kinderhookian. The Osagean part of the zone is characterized by the genus *Muensteroceras* and has been identified in the New Providence Shale of southern Indiana.

Mamet and Skipp (1971) proposed a zonation for the Lower Carboniferous of North America based on calcareous foraminifera. According to this zonation, the Osagean-aged rocks are zones 7, 8, and 9. The base of the Zone 7 is recognized by the first appearance of a subspecies of *Septaglomospiranella*. The subspecies, *Tuberendothyra tuberculata tuberculata*, has a very sparse occurrence in the fauna. Zone 8 is defined by the first appearance of two forams, *Spinoseptatournayella* and
Spinoendothyra and can be correlated to the Middle Osagean. Zone 9 has two different faunas, one representing North America and one representing Eurasia. The bases of both zones are recognized by the first appearance of Calcisphaera pachysphaerica.

Laudon (1973) zoned the Mississippian rocks of Iowa using crinoids. Twelve crinoid zones were defined from the Kinderhookian to the Meramecian. The base of the Kinderhookian is defined by the Aacocrinus chouteauensis Zone, and the upper boundary of the Meramecian is defined by the Taxocrinus huntsvillae Zone. The Osagean of Iowa contains seven of Laudon’s (1973) twelve zones. The Burlington Limestone (Osagean) contains four zones (in ascending order); the Cactocrinus proboscidialis Zone, the Agaricocrinus planoconvexus Zone, the Azygocrinus rotundus Zone, and the Dorycrinus quinquelobus Zone.

Kammer et al. (1990) redefined the Osagean – Meramecian boundary in the stratotype region using multi-faunal biostratigraphic analysis. The Osagean – Meramecian boundary was recognized within the Warsaw Formation, based on the first occurrence of species representing different faunas, including echinoderms, brachiopods, and calcareous microfossils.

Palynological Studies.

Carboniferous palynology has been a field of increasing interest since the late 1800’s. Most of the early work on Carboniferous palynology focused on the coal-fields of western Europe and the British Isles. Reinsch (1884) published the first monograph on a Carboniferous fossil sporomorph and also published the first monograph on
Carboniferous paleoflora. The first described Carboniferous megaspores were reported by Bennie and Kidston (1886). In the early 1900’s, Theissen described spores in Carboniferous thin sections from coal seams and suggested that spores could be useful for stratigraphic correlation. In the 1930’s, Raistrick indicated two caveats in dealing with Carboniferous spores. These were (1) that the spores were not identified using binomial Latin names, and (2) the coal measures are not autochthonous, so that the spores would not be useful for regional floral interpretation. With the aforementioned caveats in mind, Schopf et al. (1944) were the first to use the Linnaean classification for pollen and spores. The classification of fossil sporomorphs made another significant advancement in 1954 when Potonié and Kremp proposed a supra-generic classification based on the ‘turma’ (named after Roman army divisions), which is equivalent to the Linnaean ‘order’. Smith (1962) reporting on English coal-beds suggested a strong relationship between Carboniferous coal types and spore composition. Clayton et al. (1977) and Higgs et al. (1988) proposed comprehensive miospore zones for western Europe from several localities in the British Isles. Twenty five miospore zones exist from the Upper Devonian to the Lower Permian.

Although a comprehensive palynological zonation for the Osagean (Lower Mississippian) is not known for North America, several studies have dealt primarily with Mississippian palynology in North America. However, these studies have largely concentrated on the placement of the Devonian-Mississippian boundary. These studies include Winslow (1962), who described the Upper Devonian – Lower Mississippian boundary in Ohio; Warg and Traverse (1973), who described the Devonian –
Mississippian boundary in Pennsylvania; Streel and Traverse (1978) identified the miospores across the Devonian – Mississippian boundary near Altoona, Pennsylvania; and Molyneux et al. (1984) identified miospores and microplankton across the Bedford Shale – Berea Sandstone boundary in Ohio. Coleman and Clayton (1987) collected 24 samples from the Upper Devonian through the Lower Mississippian along I-64 near Morehead, in northeastern Kentucky for miospores. The section yielded 60 taxa that could be correlated with the PC Biozone of western Europe of Clayton et al. (1977) and Higgs et al. (1988). Clayton et al. (1998) also described Mississippian miospores from the Cuyahoga and Logan Formations in northeastern Ohio. These two formations yielded several key taxa correlative with the western European Zones. Other palynological studies on Mississippian strata in North America are of more local importance.

**Chemostratigraphic Studies.**

Recently, stable isotopes have became increasingly more important for stratigraphic purposes. Stable isotopes of carbon, oxygen, and radiogenic isotopes of strontium can be used for global correlations. These stable isotopes record composition of the seawater during the time of deposition and are set against a standard (Peedee Belemnite or brachiopod). Positive excursions in δ^{13}C are the result of increased weathering of carbonates or an increase in the burial of organic carbon, and positive excursions in δ^{18}O result from the trapping of δ^{16}O in glacial ice. Positive excursions in both of these stable isotopes suggest an ice-producing event. A major positive excursion occurred during the Upper Kinderhookian. Saltzman et al. (2000) reported a massive
positive excursion (+7.1‰) during the *Siphonodella isosticha* – Upper *crenulata* Zone (Upper Kinderhookian) in the Joana Limestone in Nevada. Similar excursions were reported from Iowa, Utah, and Belgium, and Saltzman et al. (2000) suggest that the positive excursion may be related to the Antler Orogeny. Saltzman et al. (2000) proposed the Antler Orogeny led to increase organic carbon burial in the subsiding foreland basin, possibly contributing to a cooling period. Mii et al. (1999) discussed Carboniferous isotope stratigraphies and Mississippian glaciations. Positive excursions of $\delta^{13}$C and $\delta^{18}$O were recorded in the Upper Kinderhookian, and continued throughout the early Osagean. During the early Viséan, there was a negative shift in both the $\delta^{13}$C and $\delta^{18}$O stable isotopes. The patterns of these two isotopes suggest the Tournaisian was a time of cooling, and the Viséan was a time of warming.

More direct evidence of Mississippian glaciations comes from Reyes (1972), who described the Cumaná Formation on the Copacobana Peninsula (Bolivia). The Cumaná Formation contains the Calamarca Tillite, which is a true glacial tillite that comprises up to 9% of the total formational thickness, and was believed to have been deposited between two topographic highs. Reyes (1972) explained this as probably a result of alpine glaciation. Caputo and Crowell (1985) discussed the migration of glacial centers across Gondwana during the Paleozoic. Caputo and Crowell (1985) concluded that the Itacua Formation (Tournaisian) of Bolivia and northern Argentina contains diamictites and tillites. The Tupambi Formation contains glacial deposits and is probably Tournaisian in age, as suggested by palynological data.
CHAPTER 3

LABORATORY PROCEDURES

In palynomorph extraction, no one series of processes is definite for a successful preparation. Factors arising from the type of investigation, lithology, and logistics all control the steps involved in palynomorph processing. The processing techniques used in this study were based in part on those reported by Litwin and Traverse (1989) (Figure 4).

In the palynology laboratory, currently housed in the Byrd Polar Research Center at The Ohio State University, the samples were crushed, weighed, and placed in 10% hydrochloric acid in 1000 ml plastic beakers (HCl) for approximately 24 hours. Once the carbonates were dissolved, the samples were decanted three times with distilled water. If the sample was primarily carbonate minerals (CO$_3$), the acid treatment discussed below may be excluded.

Following the HCl decanting steps, siliciclastic samples were switched to a 500 ml Teflon beaker and placed in 49% hydrofluoric acid (HF). Each sample was immersed in the hydrofluoric acid for approximately 24-48 hours to dissolve the silica-rich
Figure 4. Flow chart summarizing the preparation techniques for palynomorphs.
minerals. After the HF immersion time elapsed, the samples were decanted four times with distilled water. Following the HF decanting, the samples were placed in a hot HCl bath in order to remove the complex hydrofluorides (salts) that might have been produced during the hydrofluoric dissolution steps. In this step, the samples were bathed in HCl and placed on a hot plate until the beaker was slightly heated. Once the sample was slightly heated, the acid was poured off and the sediment was allowed to settle. The hot HCl bath step was repeated. After the second HCl bath, the excess HCl was poured off, and the sample was decanted three times with distilled water. After the third decanting, the residue was transferred to a 500 ml plastic test tube. The sample was then centrifuged at 2000 rpm for 1 minute, 30 seconds, and the excess water was drained.

Nitric acid (HNO₃) was added to the sample and the entire test tube was immersed in a beaker filled with water and placed on a hot plate for eight minutes. This step was necessary to oxidize any pyrite in the sample. Once the eight minutes had elapsed, the test tube was filled with distilled water and centrifuged at 2000 rpm for 1 minute, 30 seconds. The excess water was then drained and the test tube was refilled with distilled water and centrifuged again at 2000 rpm for 1 minute, 30 seconds.

Following the second centrifugation and removal of excess water, the sediment was transferred to a 100 ml glass test tube, where it was washed with 10% HCl, so that the step discussed below would be productive. After the sediment was transferred, the sample was then centrifuged at 2000 rpm for 1 minute, 30 seconds. After the centrifuging, the excess HCl was drained completely.
The following step involves the actual separation of the palynomorphs. Five to ten cubic centimeters of heavy liquid (ZnCl$_2$) was added to the sample. The sample was extensively mixed with a pipette and centrifuged at 2000 rpm for 1 minute, 30 seconds. When removed from the centrifuge, particles in the sample were separated, with the palynomorph fraction ‘floating’ above the remaining sediment. The palynomorphs were then removed with a pipette and placed in another 100 ml glass test tube filled with 10% HCl.

After the palynomorphs were placed in the 100 ml test tube filled with HCl, the sample were centrifuged at 1500 rpm for 1 minute. The excess water was drained, the test tube was refilled with distilled water, and the sample was centrifuged at 800 rpm for twenty seconds. After the centrifuging, the excess water was the washing was repeated twice.

Following the washing, slides were prepared to mount the palynomorphs. Slide preparation included placing a drop of Clearcol on the cover-slip, then adding a drop of the residue containing palynomorphs from the test tube, and spreading the sample and Clearcol evenly over the entire cover-slip with a toothpick. The cover-slip was allowed to dry completely. Once the cover-slip was dry, Permount was added to a glass micro-slide. (Permount is a permanent mounting fluid for microscope slides). Immediately after adding the Permount, gently place the cover-slip was placed gently on the micro-slide, palynomorph side down. Once the slide dried, it was ready to be analyzed.
Spore Counting Method.

Each sample with at least 300 minimum spores was counted for paleoecological analysis. This paleoecological analysis is based on the work by Winslow (1959) and Peppers (1996). Although the biological affinities of most Carboniferous miospores are not well known, some species have been assigned to macrofloral counterparts. *Punctatisporites* and *Retusotriletes* are believed to be affiliated with marattiaceous ferns, or tree ferns. *Calamospora* specimens are believed to have originated from the sphenopsids, a pteridophyte with a jointed stem. Spores belonging to the genera *Cristatisporites, Crassisspora, Endosporites*, and *Cirratriradiates* are believed to have originated from the herbaceous lycopods. Specimens of *Vallatisporites* and *Verrucosisporites* were also counted, due to their structural uniqueness and their abundance. The marine abundance is calculated from the presence of several species of acritarchs and prasinophytes, along with rare sc olecodonts.

Each microslide was centered on the microscope stage and the miospore counting began. Each specimen in the field of view belonging to one of the pre-arranged groups received one ‘click’ on the point counter. The basis for the pre-arranged groups was taken from Peppers (1996). Because most Paleozoic miospores have unknown biological affinities, only select taxa with known affinities were used. These include the sphenopsids (*Calamospora*), marattiaceous ferns (*Punctatisporites*), herbaceous lycopods (*Densosporites, Cirratriradiates, Cristatisporites*), *Verrucosisporites, Vallatisporites*, and a marine fraction (acritarchs). The microslide was moved to the right
until the total count of palynomorphs reached 300. Relative abundance among groups was calculated. These results, shown graphically, will be discussed below.
CHAPTER 4

MIOスポRE BIOSTRATIGRAPHY
AND STRATIGRAPHIC CORRELATION

During the last century, palynology has become more important for Paleozoic studies. In the middle to late 1800’s and the early 1900’s, Paleozoic palynology was the center of many studies due to the increased use of coal for industrial purposes. Specifically, paleoecologic interpretations and biostratigraphy were the primary objectives of these early studies. Today, Paleozoic palynology studies not only center around paleoecology and biostratigraphy, but also include palyno-facies analyses and thermal maturation studies. This report is a detailed continuation of a preliminary study conducted in the late 1980’s by Coleman and Clayton. The study of Coleman and Clayton (1987) included several samples from the study area (KY and IND), and they concluded that most of the miospores from the study area could be compared to the previously defined miospore zones of western Europe.
The miospore assemblages described from the study area are identified and compared to the western European zones of Higgs et al. (1988) (Figure 5). The biozones were by first appearance of a specific taxon and a characteristic assemblage. The outcrops from Kentucky, Tennessee, and Indiana contain characteristic taxa of the PC (*Spelaeotritiletes pretiosus* – *Raistrickia clavata*) Biozone, the CM (*Schopfites claviger* – *Auroraspora macra*) Biozone, and the Pu (*Lycospra pusilla*) Biozone. All three of these biozones occur within the Osagean Series (North American) and the Tournaisian – Visean Series (western Europe). In some parts of the study area, the base of the Borden succession is immediately above a condensed section that is primarily Kinderhookian in age. These Kinderhookian rocks may contain parts of the HD and BP Biozones. These two zones are based on the first appearance of *Krauselisporites hibernicus* and *Spelaeotritiletes balteatus* respectively. The occurrence of these two zones in the condensed interval throughout the research area warrants more study. Comparisons between the North American and western European classification will be made throughout the text, along with comparisons between the miospore and conodont biostratigraphic zones. A summary of these stratigraphic and biostratigraphic comparisons can be seen in Figure 6. The miospores in this report will be discussed with respect to their occurrence in three regions within the study area: northeastern Kentucky, south-central Kentucky, and northeastern Kentucky/southeastern Indiana.
Figure 5. Mississippian (Lower Carboniferous) miospore biozones of western Europe. (modified from Higgs et al., 1988)
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<th>N.A. Series</th>
<th>Kockuk</th>
<th>Visean</th>
<th>Tn3c</th>
<th>Chadian</th>
<th>Molinian</th>
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<td>Missouri</td>
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**Figure 6.** Correlation chart showing relationship between North America, Europe, conodonts, and microspores, based on the author's interpretation.
Northeastern Kentucky.

The outcrops in northeastern Kentucky include the Evans Chapel and Griffen Hollow sections along Kentucky Highway 546 in the northeastern part of the state; exposures of the Cowbell Member along Kentucky State Route 9; the outcrops around the Morehead, Kentucky area, and the outcrops of the Cowbell and Nada Members near Frenchburg, Kentucky. All of the Borden Delta outcrops (below the Nada Member) in northeastern Kentucky were deposited during relative sea level fall and are represented (in ascending order), by the Farmers Member, the Nancy Member, and the Cowbell Member (Figure 7). The Nada Member was deposited during a sea level rise. Evidence for the sea level during Borden time is described in the next chapter (Chapter 5). Detailed descriptions of each outcrop are given in Appendix A.

The miospore assemblage in northeastern Kentucky is representative of the PC (Spelaeotrilites pretiosus – Raistrickia clavata) Biozone. The microfloral assemblage in northeastern Kentucky is dominated by species of Punctatisporites and Retusotriletes, including P. minitus, R. famenensis and R. planus (Figure 7). Other common taxa include specimens of Calamospora, Neoraistrickia, Vallatisporites, Verrucosisporites, Umbonatisporites, and Grandispora. Specimens of Discernisporites micromanifestus and Geminospora spongiata are present in lesser abundance. The zone-defining species of Spelaeotrilites pretiosus is present throughout the succession but are not the most dominant genera.

The PC (Spelaeotrilites pretiosus – Raistrickia clavata) Biozone is the oldest Osagean biozone and was first described by Clayton et al. (1978). In western Europe, the
Figure 7. Miospore biostratigraphy for northeastern Kentucky. The black dots represent collected samples.
base of the PC Biozone lies just below the base of the *Polygnathus communis corina* Conodont Zone (Clayton et al., 1978). Clayton et al. (1978) recognized the base of the PC Biozone just below the level of the disappearance of the siphonodellids. Therefore, it correlates with the Tn2b-Tn2c boundary, upper Middle Tournaisian.

Higgs (1997) discussed the miospore biostratigraphy of six boreholes from the West Flanders region of Belgium, where he proposed that the PC Biozone does not extend upward into the Upper Tournaisian (Tn3). However, the sections studied in this report indicate that the upper part of the PC Biozone is equivalent to part of the Tn3 substage. The upper boundary of the PC Biozone correlates with the Tn3b-Tn3c subseries boundary.

Based on conodonts, the Kinderhookian – Osagean boundary (*S. isosticha – G. typicus*) is located within the Henley Bed (basal Farmers Member) (Sandberg and Mason, 2002). The disappearance of the siphonodellids marks the base of the *Gnathodus typicus* conodont zone and is coeval with the base of the Osagean Series. Coleman (1991) reported the first appearance of *Spelaeotriletes pretiosus* in the upper 1.0 m of the Henley Bed, marking the base of the PC (*Spelaeotriletes pretiosus – Raistrickia clavata*) Biozone. This study reports the first occurrence of *S. pretiosus* slightly higher stratigraphically. Therefore, the lower part of the Henley Bed, below the first appearance of the *S. pretiosus*, may be representative of the Tn2 and the lower part of the Tn3 (Kinderhookian), along with the possible presence of the BP and HD Biozones.

The HD (*Krauselisporites hibernicus – Umbonatisporites distinctus*) Biozone and the BP (*Spelaeotriletes balteatus – Rugospora polytycha*) Biozone are missing in the
study area. This hiatus may be an erosional feature or a result of non-deposition. The Tournaisian succession in the study area contains the VI (*Vallatisporites verrucosus – Retusotrilites inhocatus*) Biozone at the base, which is represented by the Sunbury Shale, and is overlain by the PC and the CM Biozones respectively, which represents the two youngest Tournaisian miospore biozones (Figure 5). The base of the HD Biozone, which is not present in the study area, is defined by the first appearance of *Krauselisporites hibernicus*. Many species present in the underlying VI (*Vallatisporites vallatus – Retusotrilites inhocatus*) Biozone extend into the overlying zones, but the first appearance of *K. hibernicus* is the zone defining species. The overlying BP Biozone, which is also not present in the study area, has very poor age control. The zone is defined basally by the first appearance of *Spelaeotrilites balteatus*, and many other important taxa make their first appearance near the base of this zone, including the long ranging species *Vallatisporites vallatus*. Due to the absence of important first appearance taxa, it is believed the HD and BP Biozones are absent in this part of North America. This part of Laurentia was submerged during this time, so the depositional center located in eastern North America may have been an area of restricted input or was too distal from the shoreline to receive major inputs of miospores. Prevailing winds and drainage patterns in this part of North America at this time during the Early Mississippian may not have been conducive to transport, deposition, and preservation of spores indicative of the HD and BP Biozones. Alternatively, the terrestrial flora that produced the spores characteristic of the HD and BP Biozones may not have been present in this part of Laurentia during the Lower Mississippian. The exact factors contributing to the absence of these two biozones
needs to be studied in more detail. If the HD and BP Biozones are in fact present in the
study area, they may be included in the condensed section of the Henley Bed (basal
Farmers Member) and the “Maury Shale”.

The miospore assemblage in northeastern Kentucky is equivalent to the
previously established PC Biozone in western Europe. The miospores of the PC Biozone
(Lower Osagean) are correlative with the *Gnathodus typicus* (Upper *typicus*) conodont
zone, the base of which occurs in the middle of the Henley Bed (Sandberg and Mason,
2002). Based on miospores and conodonts, the Borden succession in northeastern
Kentucky is no older than Tn3b. According to Sandberg and Mason (2002), the Nancy
Member in this succession contains the Cave Lake ammonoid fauna, comprising
*Kazakhstania colubrella*, *Muensteroceras owenii*, and “*Karagandoceras*” n. sp., which is
in the Upper *typicus* Zone and the PC Biozone. Thus, this ammonoid fauna confirms the
Tn3b (Osagean) age.

**South-central Kentucky**

The outcrops in south-central Kentucky include the type-section of the Nancy
Member located in Pulaski County State Park, approximately 8 km east of Nancy,
Kentucky; the “Maury Shale” exposures at Burkesville, Kentucky, and at Dale Hollow
Dam, Tennessee; and the multiple sections of the Fort Payne Formation exposed along
the shores of Lake Cumberland. Detailed descriptions of the sections from south-central
Kentucky are in Appendix A.
The type section of the Nancy Member is located along State Route 3981 approximately 8 km east of Nancy, Kentucky. The exposure includes strata from the Famennian (Upper Devonian) to the middle Tournaisian (Lower Carboniferous). The Chattanooga Shale is exposed at the base of the section in Pulaski County State Park. *Retispora lepidophyta* and *Rugospora flexuosa* are characteristic taxa defining the Upper Devonian (LN Biozone; *Retispora lepidophyta – Verrucosisporites nitidus*), and both are present in the Chattanooga Shale in the Pulaski County State Park exposure. Worldwide, these two species disappear at the Devonian – Carboniferous boundary.

Overlying the Chattanooga Shale in south-central Kentucky is the “Maury Shale”. The “Maury Shale” is a condensed section and is only about 30-50 cm thick. Leslie et al. (1996) zoned the “Maury Shale” using conodonts from the section near Burkesville, Kentucky (Figure 8). The conodont samples indicated the lower part of the “Maury Shale” is no older than the *duplicata* Conodont Zone and the upper half of the lower part of the “Maury Shale” is equivalent to the *sandbergi – lower crenulata* Conodont Zone. The remaining samples yielded reworked conodonts, but the uppermost part of the “Maury Shale” yielded conodonts no older than the middle *anachoralis – latus* zone, indicating the entire “Maury Shale” at this locality is Tournaisian in age.

No significant miospores were recovered from the “Maury Shale” exposure in Pulaski County State Park or Dale Hollow Dam. The “Maury Shale” at both Pulaski County State Park and at Dale Hollow Dam did yield a high percentage of
Figure 8. Conodont zonation of the “Maury Shale” near Burkesville, Kentucky. (modified from Leslie et al., 1996).
amorphous organic matter (AOM), however the distal location and sediment-starved conditions that existed during the deposition of the “Maury Shale” played a significant role in the lack of terrestrial palynomorphs.

The Nancy Member at the type section yielded a diverse and abundant assemblage of miospores (Figure 9). The Nancy Member in the type area contains the contact between the PC (*Spelaeotriletes pretiosus – Raistrickia clavata*) Biozone to the CM (*Schopfites claviger – Auroraspora macra*) Biozone. The assemblage composition differs slightly from the PC Biozone in northeastern Kentucky. The dominant genera in northeastern Kentucky, *Punctatisporites* and *Retusotriletes*, are still present in south-central Kentucky but not in the same abundance as in northeastern Kentucky. Other dominant taxa within the Nancy stratotype include *Calamospora microrugosa*, several species of *Vallatisporites*, *Verrcosisporites nitidus*, and *Microreticulatisporites araneum*. Specimens of *Camptotrilites* and *Dictylotriletes* were also observed.

In sample 00JR8-6, which was collected approximately 22 m above the “Maury Shale” – Nancy Member contact, *Schopfites claviger* makes its first appearance. The first appearance of *Schopfites claviger* marks the base of the CM Biozone. The base of the CM (*Schopfites claviger – Auroraspora macra*) Biozone is equivalent to the occurrence of the Tn3c sub-series (Upper Tournaisian), which was originally described by Neves et al. (1972) from the sections in the Midland Valley of Scotland. Through time, several species characteristic of the CM Biozone were found to extend downward into the PC Biozone, which led Clayton et al. (1978) to redefine the base. Typical CM Biozone
Figure 9. Miospore biostratigraphy of the type section of the Nancy Member, south-central Kentucky. The black dots represent samples collected.
palynofloral assemblages include *Baculatisporites fusticulus, Plicatispora quasilabrata, Raistrickia corynoges*, and several species of *Retusotriletes*.

The Nancy Member in south-central Kentucky straddles the PC Biozone-CM Biozone boundary, which makes it slightly younger than the Nancy Member in northeastern Kentucky. The PC-CM Biozone boundary assignment for the Nancy Member in south-central Kentucky makes it correlative with the Tn3b-Tn3c boundary. The occurrence of the Tn3c in south-central Kentucky makes it correlative with the middle to upper part of the Burlington Limestone of the reference sections in the Mississippi Valley. Biostratigraphically, the type section of the Nancy Member is correlative with the uppermost *Gnathodus typicus* Zone and the lower part of the *anchoralis-latus* (North American) Conodont Zone, which is coeval with the PC-CM Biozone boundary.

In the western half of south-central Kentucky, the miospore biostratigraphy is not as clearly defined. The “Maury Shale” in the western part of south-central Kentucky, specifically the exposure near Burkesville, yielded some miospores. Several key taxa were recovered, including *Spelaeotriletes obustus* from the basal-most sample. *Spelaeotriletes pretiosus* is present in the upper most sample. Biostratigraphically, the only information from this low-abundance, low-diversity microfloral assemblage is that the lowermost sample is Kinderhookian, possibly VI Biozone, in age. The uppermost sample is clearly Osagean. Thus, the Kinderhook-Osage boundary is located within this condensed interval. This age can be assigned with confidence due to the occurrence of
S. pretiosus, which marks the base of the PC Biozone, the oldest of the Osagean miospore biozones (Figure 10).

Along with the miospores, two long-ranging species of prasinophytes were recovered from the “Maury Shale” at the Burkesville locality. Although these prasinophytes are not biostratigraphically useful, they do have sedimentological implications worthy of mention. According to Dorning (1981), these species, namely Pterospermella captiana and Cymatiosphaera rhacomba, are indicative of deep water deposition.

In the western half of south-central Kentucky, the Fort Payne Formation overlies the “Maury Shale”. The Fort Payne Formation was sampled at several localities around the Lake Cumberland Region, and no significant spores were collected. Horowitz, et al. (1979) reported the occurrence of Lycospora pusilla from the Fort Payne Formation in Tennessee; however, no specimens of L. pusilla were found in the Fort Payne Formation in this study. The miospore assemblage from the Fort Payne Formation in the western part of south-central Kentucky yielded an assemblage that is low-diversity and low-abundance. The samples are dominated by high percentages of amorphous organic matter (AOM), and the only identifiable spore species from this part of the Fort Payne Formation are Convolutispora vermiformis, Rotapspora fracta, and Knoxisporites sp. A (Figure 10). This low-abundance, low-diversity miospore assemblage, when combined with the assemblage recovered by Horowitz et al. (1979), indicates the Fort Payne Formation in this part of the study area is lower Visean.
Figure 10. Palynological occurrences in the western half of south-central Kentucky. The black dots represent samples collected.
The miospores from the Fort Payne Formation were few in number, associated with high amounts of amorphous organic matter (AOM), and much darker in coloration than any other spores collected for this study. This ‘darker-color’ may be a result of some thermal maturation and may indicate that the carbonate dominated Fort Payne Formation has spent time in the ‘oil window’. More research is needed to define the detailed thermal history of these rocks and to determine whether any more hydrocarbons can be developed from this unit.

North-central Kentucky and southeastern Indiana.

The outcrops in north-central Kentucky and southeastern Indiana are the westernmost exposures of the Borden Delta in the study area. These exposures include the New Providence Shale and the Kenwood Siltstone, including the classic section at Finley Hill, the Millport Knob section at the intersection of Indiana State Route 135 and Delany Port Road; and the Waldrip locality along the shores of Monroe County Reservoir outside Bloomington, Indiana. Other small isolated outcrops in the area between Louisville, Kentucky, and Bloomington, Indiana, were also visited. Primarily, the succession of Borden rocks in this part of the study area were deposited during consecutive periods of sea-level rise and fall. Evidence of these sea level fluctuations will be discussed in the next chapter (Chapter 5). Detailed descriptions of all the sections from this part of the study area can be found in Appendix A. The miospore biostratigraphy and biostratigraphic correlations in this part of the study area are quite
complex due to differing age associations between different floral and faunal occurrences of North America and Europe.

The lowermost Osagean rocks southeastern Indiana and north-central Kentucky belong to the New Providence Shale, whose age has been the topic of much debate age since its original description by Borden (1874). Springer (1911), Conkin (1957), Rexroad and Scott (1964), and Kammer (1985) have all proposed different ages for the New Providence Shale, ranging in age from middle Tournaisian to early Visean, based on crinoids, brachiopods, and conodonts. Equivalent strata of this age in the Mississippian type area range from the Fern Glen Formation to the Keokuk Limestone.

The New Providence Shale in northwestern Kentucky and southeastern Indiana yielded a fairly low-abundance palynofloral assemblage. The lowest samples of the New Providence Shale contain *Schopfites claviger*, which, as discussed previously, is an index fossil for the CM (*Schopfites claviger – Auroraspora macra*) Biozone in western Europe (Figure 11). *Schopfites claviger* has a shorter range in Europe (uppermost Tournaisian to middle Visean) than in North America (uppermost Tournaisian to lower Namurian; Neves & Belt, 1970). The miospore assemblage of the New Providence Shale also contains specimens of *Calamospora microrugosa*, *Cristatisporites menendezii*, *Grandispora corunata*, and several species of *Vallatisporites*. *Schopfites claviger* disappears in the upper part of the New Providence Shale and does not reappear until higher in the section (Spickert Knob Formation). The Kenwood Siltstone did not yield any diagnostic miospores, but it did contain a high amount of amorphous organic matter (AOM).
Stratigraphically overlying the New Providence Shale and the Kenwood Siltstone is the Spickert Knob Formation. The Millport Knob section along Indiana State Route 135 is probably the best exposure of the Spickert Knob Formation in the study area. This locality includes the Spickert Knob Formation (Carwood and Locust Point Members) and the Edwardsville Formation, including an excellent exposure of the Floyds Knob Bed. The miospore assemblage in this part of the study area is closely related to the CM (S. claviger – A. macra) Biozone. The only caveat is that the zone species, S. claviger, occurs sparingly throughout the succession. Specimens of this zonal fossil occur in the basal two samples of the Spickert Knob Formation (Locust Point Member) and disappears in the middle part of the section, only to reappear briefly near the top of the Spickert Knob Formation (Carwood Member). This short-ranged appearance / disappearance of S. claviger makes a true correlation with the western European biozones difficult.

The base of the exposure at Millport Knob is located within the lower part of the Locust Point Member (Spickert Knob Formation). Palynomorph samples were taken at nine intervals throughout the section. Miospores from samples in the Spickert Knob Formation are abundant and diverse (Figure 11). The miospore assemblage is dominated by species of Vallatisporites, with specimens of Punctatisporites minitus, Retusotriletes famenensis, and Retusotriletes planus also abundant. The samples throughout the section contain specimens of Schopfites claviger, however it is not present in all samples. The other zone-defining species, Auroraspora macra, is also present throughout the section, but are less abundant than S. claviger. Common species in the Millport Knob section
Figure 11. Miospore biostratigraphy of southeastern and south-central Indiana. (Dashed line indicates zone species not collected). The black dots represent samples collected.
also include specimens of *Spelaeotriletes pretiosus*, *Baculatisporites fisticulus*, *Raistrickia corynoges*, and *Plicatispora quasilabrata*. The Carwood Member, which is the upper member of the Spickert Knob Formation, contains most of the microflora visible in the lower part of the formation, but the abundances of *Grandispora* and *Cristatisporites menendezii* increase.

Near the top of the Millport Knob section, the Floyds Knob Bed is well exposed. The Floyds Knob Bed at Millport Knob is a resistant, silt-rich limestone, which is easily distinguishable in outcrop and represents the base of the Edwardsville Formation. The microflora present in the Floyds Knob Bed is similar to the assemblage in the underlying Spickert Knob Formation (Figure 11). The primary difference is that the sample in the base of the Floyds Knob Bed contains several specimens of *Lycospora pusilla*. The first appearance of *L. pusilla* marks the base of the Pu (*pusilla*) Biozone, which correlates with the base of the Visean series (Vn1) in Europe. Although the exact age of the top of the CM Biozone is not known, Phillips and Clayton (1980) assigned the CM-Pu zonal boundary on Clare Island, in the west of Ireland, slightly below the Tournaisian-Visean boundary. At Millport Knob, the Edwardsville Formation contains a very similar microflora to the underlying assemblage in the Spickert Knob Formation, including species of *Calamospora*, *Punctatisporites*, *Baculatisporites*, and *Gorgoniospora*, and the stratigraphically most important species *Lycospora pusilla*.

The disappearance and reappearance *S. claviger* in the samples throughout the section makes a true correlation with the CM Biozone of western Europe difficult. Based on the Millport Knob spores, the Spickert Knob Formation is no older than Tn3c,
however it is probably much younger. The first occurrence of *Lycospora pusilla* in the Floyds Knob Bed demonstrates a lower Visean (Vn1) age, representative of the Pu Biozone.

The first occurrence of *L. pusilla* in the Floyds Knob Bed (Edwardsville Formation) further confounds the biostratigraphic problem of the Borden rocks in Indiana. The New Providence Shale in northern Kentucky-southeastern Indiana previously has been assigned a lower Keokuk Limestone-equivalent age (Visean), using several different faunal assemblages including crinoids.

Coleman (1991) defined three miospore assemblages for the Borden Delta succession in Indiana. According to Coleman (1991), the *S. claviger* Assemblage occurs in the lower part of the New Providence Shale, the *Tumulispora* sp. B Assemblage occurs in the upper New Providence Shale and the lower part of the Spickert Knob Formation, and the *Tricardisporites* sp. A – *Dictylotriletes* sp. B Assemblage is present in the rocks of the upper Spickert Knob and Edwardsville Formations. Each of these miospore assemblages is defined by first occurrence data. In the lower part of the Indiana section (*S. claviger* Assemblage), *S. claviger* is prominent. Stratigraphically higher in the New Providence Shale, *S. claviger* disappeared and did not reappear in her samples. Samples in the present study from the Spickert Knob Formation; however, did contain specimens of *Schopfites claviger*. Although the author did not recover all the zonal species in this section of the Borden Delta, the three assemblages assigned by Coleman (1991) will be used; however slightly modified.
According to the miospores in north-central Kentucky and southeastern Indiana, the succession encompassing the New Providence Shale, Kenwood Siltstone, Spickett Knob Formation, and Edwardsville Formation cannot be correlated to the traditional miospore zones of western Europe. The assemblages proposed by Coleman (1991) are only directly applicable to the classification of the Borden rocks in southeastern Indiana. Thus, the miospores in the western part of the study area do not correlate exactly with the previously defined miospore zones defined by Higgs et al. (1988) of western Europe.

The discrepancy in this correlation may be a result of several reasons. Index taxa are missing and the assemblage composition is slightly different than in western Europe, suggesting the possibility of terrestrial provincialism during the Early Mississippian. The miospores could also differ in this area due to the fact that the streams carrying sediments and miospores into this part of the study area were part of a different drainage basin, populated by a different floral assemblage. Although the Borden Delta in the eastern and south-central part of the study area was fed by streams draining the Appalachian Highlands in the east, it is possible the Borden Delta in the western part of the study area were draining a part of the Canadian Shield, which may have contained a slightly different macrofloral assemblage. It is also possible that the sedimentology and eustatic behavior was a factor in sediment and miospore dispersal.

**Stratigraphic Summary.**

The Borden Formation in the study area exhibits a diverse and abundant miospore flora. The rocks in northeastern Kentucky contain an assemblage characteristic of the PC
Biozone. The PC Biozone is coeval with the *Gnathodus typicus* and *Polygnathus communis corina* (European) conodont zones. The Borden Delta rocks in northeastern Kentucky are at least Tn3b equivalent, or middle Burlington.

The eastern part of south-central Kentucky, primarily the thick exposure in Pulaski County State Park, contains the boundary between the PC Biozone and the CM Biozone. This boundary coincides with the boundary between Tn3b and Tn3c, with the CM Biozone being strictly Tn3c. These uppermost Tournaisian rocks are coeval with the *anchorlais – latus* Conodont Zone, and the upper Burlington. The western part of south-central Kentucky is dominated by the Fort Payne Formation, which is equivalent to the Keokuk in the Mississippi Valley sections; however the base, referred to in the text as the “Maury Shale”, represents the Kinderhookian and the lower part of the Osagean, mostly Burlington and pre-Burlington equivalents.

The exposures in north-central Kentucky and southeastern Indiana contain the youngest rocks in the study area. The basal deposits of the Borden Delta in this part of the study area is represented by the New Providence Shale. The lower part of the New Providence Shale is correlative with the CM Biozone, however *S. claviger* is not consistent throughout the succession. The upper part of the New Providence Shale does not contain any specimens of *S. claviger*. Specimens of *Schopfites claviger* reappear in the Spickert Knob Formation, making it at least Tn3c, or uppermost Tournaisian in age. Therefore based on index taxa from several other faunal groups, the New Providence Shale is considered lowermost Visean. The Spickert Knob Formation miospore assemblage is not analogous with the previously established miospore biozones either;
however, specimens of *S. claviger* appear at several interval throughout the Spickert Knob Formation. The Floyds Knob Bed, stratigraphically above the Spickert Knob Formation, yields the first occurrence of *Lycospora pusilla*. The first occurrence of *L. pusilla* is coeval with the basal Visean (Vn1a). Crinoid-based ages also indicate that the New Providence Shale in this area is Visean (Vn1) in age. This interval containing the New Providence Shale through the Floyds Knob Bed needs a detailed multi-faunal and floral biostratigraphic analysis in order to gain a complete understanding of the facies and age relations in this area. This report agrees with Coleman (1991) in her assignment of three ‘Assemblages’ throughout the Lower Mississippian sequence in this part of the study area. An alphabetical list of taxa and the sample localities at which they occur can be found in Appendix B.
CHAPTER 5

SEDIMENTOLOGY, GLACIO-EUSTASY, 
AND SEQUENCE STRATIGRAPHY

The Borden Delta in the eastern part of North America represents some of the 
only clastic deposition during the Osagean (Early Mississippian) (Figure 2). Most of 
North America during the Osagean was dominated by carbonate deposition. Today, we 
see the remnants of these carbonate environments as the Redwall Limestone of the Grand 
Canyon, the Chappel Limestone of west Texas, the Madison Limestone of the 
northwestern North America, and the Mississippian stratotype sections of the Mississippi 
River Valley. The Antler Orogeny was active in the western part of the North America, 
resulting in some flysch deposition. The eastern part of North America was home to the 
newly formed Acadian Highlands. It was the erosion, transport, and deposition of these 
Acadian sediments that caused the progradation and migration of the Borden Delta 
through the study area.
Tectonics and Sedimentation.

The sedimentologic history of the Borden Delta has been the subject of much debate since the Borden Formation was originally described by Cummings (1922). The idea of tectonic control is questioned by the author of this report due to the fact that the Early Mississippian was a time of relative tectonic quiescence. The most widely accepted model was proposed by Ettensohn and Pashin (1993) (Figure 12). Ettensohn and Pashin (1993) described four tectophases for the Acadian Orogeny. The first tectophase ranged from the Emsian to the Eifelian; the second tectophase ranged from the Eifelian to the early Givetian; the third tectophase ranged from the late Givetian to the Famennian; and the fourth and final tectophase spanned from the Famennian into the early Mississippian. The flexural model for the final Acadian tectophase includes a newly emplaced load in the Acadian Highlands in the east (Ettensohn and Pashin, 1993). This emplacement caused the formation of a flexural moat (foreland basin) and the distal migration of the peripheral bulge. The flexural moat produced an anoxic environment, depositing the black shale (Sunbury Shale) deposited below the pycnocline. Later during the Kinderhookian – Osagean, as the final Acadian tectophase waned, a relaxation phase became prominent. During this relaxation phase, the subsidence of the flexural moat ceased, and the weathering of the Acadian Highlands resulted in the deposition and progradation of the sediments of the Borden Delta. During the Osagean-Meramecian, the peripheral bulge began migrating back toward the source (eastward), shallowing the
Figure 12. Final tectophase and relaxation phase for the deposition of the Lower Mississippian rocks of eastern North America. (modified from Ettensohn and Pashin, 1993)
water, producing carbonates such as the Floyds Knob Bed and part of the Fort Payne Formation. Although this model is generally accepted, the current report will propose additional factors effecting the deposition of the Borden Delta.

**Basin Morphology and Sedimentation.**

Historically, the Borden Delta is thought to have been deposited in a classic foreland basin-filling setting. The basin-filling succession in this area includes deltaic bottomset, foreset, and topset beds, prograding from east to west across the study area. This report will describe in detail the depositional architecture and the changes in basin-floor topography across the research area, which results in different stratal packages from east to west (from Kentucky to Indiana).

Beaumont et al. (1988) described the architecture of sediment in the basin of the study area using isopachs of sediment thickness. Beaumont et al. (1988) used a computer model to estimate load emplacement and load removal, along with subsequent sediment accumulation within the basins (Michigan and Illinois). Each isopach map produced by Beaumont et al. (1988) for the Michigan and Illinois Basins was calculated by taking into account the size of the load emplaced and the size of the unconformity produced with the onset of the ‘relaxation phase’. As illustrated in Figure 13, isopachs during the Osagean and the Meramecian show evidence of a non-positive structure in the area of the Cincinnati Arch. This part of the study area was fairly flat, and unaffected by subsidence. South of the Cincinnati Arch, the study area deepens to the south and the east, into Tennessee and Georgia, which was believed to be connected with the deep ocean. This
Figure 13. Isopach map for the Osagean – Meramecian of eastern North America. (modified from Beaumont et al., 1989)
area exhibits a shelf with a recognizable shelf break, resulting in pronounced clinoform development.

Topographically, the western part of the study area is part of the eastern edge of the Illinois Basin. The basin floor topography in the Illinois Basin is different than the southern and eastern part of the study area due to the existence of a ramp, rather than an area with a clear shelf-break. The angle of slope also differed between the two areas. The eastern and southern part of the study area had a slope of approximately 2-3 degrees on the foresets of the Borden Delta (Peterson and Kepferle, 1970). In contrast, the Illinois Basin had a slope of approximately 0.5 degrees (Ahmad, 2000), and it was a topographic basin rather than a stratigraphic basin, with a ramp on the eastern flank. The sediment response and stratal geometries in the western part of the study area (Illinois Basin) are markedly different than in the eastern part of the study area, primarily due to the different basin geometries.

New Views on Sedimentation Controls.

As previously discussed, the factors traditionally thought to control the deposition and geometry of the Borden Delta are tectonic (Ettensohn and Pashin; 1993) (Figure 12). The purpose of the following discussion is to propose new, global factors (climatic and eustatic) that may also have played a major role in the deposition of the Borden Delta sediments in the eastern part of North America during the earliest Carboniferous (Osagean; Tournaisian-Visean).
**Stable Isotope Patterns.**

Stable isotopes, primarily $\delta^{13}$C and $\delta^{18}$O, can be used to identify ancient climatic patterns. Fluctuations in carbon isotopes are proxy indicators for rates of organic matter burial and paleo-atmospheric conditions. Positive shifts in $\delta^{13}$C are characteristic of cooler climates, resulting from an increase in the burial of organic matter or an increase in silicate weathering. Positive shifts in $\delta^{18}$O also indicate a period of cooling.

Saltzman et al. (2000) and Mii et al. (1999) indicated the presence of a positive $\delta^{13}$C excursion that occurred slightly below the Kinderhookian-Osagean boundary. The excursion, as great as +7.1‰ in the Arrow Canyon section of Nevada (Saltzman et al., 2000), is one of the largest during the Paleozoic (Figure 14). Saltzman et al. (2000) also reported a positive $\delta^{13}$C excursion from sections in Iowa and Belgium. As seen in Figure 15, Mii et al. (1999) also reported $\delta^{13}$C and $\delta^{18}$O curves for the Carboniferous of North America. Bruckschen and Vezier (1997) used brachiopod shells to obtain similar curve for carbon and oxygen isotopes from Europe (Figure 16). The fact that both carbon and oxygen stable isotopes exhibit a positive excursion at the same level in the rock record at different locations suggest the presence of a more global, possibly glacial, event.

**Glacial Evidence.**

The best direct evidence for a Lower Carboniferous glacial event is the tillites that are described from the Lower Carboniferous of several areas in Gondwana, including the Pimento Basin (Brazil), the Amazonas Basin (Brazil), and the Chaco-Paraná Basin (Argentina) (Caputo and Crowell, 1985). These glacial deposits are all believed to be
Figure 14. Carbon stable isotope excursion for the Joana Limestone in Arrow Canyon, Nevada. (modified from Saltzman et al., 2000)
Figure 15. Carbon and oxygen stable isotope curves for the Carboniferous of North America. (from Mii et al., 1999)
Figure 16. Carbon and oxygen isotopes for the Lower Carboniferous of western Europe, based on brachiopods. (modified from Bruckschen and Vezier, 1997)
Visean in age. However, the best evidence of a Tournaisian glacial event may be in northern Argentina and Bolivia. Strata of Early Carboniferous (Tournaisian) age are found in the southern Subandean Zone and the Altiplano area in the Andes to the west (Figure 17). In the Subandean Zone, from the Peru-Bolivia border south through Santa Cruz into northern Argentina, two formations contain glacial strata, the Ituacua Formation and the Tumpambi Formation. The Ituacua Formation is 50 m of purple and gray diamictites that are laterally associated with quartz sandstone, red and gray shale, and sandy shale (Reyes, 1972). The clastics of the Ituacua Formation were interpreted to have been deposited between topographic highs, during a glacially induced sea level rise. The diamictites are glaciogenic, and the other clastics are interpreted as glacial outwash and moraine deposits. Based on palynomorphs, the Ituacua Formation is middle Tournaisian in age, occurring in the Leiozonotriletes Zone (Reyes, 1972). Overlying the Ituacua Formation is the Tupambi Formation, which is composed of sandstones, shales, and diamictite-bearing siltstones. The Tupambi Formation sits directly on Devonian strata where the Ituacua Formation is absent. This succession (Ituacua and Tupambi Formations) is believed to be Tournaisian in age based on the palynomorphs, primarily miospores.

The Lake Titicaca Area also has important deposits pointing to the presence of a Tournaisian glaciation. Reyes (1972) reported that the Cumaná Formation on the Copacobana Penninsula (Bolivia) is composed of cross-bedded kaolinitic sandstones, greenish-gray sandy and shaly-siltstones, carbonaceous shales, and basal diamictites. The thickness of the basal diamictites in as much as 86 m. The basal diamictite, known
Figure 17. Carboniferous stratigraphy of western South America; including glacial deposits within the Itacua and Cumana Formations. (modified from Reyes, 1972 & Caputo and Crowell, 1985)
as the Calamarca Tillite (Figure 17), is a true glacial deposit. The basal part of this tillite contains red and white granite, gneiss, and quartz clasts up to 50 cm in width, all containing obvious striations. This part of the Cumamá Formation has been dated as Tournaisian using palynomorphs.

The duration of Late Paleozoic glaciations has been a topic of debate. Crowell (1978) suggested the Late Paleozoic glaciations had durations of approximately 95 million years, lasting from the Early Carboniferous to the Middle Permian. Caputo and Crowell (1985) suggested the Late Paleozoic glaciation lasted about 90 million years, ranging from the Tournaisian to the Kazanian. These reports both place the beginning of the Late Paleozoic glaciations in the Tournaisian (Early Mississippian).

The glaciation that produced the diamicrites and tillites in parts of Gondwana may have been the cause for the sea-level drop associated with the $\delta^{13}$C excursion discussion above. The Early Carboniferous glaciation was not widespread, however it was large enough to have a global impact. Although the exact size of the Tournaisian glaciations is not known, some inferences can be made. Crowley et al. (1991) reported that the Permo-Carboniferous ice event covered an area of approximately $13 \times 10^6$ square kilometers. A glaciation of this size would have dropped sea level by about 70 m, and with erosion, the sea level drop could have been as large as 100-120 m. Tournaisian glaciations were probably not as large, however a total drop of 50 m to 70 m could have resulted in exposure of the shelf and bypassing of sediments to deeper water. González (1990) proposed a model for the ice extent in South America during the early and middle Carboniferous. This model suggested that the ice covered the area of the Protocordillera,
just to the east of the Calingasta – Uspallata Basin. In these distal parts of this basin, González (1990) suggested the ice sheet was in contact with the marine environment, producing an extensive floating ice shelf and an iceberg zone. In contrast, Caputo and Crowell (1985) suggested migration paths for the glacial centers across Gondwana throughout the Paleozoic. This model suggests that the glacial center was to the west of the Brazilian shield during the Devonian – Carboniferous transition.

**Carboniferous Waters and Climate.**

As discussed above, the Early Carboniferous (Mississippian) exhibits a pattern of glacial and interglacial periods. Bruckschen and Vezier (1997) reported the beginning of glaciations at the base of the Tournaisian, and the δ¹⁸O values fluctuate through the Late Visean (Figure 16). According to Bruckschen and Vezier (1997), the δ¹⁸O fluctuations during this 26.5 million year period are on a 10⁶ year time scale. Several factors can control the global fluctuations of the oxygen cycle on this time scale. Bruckschen and Vezier (1997) suggested that the change in δ¹⁸O during the Tournaisian could have been caused by hydrothermal activity. Although there may have been hydrothermal activity in the Ouachita Region during the Tournaisian, the isotopic exchange between seawater and the lithosphere would take place on the 10⁷ – 10⁸ year time scale. Neither ambient temperature of seawater nor the natural change in the δ¹⁸O can be solely responsible for the fluctuations in the Tournaisian and Visean. However, a combination of both could produce changes on a 10⁶ year time scale. These two factors can be achieved by a glacial
event, and as previously mentioned, there are glacial deposits of Tournaisian age in Gondwana.

Combining the glacial evidence with the isotopic and stratigraphic data, it seems quite likely that Lower Mississippian deposits, both in the study area and several localities globally, record a glacio-eustatic fingerprint.

GENERAL SEDIMENTOLOGY AND SEQUENCE STRATIGRAPHY

Sequence stratigraphy is an integrative tool used to correlate genetically related sedimentary successions bounded at the top and base by unconformities or their correlative conformities. The idea of depositional sequences had its origin in the early 1960’s. Sloss (1963) subdivided the sedimentary record of the North American craton into six major sequences ranging from late Precambrian to the present (Figure 18). An individual Sloss sequence is defined as a lithostratigraphic unit greater than the group or supergroup, bounded by unconformities, and traceable across large distances, such as the interior craton of North America (Sloss, 1963). The rocks in the study area are included in the Kaskaskia Sequence of Sloss (1963). The original definition of the Kaskaskia Sequence encompassed rocks from the upper Lower Devonian to the uppermost Mississippian. In 1977, Vail et al. refined the concept of the depositional sequence. Vail et al. (1977), all former students of Sloss at Northwestern University, defined the sequence as a group of genetically related strata bound at the base and top by unconformities or their correlative conformities.
Figure 18. Sequences of the cratonic interior of North America; known as ‘Sloss Sequences’.
(modified from Sloss, 1963)
Vail et al. (1991) recognized five different orders of sequences based on time. A first order sequence occurs with a cyclicity of >50 million years. The first order sequence typically occurs on a 300 million year time scale and is also known as a megasequence. The Phanerozoic is divided into two megasequences (Haq et al., 1988). The second order sequence has a cyclicity of 5-50 million years and is known as a supersequence, and chronologically, has the closest correlation to a Sloss sequence. Vail et al. (1991) defined the third order sequence that as one with a cyclicity of 0.5-5 million years. The third order sequence is the fundamental building block of sequence stratigraphy, because third order cycles are observable in outcrops and in subsurface data. Third order cycles can be defined by distinct stacking patterns. These stacking patterns include lowstand, transgressive, and highstand system tract. Fourth order sequences occur with a cyclicity of 100,000 to 500,000 years and contain the same stacking patterns as in the third order sequence. However, the stacking patterns of the fourth order sequences create the individual systems tracts of the third order sequence. The fifth order sequence of Vail et al. (1991) occurs on the scale of 10,000 to 100,000 years and is primarily controlled by the Earth’s orbital forces (also known as Milankovitch forces), such as obliquity and precession.

This report defines the existence of four third order sequences (Vail et al., 1991) within the Lower Mississippian (Osagean; Tournaisian-Visean) of Kentucky and Indiana. The sequences identifiable in the study area are the Vanceburg Sequence in northeastern and south-central Kentucky, the Cumberland Sequence in south-central Kentucky, and
the New Providence and Millport Knob sequences in north-central Kentucky and southeastern Indiana.

Based on the lithologies, depositional histories, eustatic interpretations, and sequence stratigraphy, the study area has been divided into three Primary Depositional Centers (PDC-I, PDC-II, and PDC-III) (Figure 19). Each Primary Depositional Center has an internally consistent succession that is different from the successions in the other two PDC’s. Each Primary Depositional Center also has a characteristic sequence stratigraphic framework. Areas exist between the Primary Depositional Centers that have not been analyzed. Future study will provide a detailed understanding of the depositional history of the small areas where the three PDC’s converge. A composite chart showing the relationships between the three primary depositional centers, sea level, sequence stratigraphic relations, and the miospore biostratigraphy can be seen in Figure 20.

*Primary Depositional Center I.*

The succession of rocks in northeastern Kentucky, which includes the Farmers Member, the Nancy Member, the Cowbell Member, and the Nada Member (ascending order) comprise Primary Depositional Center I (PDC-I). Outcrops associated with PDC-I including the outcrops along the AA Highway in northeastern Kentucky, the exposures of the Cowbell along Kentucky State Route 9, the exposures of Cowbell and Nada sediments near Frenchberg, Kentucky, and all the outcrops around the Morehead, Kentucky area. Most of the Borden rocks in PDC-I was deposited during the lowstand
Figure 19. Locations of the Primary Depositional Centers in the study area.
Figure 20. Composite diagram showing eustatic and chronostratigraphic relationships between the three primary depositional centers.
systems tract of the Vanceburg Sequence; however the Nada Member was deposited
during the transgressive system tract.

*Primary Depositional Center II.*

The Borden Delta rocks in PDC-II are different from the Borden exposures in
PDC-I. The exposures assigned to PDC-II include the stratotype of the Nancy Member,
located in Pulaski County State Park, the exposures of the Fort Payne Formation located
around the Lake Cumberland Region, and various other individual outcrops around
Burkesville, Kentucky. These rocks have been divided into eastern and western
exposures by the Borden front. Sequence stratigraphically, the Borden rocks in PDC-II
reflect deposition of two 3rd order sequences. The Nancy Member is the only
representative of the Vanceburg Sequence to reach the distal parts of the basin in PDC-II.
The Fort Payne Formation and Muldraugh Formation represent rocks deposited during
the Cumberland Sequence. The Fort Payne Formation, located in the western part of
PDC-II, represents the transgressive systems tract of the Cumberland Sequence. This
transgression is interpreted to be the result of the early Visean sea level rise. The
Muldraugh Member, which can be observed overlying the Nancy Member in Pulaski
County State Park, is the highstand systems tract of the Cumberland Sequence and is also
the shallow water equivalent of the Fort Payne Formation.
Primary Depositional Center III.

The westernmost exposures within the study area have been assigned to Primary Depositional Center III. Outcrops assigned to PDC-III are located in north-central Kentucky and southeastern Indiana. Some of these exposures include the classic Button Mold Knob locality, the exposures of the New Providence Shale in the Brooks County Stone Quarry, the succession at Millport Knob, and the classic Waldrip locality outside of Bloomington, Indiana. Sequence stratigraphically, the rocks in PDC-III represent two 3rd order sequences, the New Providence Sequence and the Millport Knob Sequence. The only systems tract of the New Providence Sequence that can be observed is the transgressive systems tract, which is represented by the New Providence Shale. The overlying Millport Knob Sequence is represented by the lowstand deposits of the Kenwood Siltstone, the transgressive deposits of the Spickert Knob Formation, and the highstand deposits of the Edwardsville Formation. A classic maximum flooding zone can be observed in PDC-III. This deposit is known as the Floyds Knob Bed, and it separates the transgressive systems tract from the highstand systems tract in the part of PDC-III.

North-central Kentucky, Primary Depositional Center - I

The Borden Delta succession in north-central Kentucky is dominated by fine-grained clastic deposits. The rocks in the Borden Delta in this part of the study area are divided into (in ascending order) the Farmers Member (including the Henley Bed), the
Nancy Member, the Cowbell Member, and the Nada Member (Figure 21). This succession represents the bottomset, foreset, and topset beds of the Borden Delta.

The Farmers Member represents the initial clastic deposition of the Borden Delta. The lower part of the Farmers Member contains the Henley Bed. The Henley Bed directly overlies the Sunbury Shale (Kinderhookian) in the eastern part of the study area. As the peripheral bulge began to migrate back toward the source (Ettensohn and Pashin, 1993), the anoxic waters of the Sunbury Shale gave way to the oxic waters of the Henley Bed. The Henley Bed has been interpreted to be the deep basinal deposits located on the basin floor in front of the prograding Borden Delta. Near the end of Henley Bed (S. *isosticha* Zone) deposition and the close of the Kinderhookian, there was a sea level drop, which resulted in a forced regression. Thus, the forced regression is located within the Henley Bed.

A regression can form as a result of two conditions. Under one condition, the shoreline will migrate basinward during a sea level rise. Although the sea level is rising, the sediment input exceeds the available accommodation space, and the shoreline migrates basinward. Under the other condition, the shoreline migrates basinward as a direct result of sea-level fall. This type of regression is known as a forced regression (Posamentier et al., 1992). As the sea level dropped during the late Kinderhookian (S. *isosticha* Zone), possibly as a result of glaciations in Gondwana, the highstand deposits of the Henley Bed dropped below the shelf break, resulting in a forced regression. The sea level drop below shelf break not only resulted in a forced regression but also caused sediment bypassing that deposited the stacked turbidites of the Farmers Member.
Figure 21. Basic stratigraphic succession in Primary Depositional Center I; northeastern Kentucky.
According to Bryan (1983), the stacked turbidites of the Farmers Member in PDC-I are submarine fan complexes. Several fans were identified on geophysical logs in northeastern Kentucky and western West Virginia, including the larger Grayson Lake and Arabia Fans. These turbidites are believed to have been deposited by unchannelized flows due to the undisturbed surface of the Sunbury Shale. The Farmers Member is composed of coarse, silt-rich, stacked turbidites separated by thin pelagic shales, representative principally of the T_c, T_d, and T_e Bouma layers (Bouma, 1962) (Figure 22). Bouma division A (T_a) is deposited rapidly, creating a massive, graded bed. This lowermost division represents the upper flow regime. Bouma division B (T_b) is characterized by plane parallel laminae also deposited under upper plane bed conditions. Bouma division C (T_c) is deposited during the upper part of the lower flow regime and is characterized by ripples or convolute laminae. Bouma division D (T_d) is deposited during the lower flow regime and is characterized by an upper zone of thinly-bedded, parallel laminae. Bouma division E (T_e) represents pelagic sedimentation deposited between turbidites. In the Farmers turbidites, the lower flow regime is dominant due to the distal location and detachment from the toe of the slope and the fact the shelf slope was not excessively steep.

The relationship between the Farmers Member and the underlying Henley Bed is that of a middle fan and lower fan facies respectively (Figure 23). Walker’s (1978) model for submarine fans divided a fan complex into the upper fan, middle fan, and lower fan environments. The Henley Bed represents the lower fan, dominated by pelagic deposition interbedded with a few turbidites. The Farmers Member is considered to
Figure 22. Ideal turbidite sequence as classified by Bouma (1962). (modified from Bouma 1962)
Figure 23. Relationship of the Farmers Member and the Henley Bed superimposed on submarine fan model from Walker (1978).
represent the middle fan environment. The middle fan is composed of stacked turbidites deposited as suprafan lobes. Along Kentucky Highway 546 in northeastern Kentucky, three to four lobe progradations (or migrations) are present. Each fan progradation is characterized by a coarsening upward sequence, with the sand to shale ratio increasing upward.

Sequence stratigraphically, the rocks of the Borden Delta in PDC-I (northeastern Kentucky) are part of the Vanceburg Sequence. The Vanceburg Sequence is the oldest of the four 3rd order sequences in the study area. It is named for the exposures of the Borden Delta and part of the Vanceburg Sequence in northeastern Kentucky, near the town of Vanceburg. {This sequence and all sequences herein were named using the procedures for establishing unconformity-bounded units (p. 49-50) from the International Stratigraphic Guide, 1994.} The unconformity that marks the base of the Vanceburg Sequence (within the Henley Bed) resulted from the forced regression associated with the sea level drop at the end of the Kinderhookian, which is attributed to glaciations in Gondwana. As sea level dropped below the shelf, massive sediment bypass occurred. These sediments, represented by the Farmers Member, were deposited in the basin as a basin floor fan complex (Figure 24). A basin floor fan (bf) complex is an area of siliciclastic-dominated deposits that are detached from the toe of the slope and deposited during relative sea-level fall (Van Wagoner et al., 1990). According to Posamentier and Allen (1993), the term ‘basin-floor fan’ simply refers to a fan-shaped body of sediment that occurs on the basin floor and does not carry any implications for sedimentation or position in a depositional sequence. However, in the case of the Farmers Member in
VANCEBURG SEQUENCE
PDC-I  Northeastern Kentucky

Type 1 Sequence Boundary
(Kinderhookian-Osagean boundary, within Hemley Bed)

Figure 24. Vanceburg Sequence showing LST & TST deposits of Borden Delta northeastern Kentucky.
northeastern Kentucky, the basin-floor fan complex defines the base of a 3rd order sequence, therefore it does have depositional implications.

Stratigraphically above the Farmers Member in PDC-I is the Nancy Member. The Nancy Member is composed of gray shales interbedded with thin, continuous turbidites. The basal contact of the Nancy Member is gradational with the underlying Farmers Member. The Farmers/Nancy transition zone contains sedimentological characteristics of both the Farmers Member and Nancy Member. As the progradation of the Borden Delta continued, the Nancy Member was deposited above the Farmers Member, and it is geographically more widespread than the Farmers Member. The Nancy Member was deposited at the toe-of-the-slope. These toe-of-the-slope deposits are dominated by shales. The finer grains are dominant in the Nancy Member because the massive amounts of direct sediment bypass witnessed in the Farmers Member had slowed. Under ideal conditions (steady state sea-level), the lower Nancy Member received the finest clastics of the Borden Delta due to the distal location on the toe-of-the-slope. Overall, the Nancy Member coarsens upward, and the percentage of turbidites decreases upward. This overall coarsening upward sequence of the Nancy Member is a result of deltaic progradation. The thin turbidites within the Nancy Member were transported into the basin from the shelf to the east. The Nancy Member of the Borden Formation represents the bottomset beds of the Borden Delta.

Within the Vanceburg Sequence, the Nancy Member is comparable to a slope-fan deposit (Figure 24). According to Van Wagoner et al. (1990), the classic slope-fan deposit is the portion of the lowstand systems tract represented by the deposition of
turbidites and debris flows located at the toe of the slope during relative sea-level fall. The slope-fan deposit should downlap onto the basin floor fan. This downlapping surface is difficult to recognize in the rock record due to the distal location within the basin, the lack of laterally continuous exposures, and transitional nature of the Farmers-Nancy contact. The Farmers-Nancy transition zone contains characteristics of both members. The shale percentages increase from the Farmers Member into the transition zone, while the frequency of the turbidites decreases. The Farmers-Nancy transition zone, defined as the zone containing characteristics of both units, is approximately 2.5 meters thick but varies locally.

As the progradation and migration of the Borden Delta continued, the Cowbell Member was deposited directly on the Nancy Member. The Cowbell Member in northeastern Kentucky is composed of gray, fine to medium siltstones. These siltstone layers are representative of the foreset beds of the Borden Delta. Cross-bedding is present throughout the Cowbell Member in northeastern Kentucky. The Cowbell Member thickens to the northeast, where it reaches a maximum thickness along the Ohio River (Mason, 1981), and it subsequently thins to the southwest. Northeastern Kentucky is the only part of the study area where the Cowbell Member is present. Just as in the Farmers-Nancy contact zone, the basal contact between the Cowbell Member and the underlying Nancy Member is gradational. Again, this gradational contact is a result of the prograding nature of the deltaic complex and the time-transgressive nature of the boundaries. The upper contact of the Cowbell Member with the Nada Member is also gradational, but to a lesser degree. The foreset beds of the Borden Delta (Cowbell
Member) are interfingered with the topset deposits that are represented by the Nada Member. Distinct contrasting lithologic characteristics make this contact more identifiable than the others.

Sequence stratigraphically, the Cowbell Member in northeastern Kentucky (PDC-I) is comparable with a lowstand prograding wedge (Figure 24). The classic lowstand prograding wedge forms during the later part of the lowstand systems tract and is characterized by progradational (or aggradational) parasequences. The basal contact of the lowstand prograding wedge should downlap onto the slope-fan deposit. Slight downlapping surfaces between the Cowbell and Nancy Members are present along Kentucky State Route 546 at the Griffen Hollow section. The Cowbell Member in northeastern Kentucky represent the delta front facies of the Borden Delta, basinward of the shelf break.

The Nada Member is the youngest Borden Delta deposit in northeastern Kentucky. The Nada Member is composed of gray to light brown argillaceous shale interbedded with discontinuous carbonate and silt-rich lenses. Glauconite and phosphate are present throughout the Nada Member but are most common near its base. The Nada Member can be locally very fossiliferous, especially in carbonate lenses (Li, 2000). The fauna includes high abundances of brachiopods, bryozoans, crinoids, and rugose corals. This delta top (Nada Member) covered a large area of the shelf with shallow, well-oxygenated water, during a sea level rise. The carbonate lenses in the Nada Member may be attributed to the lack of siliciclastic input; however they are probably tempestites. As paleo-storms moved across the shelf, the sediment was churned into the water column,
leading to the formation of the thin carbonate lenses. The slow rate of sedimentation can also be inferred by the presence of glauconite and phosphate throughout the Nada succession. Glauconite is an iron-silicate that forms in areas of low sedimentation in the presence of organic matter. Primary glauconite is formed by alternation of other minerals that occur at the sediment-water interface or at shallow depths (Boggs, 1987). The upper contact of the Nada succession is marked by an unconformable surface. The Renfro Member unconformably overlies the Nada Member and was not deposited until the early to middle Visean. The Renfro Member was deposited during the sea-level rise that accompanied the Tournaissian – Visean boundary. Most importantly, the unconformity separating the Nada Member from the Renfro Member represents Borden Delta abandonment in northeastern Kentucky.

Sequence stratigraphically, the Nada Member is analogous with the delta top, indicative of relatively shallow water marine deposits. The Nada Member represents the early stages of the transgressive systems tract (Vanceburg Sequence) (Figure 24). The presence of glauconite throughout the Nada Member in northeastern Kentucky is indicative of slow sedimentation. The upper contact of the Nada Member (with the overlying Renfro Member) is marked by a distinct disconformity. The overlying Renfro Member is believed to be Visean in age, probably early Visean. The presence of glauconite and phosphate within the Nada Member indicates slow sedimentation and the presence of a disconformity at the top of the Nada Member suggests the abandonment of the Borden Delta in this part of the study area.
Most of the Borden Delta rocks in PDC-I (Farmers, Nancy, and Cowbell) were deposited during a sea level lowstand; however, the Nada Member was deposited during the subsequent transgression. The lowstand resulted from a forced regression associated with Gondwana glaciations. The basal beds of the Vanceburg Sequence are the basin floor fan deposits (Farmers Member), which were deposited during the initial sediment bypass. As the delta began to be deposited and prograde, the slope-fan (Nancy Member) was deposited directly above the basin floor fan. The massive siltstones of the lowstand prograding wedge (Cowbell Member) were deposited just past the break in the clinoform and finally, the deposition of the delta platform (Nada Member) marked the end of active clastic sedimentation and progradation, leading to delta abandonment in the area.

**Modern Sedimentological Analogs.**

The Borden Delta in the study area was analogous with the modern Orinoco Delta. In a model proposed by Galloway and Hobday (1983) (Figure 25), the Orinoco Delta is classified primarily wave-dominated, with a small influence from fluvial and tidal controls (Figure 26). A wave-dominated delta is characterized by a coarsening upward sequence, extensive sandy lobes, and no fluvial fingerprints (Bhattacharya and Walker, 1992). More recently, Hecht (1988) classified the Orinoco Delta into a more coastal drift-dominated delta in the northwest and a strongly tide-dominated delta in the southeast. This report will recognize the Orinoco Delta as a wave-dominated delta, following the classification of Galloway and Hobday (1983).
Figure 25. Classification of the three primary types of deltas.
(modified from Galloway and Hobday, 1983)
Figure 26. Schematic drawing of a wave dominated delta, analogous with the Borden Delta. (modified from Fisher and McGowen, 1969)
South-central Kentucky, Primary Depositional Center II

The Borden Delta in south-central Kentucky is dominated by distal fine-grained clastics of the Borden Delta, supplied from the east, and a mixed carbonate-siliciclastic succession associated with the Fort Payne carbonate ramp from the south (Figure 27). The Borden Delta deposits in south-central Kentucky are much thinner and overall finer-grained than the deposits in northeastern Kentucky. The only ‘true’ Borden Delta unit in both south-central Kentucky and northeastern Kentucky is the Nancy Member.

During the Kinderhookian (lowermost Mississippian), south-central Kentucky was dominated by the deposition of the “Maury Shale”. (The “Maury Shale” is not officially recognized by the Kentucky State Geological Survey as a stratigraphic unit, rather it is considered the basal beds of the Fort Payne Formation. However, this distinctive glauconite-rich unit will be referred to in the remainder of this report as the “Maury Shale”, as used in north-central Tennessee.) The “Maury Shale” is a condensed section, composed of tan to gray glauconite-rich, argillaceous shale averaging a thickness of about 30 cm. Phosphate nodules are also common throughout this unit. Based on conodont and miospore biostratigraphy, the sediment-starved conditions in the basin spanned the Kinderhookian, the lower part of the Osagean, and into the middle Osagean. These sediment-starved conditions may have been a result of a sea level highstand and the distal position of this area. Leslie et al. (1996) suggested the deposition of the “Maury Shale” in south-central Kentucky lasted approximately 17.5 million years, which would span the Kinderhookian and into the Osagean. The “Maury Shale” in south-central Kentucky, according to conodonts (Leslie et al., 1996), is no older than the lower
Figure 27. Basic stratigraphic succession for the eastern and western parts of Primary Depositional Center II; south-central Kentucky.
Siphonodella duplicata Zone and no younger than the anchoralis-latus Zone. According to the miospores, the “Maury Shale” in this part of the section is no older than the VI (verrucosus – incohatus) Biozone (Kinderhookian) and no younger than the PC (pretiosus – clavata) Biozone (lowermost Osagean).

The effects of the sea level drop (forced regression) at the Kinderhookian-Osagean boundary were not as evident in PDC-II (south-central Kentucky) as in PDC-I (northeastern Kentucky) because south-central Kentucky was located further from the source during the late Kinderhookian. The sea-level drop during the late Kinderhookian (S. isosticha Zone) is represented by continuous sedimentation in south-central Kentucky. The “Maury Shale” spans this interval with no lithologic change, and only a slightly identifiable change in the fauna (Leslie et al., 1996) and in the flora (this report). The sediment-starved conditions recorded by the “Maury Shale” in south-central Kentucky changed from being a result of highstand sediment starvation (pre-Kinderhookian highstand) to being a result of a distal location in the basin (post-Kinderhookian forced regression).

In the eastern part of PDC-II, the “Maury Shale” is overlain by the fine clastics of the distal Borden Delta. The Nancy Member overlies the “Maury Shale” and is at the base of the Mississippian succession in Pulaski County State Park. The Nancy Member in the eastern part of south-central Kentucky represents the distal toe-of-the-slope deposits or the bottomset deposits of the Borden Delta. The basal contact between the Nancy Member and the “Maury Shale” is very distinct. The Nancy Member is composed of gray, silty-shale, interbedded with continuous, fine-grained turbidites and is the only
fine-grained rocks of the Borden Formation in south-central Kentucky. The basin floor fans of the Farmers Member and the fine- to medium-grained siltstones of the Cowbell Member (deltaic foreset beds) are not present in south-central Kentucky. These coarser-grained deposits of the Borden Delta did not reach this far into the basin before the entire delta shifted to the northwest, toward the Illinois Basin. The upper contact between the Nancy Member and the Muldraugh Member is also very distinct. Although the Nancy Member coarsens upward, the much coarser, more resistant silty-carbonates of the Muldraugh Member are easy to recognize at the outcrop scale. The contact between these two units is also an unconformable surface. With the abandonment of the Borden Delta in south-central Kentucky, the deposition of the Fort Payne Formation (carbonate ramp) began to migrate into the study area from the southeast. The Fort Payne Formation is a mixed siliciclastic and carbonate unit that locally contains chert deposits, carbonate mud mounds, silty limestones, and fine siltstones. The Fort Payne Formation in PDC-II (south-central Kentucky) contains several different facies. Ausich and Meyer (1990) described siltstone facies, fossiliferous green shale, wackestone buildups, crinoidal packstone buildups, and sheetlike and channelform packstone facies. Three of the six facies described by Ausich and Meyer (1990) are autochthonous. The sheetlike and channelform packstone facies, and the siltstone facies are allochthonous. The sheetlike and channelform packstone facies contain graded beds, and the echinoderm assemblages are indicative of transport (Meyer, et al., 1989). The siltstone facies is believed to be the background sedimentation. The presence of dasycladacean algae denotes deposition in the photic zone (0 m – 60 m water depth).
The water depth during the deposition of the Fort Payne Formation has been debated. Chowns and Elkins (1974) and MacQuown and Perkins (1982) proposed a shallow-water origin for the Fort Payne Formation. These shallow-water depositional models were based on the interpretation that the geodes are anhydrite pseudomorphs and that other mineralogical characteristics reflect original, shallow-water depositional conditions.

In south-central Kentucky, the lower part of the Fort Payne Formation is believed to have been deposited in a deeper water setting. The evidence for this deposition includes: 1) an in situ fauna that displays very little evidence for current action, 2) symmetrical ecological zonation within an individual buildup, 3) the presence of Zoophycus and Helminthoidea (deep-water ichnofacies) and, 4) shallowing upward facies (Ausich and Meyer, 1990).

The shallow-water equivalent of the Fort Payne Formation is the Muldraugh Formation in the eastern part of PDC-II, which overlies the Nancy Member. A transgressive event should have yielded the time of maximum carbonate factory production across a shelf and this is the case with the Fort Payne-Muldraugh succession.

Within south-central Kentucky (PDC-II), there is a major change in depositional environments that occurs over a fairly small geographic area. The Lower Mississippian succession in Pulaski County State Park includes (in ascending order), the “Maury Shale”, the Nancy Member, and the Muldraugh Member, which is consistent throughout the eastern part of south-central Kentucky. In contrast, the succession in the western part of south-central Kentucky includes (in ascending order), the “Maury Shale” and the Fort
Payne Formation. This transition takes place between Nancy (KY) and Burkesville (KY), which are separated by about 80 km. In the eastern part of south–central Kentucky, the sediment-starved conditions resulting in “Maury Shale” deposition were terminated by the arrival of the distal deltaic deposits of the Nancy Member. The Borden Delta migration then shifted to a northwestern direction, abandoning the area of south-central Kentucky. Southwest of Pulaski County State Park the Nancy Member thins to zero (Peterson and Kepferle, 1970). While the sediments of the Nancy Member were being deposited in the eastern part of PDC-II, the western part of PDC-II was still undergoing sediment-starvation (“Maury Shale” deposition). The sediment-starved conditions of the “Maury Shale” were not terminated in the western part of south–central Kentucky until later during the Osagean (at least until the Visean). The Nancy Member in Pulaski County State Park has an age of Tn3c, based on miospore occurrences (CM Biozone). This area between the clastics in the east and the carbonates in the west reveals the location of the ‘Borden Front’ in this part of the state. The ‘Borden Front’ marks the distal-most deposition of Borden clastics in this area (Figure 28). Peterson and Kepferle (1970) initially reported the presence the Borden Delta front in the north-central part of Kentucky, between the towns of Bardstown and Elizabethtown, and it extends southeastward to Campbellsville (KY). The ‘Borden Front’ extends southeast from Campbellsville to near the town of Jabez, thus dividing the south-central Kentucky study area.

Sequence stratigraphically, the Mississippian rocks in south-central Kentucky (PDC-II) represent parts of three 3rd order sequences. Most of the condensed sediments of
Figure 28. Cross section in south-central Kentucky showing relations between the Borden Formation and the Ft. Payne Formation. (modified from Ausich and Meyer, 1990)
the underlying “Maury Shale” succession represent the highstand systems tract of an older, unnamed third order sequence and are present throughout all of south-central Kentucky. In the eastern part of PDC-II, the sediments of the Vanceburg Sequence sit conformably on top of the “Maury Shale”, and in the western part of PDC-II, the sediments of the Cumberland Sequence sit conformably on top of the “Maury Shale”. The exact relationships of these sediments are discussed below.

One of the best and most important exposures in south-central Kentucky is in Pulaski County State Park, approximately 8 km east of Nancy, Kentucky. The basal part of the section in Pulaski County State Park is the Devonian-aged Chattanooga Shale. The Chattanooga Shale is a black, thinly-bedded, fissile shale representing highstand, anoxic conditions during the late Devonian. Overlying the Chattanooga Shale in south-central Kentucky is the “Maury Shale”. The “Maury Shale” is a condensed section and is the lateral equivalent of the Sunbury Shale (northeastern Kentucky). Because the Kinderhookian-Osagean boundary is located within this condensed section, the “Maury Shale” is the correlative conformity marking the base of the Vanceburg Sequence in south-central Kentucky (Figure 29). Overlying the “Maury Shale” the eastern part of PDC-II is the Nancy Member. The Nancy Member here is comparable to a slope-fan deposit, as in northeastern Kentucky. The basin floor fan complex in PDC-I is not present in PDC-II because the Farmers Member turbidites (basin floor fan) did not reach the distal parts of the basin. The Nancy Member in south-central Kentucky exhibits characteristics of a classic slope-fan deposit, including an overall coarsening upward pattern and fine-grained clastics with turbidites or debris flows. Downlapping is not
CUMBERLAND & VANCEBURG SEQUENCES
PDC-II South-central Kentucky

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Figure 29. Cumberland and Vanceburg sequences in the western part of PDC-II, south-central Kentucky.
observed in the Nancy Member (onto the “Maury Shale”) due to the distal location of the deposition.

The upper boundary of the Nancy Member in south-central Kentucky is an unconformity. The unconformity marks both the abandonment of the Borden Delta in this part of the study area and the upper boundary of the Vanceburg Sequence in this area. Stratigraphically overlying the Nancy Member in the Pulaski County State Park is the Muldraugh Member of the Fort Payne Formation. The Muldraugh Member in south-central Kentucky is believed to be the shallow-water equivalent of the Fort Payne Formation, which represent the highstand deposits of the Cumberland Sequence. The Cumberland Sequence was deposited in south-central Kentucky after the abandonment of the siliciclastic deposition of the Borden Delta (Figure 29). The best exposures of the Cumberland Sequence are located along Highway 61, approximately 7.3 km south of State Route 90, near Burkesville, Kentucky, and along the shores of Lake Cumberland (Ausich and Meyer, 1990; Leslie et al., 1996).

The exposure south of Burkesville, Kentucky contains the Chattanooga Shale as in Pulaski County State Park, but this unit is overlain by the “Maury Shale” and the Fort Payne Formation respectively. As in the eastern part of south-central Kentucky, the “Maury Shale” records maximum flooding during highstand and spans the Kinderhookian-Osagean boundary. The sea-level drop in the late Kinderhookian and the associated unconformity are not recorded in the “Maury Shale” due to its distal, sediment-starved location. The base of the Vanceburg Sequence in the eastern part of south-central Kentucky is located within the condensed section, where it forms a
correlative conformity due to the continuous deposition of the “Maury Shale”. The “Maury Shale” (correlative conformity) also contains the base of the Cumberland Sequence in the western part of south-central Kentucky. At the end of the Kinderhookian, the highstand water of the “Maury Shale” regressed and ‘cleared-up’. These sediment-starved conditions continued in the basin due to the distal location into the Osagean. This sea level drop (lowstand systems tract) allowed the deposition of the mud-mounds found in the lower part of the Fort Payne Formation. Thus, the sediment-starvation situation lasted until the carbonates of the lower Fort Payne Formation were deposited. The transgressive systems tract of the Cumberland Sequence is represented by most of the Fort Payne Formation.

The shores of Lake Cumberland also yield exposures of the Fort Payne Formation (Cumberland Sequence). Most of the exposures of the Fort Payne Formation along the shores of Lake Cumberland are representative of the early transgressive systems tract of the Cumberland Sequence (Figure 29). Again, the mud-mounds were deposited on the basin floor, distal to the shelf break, and probably at the end of the highstand. The upper part of the Fort Payne Formation, along Highway 61 south, records the bulk of the sediments deposited during the transgressive systems tract (Cumberland Sequence). In the eastern part of PDC-II (Pulaski County State Park), the Nancy Member and the Muldraugh Member are separated by an unconformity that marks the boundary between the Vanceburg Sequence and then the Cumberland Sequence. The Muldraugh Member in south-central and central Kentucky represents the shallow-water equivalent (deposited on the shelf during highstand) of the Fort Payne Formation. The Muldraugh Member
represents the highstand systems tract of the Cumberland Sequence and was deposited aggradationally on the platform (on top of the Nancy Member in south-central Kentucky).

Khetani and Read (2002) interpreted sequence stratigraphic relations of the mixed carbonate-siliciclastic ramp from Kentucky, which includes the Fort Payne Formation-Salem Limestone interval (Upper Osagean-Lower Meramecian). This interval, according to the authors, contains four sequences. Khetani and Read (2002) defined the sequences as third order Vail sequences. The authors defined a supersequence using systems tract terminology, which according to definitions and interpretations from key references, including Vail et al. (1977) and Van Wagoner et al. (1988), is a 5 – 50 million year cycle. Supersequences are composed of sequences rather than systems tracts, hence the terminology used by Khetani and Read is misused. This report will interpret the Fort Payne Formation-Salem Limestone interval on the basis of the systems tracts proposed by Khetani and Read (2002).

Khetani and Read (2002) defined the Fort Payne Formation in Kentucky as part of two 3rd order depositional sequences (Sequence 1 & 2). The lower one-third of the Fort Payne Formation, the green-shale and mound facies, was deposited during the lowstand systems tract of Sequence 1, the oldest sequence described in the study. The transgressive systems tract of Sequence 1 is reflected on the shelf as the condensed, glauconite-rich zone, which may be comparable to the Floyds Knob Bed. The maximum flooding surface of the supersequence according to Khetani and Read (2002) is believed to be located at the top of the green-shale prone Fort Payne interval. It is not completely
clear; however, whether the remainder of the Fort Payne Formation proper, according to Khetani and Read (2002), was deposited during the transgressive systems tract (TST) of Sequence 2. The rest of the Fort Payne Formation-Salem Limestone succession comprises Sequence 3 and Sequence 4. Since these two sequences are younger than the primary strata in this report, they will not be discussed.

This report agrees with some observations of Khetani and Read (2002) and disagrees with others. The Fort Payne Formation in south-central Kentucky according to Khetani and Read (2002), was deposited during an episode spanning parts of two third order sequences. This report suggests that the Fort Payne Formation, which sits conformably on the “Maury Shale”, was deposited during the transgressive systems tract of the Cumberland Sequence. The lowstand systems tract of the Cumberland Sequence is not recognizable due to the sediment-starved conditions in the basin during this time interval. The highstand systems tract of the Cumberland Sequence is represented by the Muldraugh Member, which was deposited on top the Nancy Member in the eastern part of south-central Kentucky. Contrary to the description of Khetani and Read (2002), the current report has the entire Fort Payne Formation and the Muldraugh member as part of the same 3rd order sequence albeit different systems tracts.

Lasemi et al. (1998) discussed the sequence stratigraphy of the Fort Payne Formation and the Ullin Limestone succession in the Illinois Basin. The Fort Payne Formation in the Illinois Basin is much younger than the Fort Payne Formation south-central Kentucky. The transgressive systems tract and the highstand systems tract
assignment of the Fort Payne in the Illinois Basin are not applicable to the succession in south-central Kentucky.

**North-central Kentucky and southeastern Indiana, Primary Depositional Center III.**

The age-equivalent rocks discussed in this report from north – central Kentucky and southeastern Indiana are very important and sedimentologically quite complex. The Borden rocks in this area are the westernmost exposures in the study area and are also the youngest. In PDC-III, the rocks are represented by (in ascending order) the New Providence Shale, the Kenwood Siltstone (present locally), the Spickert Knob Formation, and the Edwardsville Formation, which includes the Floyds Knob Bed at its base (Figure 30). These deposits provide evidence of the continued progradation of the Borden Delta across the study area, however the controls on sedimentation and basin floor topography in this part of the study area were completely different from those in the eastern part of the study area.

As discussed previously, the basin morphology in northeastern and south-central Kentucky was controlled by the existence of the Cincinnati Arch, the Appalachian Basin, and the deeper-water deposits to the south. These structures gave rise to a well-defined shelf-slope depositional setting. The basin morphology in north-central Kentucky and southeastern Indiana was centered on the northeastern fringe of the Illinois Basin; and, as opposed to the previous two areas discussed (northeastern Kentucky and south – central Kentucky respectively), the stacking patterns reflect a ‘true ramp’ setting rather than a clinoform setting. The detailed sequence stratigraphic relations of the rocks in PDC-III will be discussed in detail below.
Figure 30. Basic stratigraphic succession for Primary Depositional Center III, southeastern and south-central Indiana.
The oldest Borden strata in PDC-III studied for this report is a thin, tan, glauconite-bearing, poorly consolidated shale that occurs between the New Albany Shale and the well-defined New Providence Shale. This unit is considered depositionally and temporally to be equivalent to the “Maury Shale”. (As in Kentucky, the Indiana Geological Survey does not recognize the Maury Shale as a formal lithologic unit. In discussing the stratigraphic relations in for PDC-III, the author will use “Maury Shale”.) Similar to PDC-II, the “Maury Shale” in this part of the study area is represented by a condensed section. The Brooks Crushed Stone Quarry, located on the southwestern side of the classic Button Mold Knob locality, exposes this unit. The New Albany Shale-“Maury Shale” contact in this part of the study area is believed to be a conformable surface. Once the highstand waters of the New Albany Shale retreated, the sediment-starvation conditions remained in the basin, leading to the formation of the “Maury Shale”. However, the upper part of the “Maury Shale” in this part of the study area contains a Type I sequence boundary (Vail sequence), albeit a correlative conformity. The formation of this correlative conformity resulted from the continued sediment-starvation in the basin even after sea level dropped, due to its distal location.

Overlying the “Maury Shale” in north-central Kentucky and southeastern Indiana (PDC-III) is the New Providence Shale. The New Providence Shale is interpreted to be a transgressive shale deposited during a sea level rise and marks the base of the Visean of Indiana. The New Providence Shale is composed of gray, locally fossiliferous shale. Paleontologically, the New Providence Shale contains two important faunas, 1) the Coral Ridge fauna and 2) the Button Mold Knob fauna. Kammer (1985) reported that the Coral
Ridge fauna, the older of the two, is dominated by deposit-feeding mollusks, which were believed to have thrived in a reduced-oxygen environment. The Button Mold Knob fauna represents a younger suspension-feeding community dominated by crinoids. The fauna thrived in an environment that was well oxygenated, and was very diverse. Kammer (1985) suggested that the occurrence of the Kenwood Siltstone stratigraphically above the New Providence Shale in outcrop leads to the existence of the Button Mold Knob fauna. In the areas of north-central Kentucky and southeastern Indiana where the New Providence Shale is not overlain by the Kenwood Siltstone, the New Providence Shale contains the Coral Ridge fauna. The Button Mold Knob fauna is present where the Kenwood Siltstone occurs, because the Kenwood Siltstone has been interpreted to represent a submarine canyon fill, and the Kenwood Siltstone canyon has been interpreted to have delivered well-oxygenated waters into the basin (Figure 31) (Kammer, 1985).

The Kenwood Siltstone was first suggested to have turbiditic origins by Kepferle (1967). This unit only appears locally, stratigraphically above the New Providence Shale, in areas surrounding Louisville, Kentucky. More recent interpretations of this unit suggest that it is a submarine canyon fill, which carried nutrient-rich waters into the basin (Kepferle, 1977). In this report, the Kenwood Siltstone is interpreted to be submarine channel fill. Since a submarine canyon can only be filled during highstand, and this report interprets the Kenwood Siltstone to have been deposited during a slight sea level fall, the descriptive terminology for the Kenwood Siltstone in this report will be submarine channel fill as opposed to submarine canyon fill. This new interpretation will
Figure 31. Three dimensional representation of the depositional relationship between the New Providence Shale and the overlying Kenwood Siltstone. (modified from Kammer, 1985)
still allow nutrients to be delivered to the basin, albeit during a slight regression. Although early Visean sea level was rising, the amount of sediment input exceeded the available accommodation space, allowing the transport of the sediments into the basin and oxygenation for the Button Mold Knob fauna.

The Kenwood Siltstone is a light-brown to tan moderately cemented fine to medium siltstone. A comparison of the Kenwood Siltstone and modern turbidite environments identifies several similarities including geometry, sedimentary structures, and petrology. However, the comparison of the Kenwood Siltstone and modern turbidites identifies two characteristics that are not common to both. First, the Kenwood Siltstone does not have an abundant assemblage of plant (mega) fossils as observed in modern turbidites; and second, the grain size and bed thicknesses of the Kenwood Siltstone are not similar to those of modern turbidites. The lack of plant (mega) fossils in the Kenwood Siltstone may be a result of the fact that globally there is a general lack of fossil plant assemblages. Worldwide, the Early Carboniferous (Tournaisian – early Visean) flora was dominated by small shrub-like plants and did not include large, shade-producing trees. The composition of these simple plants in the assemblages is not conducive to preservation. The problem with the grain size and bed thickness comparisons between the Kenwood Siltstone and modern turbidites may be due to the type of sediment, the conditions under which the sediments were deposited (ramp), and distance of transport prior to being incorporated into the turbidity flow.

Where the Kenwood Siltstone is present, it is overlain by the Spickert Knob Formation. Where it is not present, the Spickert Knob Formation directly overlies the
New Providence Shale. The Spickert Knob Formation is composed of gray, fine- to medium-grained siltstones, interbedded with discontinuous shales and carbonates. The Spickert Knob is composed of the Locust Point and Carwood Members (Rexroad and Lane, 1984). Siderite concretions occur in the Locust Point Member (lower Spickert Knob) but decrease in abundance upward. The Carwood Member (upper Spickert Knob) contains abundant geodes but no siderite concretions. Trace fossils are present throughout the Spickert Knob Formation. Stockdale (1939) originally described these ichnofossils as ‘curly worm marks’. These traces, known as *Helminthoida*, are present throughout the Carwood Member (upper member). Chaplin (1982) discussed trace fossils from the Borden Delta of northeastern Kentucky and reported *Helminthoida* was abundant in the shallow-water, delta platform environment. The occurrence of the ironstones and geodes and the fact the Spickert Knob Formation has a fairly constant if not slightly coarsening upward pattern, indicates a shallow-water, prograding, clastic-dominated deltaic environment.

The Spickert Knob Formation is a regressive clastic succession deposited during the sea level rise. During the sea level rise, the amount of sediment input into the Illinois Basin was greater than the available accommodation space, resulting in a basinward migration of the shoreline, indicating a regression. A similar situation occurs today along the Gulf Coast of North America. The Mississippi Delta is prograding, migrating, and filling the basin, resulting in a basinward shift of the shoreline, despite the fact that sea level is rising.
Around the Louisville, Kentucky area, the upper contact of the Spickert Knob Formation is a sharp and easily recognizable boundary with the Floyds Knob Bed. The Floyds Knob Bed is not present farther north, in central and northwestern Indiana (J. Droste, personal communication). The Floyds Knob Bed, originally described by Stockdale as the Floyds Knob Formation in 1929, is composed of varying lithologies throughout north – central Kentucky and Indiana. These lithologies include siltstones, oolite-dominated carbonates, crinoidal packstones, and silty limestones. The Floyds Knob Bed was deposited during the sea level rise during the early Visean, and may be comparable in age to the transgressive deposits of the Fort Payne Formation discussed earlier. The Floyds Knob Bed represents the maximum inundation during this depositional phase. The maximum inundation of the Floyds Knob Bed separates the underlying transgressive beds of the Spickert Knob Formation from the overlying aggradational (to slightly progradational) highstand beds of the Edwardsville Formation. The Edwardsville Formation is the youngest stratum analyzed in the study area. The Edwardsville Formation was deposited on the delta platform and is composed of varying lithologies. The Edwardsville Formation is a shale-rich succession of siltstones interbedded with discontinuous carbonate and silt-rich lenses. The Edwardsville Formation is locally very fossiliferous, especially with crinoids. Lane (1973), Ausich (1980), and Ausich, Kammer, and Lane (1979) described the paleoecology of the Edwardsville Formation in detail.

The overall sedimentology of the Borden Delta in PDC-III is quite different from the sedimentology described in PDC-I and PDC-II. In northeastern and south-central
Kentucky, the basin floor (Figure 13) morphology had a clear break in slope. The clinoform affected the distribution and deposition of Borden sediment yielding deltaic bottomset, foreset, and topset beds. These beds are in the Nancy, Cowbell, and Nada Members respectively. The Borden Delta in these two areas has a modern analogue in the Orinoco Delta of northeastern Colombia. The Orinoco Delta is a wave-dominated delta, with lesser influences from fluvial and tidal controls (Galloway and Hobday, 1983). Once the Borden sediments migrated to the western part of the study area, different controls affected the distribution and deposition of the sediments. In the western part of the study area, the basin floor morphology changed from the clinoform to a ramp. This ramp was located on the eastern fringe of the Illinois Basin, which is believed to have been a topographic basin, rather than a basin formed as a result of sediment loading. During most of the Paleozoic, the Illinois Basin was a broad, slowly subsiding embayment that was connected to the deep ocean to the south. The embayment is believed to have been a failed arm of the Reelfoot Rift-Rough Creek Graben that formed during the latest Precambrian (Kolata and Nelson, 1991). From the Latest Devonian through the Middle Mississippian, the rate of subsidence of the Illinois Basin increased dramatically. The evidence for this increase in subsidence is present in the rock record, starting with the deep-water New Albany Shale (Devonian) and the subsequent infilling of the Fort Payne-Ullin succession (Lasemi et al, 1998). It is the belief of this author that the basin floor topography, sedimentation rates and patterns, and sea level were all important factors controlling the depositional geometries of the Borden Delta in this part of the study area.
Ahmad (2000) and Droste (2002, personal communication) suggested that the basin floor in southeastern Indiana was a ‘true ramp’, rather than a clinoform. Ahmad (2000) further suggested that the setting was a ‘stepped ramp’, containing a proximal, medial, and distal ramp. This ‘stepped ramp’ may have been a result of autostepping, which is a process in which delta-front lobes migrate laterally and that shift landward, and subsequently do not cover the previously deposited lobes (Muto and Steel, 2001). (The concepts of autostepping, autobreak, and autoretreat and their application to the New Providence Shale will be discussed in greater detail in the sequence stratigraphy section below.)

Sequence stratigraphically, the stratal packages in north-central Kentucky and southeastern Indiana are different than any other regions in the study area. The rocks in this part of the study area (north-central Kentucky and southeastern Indiana) range in age from the Kinderhookian to Late Osagean (Tournisian-Visean). The succession in this part of the study area contains parts of three 3rd order sequences, (a small part of an unnamed sequence, the New Providence Sequence, and the Millport Knob Sequence Figure 32 and Figure 33).

As mentioned above, the youngest Kinderhookian-aged strata in the western part of the study area is the “Maury Shale”. Within the upper part of the “Maury Shale” there is a sequence boundary, marked by a correlative conformity. This correlative conformity is a result of a forced regression. The location of the depositional center and the associated basin floor topography dictated different sediment responses than in northeastern Kentucky and south-central Kentucky. The sediment-starved conditions of
NEW PROVIDENCE SEQUENCE
PDC-III – Southeastern & South-central Indiana

Figure 32. New Providence Sequence in NW Kentucky and SE and central Indiana, PDC-III
MILLPORT KNOB & NEW PROVIDENCE SEQUENCES
PDC-III – Southeastern & South-central Kentucky

Figure 33. Millport Knob and New Providence Sequences in NW Kentucky and SE and central Indiana, PDC-III.
this condensed section are a result of a highstand during the lower part of the “Maury Shale”; and once the sea level dropped during the middle Tournaisian (Kinderhookian-Osagean), the sediment-starved conditions resulted from the distal basin location. This sequence boundary also marks the base of the New Providence Sequence. The early Visean sea-level rise deposited the fine-grained New Providence Shale during a sea level rise. The New Providence Shale represents the transgressive systems tract of the New Providence Sequence. The New Providence Shale is a gray, fossiliferous shale interbedded with discontinuous carbonate lenses.

Ahmad (2000) described the New Providence Shale as a transgressive systems tract that was deposited on the northeastern fringe of the Illinois Basin as a stepped ramp. The formation of this stepped ramp is believed to be a result of autoretratret and autobreak. Muto and Steel (2002), in an article defending deposition and transport to the deep-sea during sea level fall and lowstand, defined autoretratret and autobreak. The theory of autoretratret states that, under conditions of sea level rise and constant sediment supply, the basinward advance of the shoreline stops and, subsequently, performs a landward retreat (autoretratret). Once the autoretratret begins and reaches a critical limit, the clinoform geometry is destroyed. This destructive process is referred to as the autobreak (Muto, 2001). Autosteepping is the process by which the lateral migration of the deltaic lobes and the subsequent landward shift of the shoreline fails to cover the older, previously deposited lobes. These processes are responsible for the formation of the forced ramp of the New Providence Shale. The rate of relative sea-level rise and the rate of sediment supply played an important role in the timing of the autoretratret and autobreak, although
factors such as width of the shelf and slope of the shelf are also extremely important. In the case of the New Providence Shale, the timing of the autoretreat and autobreak may have been nearly simultaneous. The ‘quickness’ of these processes, which may have increased the shelf width, may have been enhanced during the Lower Mississippian (Visean) in northeastern Kentucky and southeastern Indiana due to the increased subsidence of the Illinois Basin (Kolata and Nelson, 1991). Once these processes took place, the autostepping would have started, producing the stepped ramp conditions of the New Providence Shale. Along with increased subsidence, relative sea level was rising, and the sediment supply to the basin was constant, leading to the transgressive deposits of the New Providence Shale.

Locally, the top of the New Providence Shale is marked by a sharp contact with the Kenwood Siltstone. This surface is a Type II sequence boundary, in which sea level dropped but not enough to expose large portions of the shelf. The Kenwood Siltstone represents the lowstand systems tract of the Millport Knob Sequence. The hiatus between the two sequences (New Providence and Millport Knob) may have been relatively short; however it was enough to increase weathering and consequently increase the amount of sediment into the basin. Kepferle (1977) suggested that the Kenwood Siltstone was deposited as the result of turbidity currents (submarine channel fill). In order for these sediments to be transported into the basin, there had to have been an increase in weathering, either on the shelf of farther landward or a shift in the dispersal of existing sand. As a result of either scenario, an erosion surface was produced. The Kenwood Siltstone represents a regressive siltstone deposited during sea level lowstand.
The transgressive systems tract of the Millport Knob Sequence is marked by the deposition of the Spickert Knob Formation. This coarsening upward, basin-filling sequence is composed of gray, fine- to medium-grained siltstone interbedded with discontinuous carbonate lenses, especially near the top of the succession. Overlying the Spickert Knob Formation in this part of the study area is the Floyds Knob Bed. Sequence stratigraphically, the Floyds Knob Bed indicates the zone of maximum flooding. The maximum flooding zone is the boundary that separates the transgressive systems tract (retrograding) and the aggrading (or prograding) highstand systems tract, which in the Millport Knob Sequence is represented by the Edwardsville Formation. The Edwardsville Formation is a siltstone with interbedded carbonates, sandstones, and shales, and it is locally very fossiliferous. The Edwardsville Formation is bound at its base by the maximum flooding zone and at its top by the sequence boundary. It represents late stages of sea-level rise and the early stages of sea-level fall, which would account for the progradation of the Edwardsville sediments. The Edwardsville Formation contains the youngest strata of the Millport Knob Sequence and the youngest rocks in the study area.

Summary

Subsidence and glacio-eustasy were the primary factors controlling the deposition of the Borden Delta sediments across the study area. Factors such as sediment input, climate, and basin floor topography dictated stratal geometries and the accompanying bounding surfaces.
Across the study area, parts of four 3rd order depositional sequences are present. The oldest is the Vanceburg Sequence, which is located in PDC-I. Most of the Vanceburg Sequence exposures are indicative of the lowstand systems tract deposits, resulting from a forced regression during the early Osagean. This forced regression occurred as a result of glaciations in Gondwana. As sea level dropped near the Kinderhookian-Osagean boundary (S. isosticha Zone), sediment bypassing on the shelf resulted in deposition of the Farmers Member (basin floor fan) in PDC-I. As the Borden Delta began to prograde from east to west across the study area, the Nancy Member (slope-fan), and the Cowbell Member (lowstand prograding wedge) were deposited in the basin. The Nada Member (transgressive systems tract) was deposited above the Cowbell Member during sea level rise. The glauconite occurrence within the Nada Member and the occurrence of the unconformity at the top of Nada Member in PDC-I are indicative of the Borden Delta abandonment in this part of the study area.

In PDC-II, the base of the Vanceburg Sequence is represented by a correlative conformity formed by the underlying “Maury Shale”. The areas of sediment starvation and subsequent “Maury Shale” deposition resulted from of two conditions. One was the sediment-starvation due to sea level maximum flooding. The lower part of the “Maury Shale” formed in response to these conditions. The sea level drop (forced regression) at the Kinderhookian-Osagean boundary and the associated type-I sequence boundary were not recorded in the “Maury Shale” condensed section (correlative conformity). The upper part of the “Maury Shale” condensed section was also deposited during sediment-starvation, however, the sediment-starved conditions resulted from the distal basin
location. The slope-fan deposits (Vanceburg Sequence) finally reached the distal parts of the basin. This can be seen in the Pulaski County State Park section were the Nancy Member sits on top the “Maury Shale”. The Nancy Member sediments are the only true Borden Delta sediments to reach these distal basin localities in this region. As the Borden Delta continued to be active, the entire Borden Delta migrated to the northwest, towards the Illinois Basin. The abandoned area in PDC-II was taken over from carbonate deposition during the early Visean. The lower part of the Fort Payne Formation was deposited during a brief lowstand. During this time, the mud-mounds were formed. The transgression associated with the early Visean resulted in the deposition of the bulk of the Fort Payne Formation. The western part of PDC-II has the transgressive systems tract (Cumberland Sequence) deposits of the Fort Payne Formation sitting on top the “Maury Shale”. The sediment starved conditions of the “Maury Shale” in the western part of PDC-II may have been active for a slightly longer time than in the eastern part of PDC-II, but that warrants further study. The highstand systems tract of the Cumberland Sequence is represented by the Muldraugh Member, which can be observed on top of the Nancy Member in Pulaski County State Park.

In PDC-III, the “Maury Shale” is again present at the base of the section. The condensed and sediment-starved conditions of the “Maury Shale” may span a longer time than in PDC-II, but further study is needed. Overlying the “Maury Shale” in PDC-III is the New Providence Shale. The New Providence Shale represents the transgressive systems tract of the New Providence Sequence. The early Visean sea level rise resulted in the deposition of the New Providence Shale. A type-II sequence boundary is present at
the top of the New Providence Shale. Locally in PDC-III, the lowstand systems tract of
the overlying Millport Knob Sequence can be observed overlying the New Providence
Shale. These deposits are represented by the Kenwood Siltstone, which was transported
into the basin as a result of the slight sea level change associated with the type-II
sequence boundary. Where the Kenwood Siltstone is not present, the New Providence
Sequence is overlain by the transgressive systems tract deposits of the Millport Knob
Sequence. These deposits are represented by the Spickert Knob Formation, which is a
regressive siltstone deposited during sea level rise. Overlying the Spickert Knob
Formation in the southern part of PDC-III is the Floyds Knob Bed. The Floyds Knob
Bed is the maximum flooding zone of the Millport Knob Sequence. This maximum
flooding zone separates the underlying transgressive systems tract from the overlying
highstand systems tract, which is represented by the Edwardsville Formation. The rocks
of the Edwardsville Formation are the youngest rocks in the study area.
Microfloral Provinces.

Although the Lower Mississippian miospore assemblages from the Borden Delta are very useful stratigraphically, the biological affinities of all spores are not well known. Mississippian plant paleoecology is not well understood, with a few rare exceptions (i.e., Midland Valley Basin, Scotland).

Floral provincialism was an innovation of the Lower Carboniferous terrestrial realm. Microfloral provinces have been recognized in two different ways: as microfloral suites reflecting biogeography, and as palyno-regions reflecting both paleoclimatic and biogeographic differences. Differences in macrofloral assemblages were first noticed from compositional differences in the microfloral assemblages (miospores) in the Northern Hemisphere (Sullivan, 1965, 1967; Clayton, 1985).
Carboniferous miospore distribution and occurrences worldwide led Sullivan (1965) to propose three distinct spore suites for the Mississippian (Figure 34). The *Monilospora* Suite, the *Grandispora* Suite, and the Kazakhstan Suite.

The *Monilospora* Suite is primarily composed of specimens including *Convolutispora clavata, Tetraporina glabra, Densosporites bialatus, Lophozonotriletes appendices, and Monilospora moniloformis*. The suite was originally described by Playford (1962, 1963) from localities in Spitzbergen. Sites containing similar miospore assemblages have also been identified from western Russia (Luber and Waltz, 1938; Ischenko, 1956), northern Canada, western Canada (Hacquebard and Barass, 1957; Staplin, 1960), and northwestern Australia (Venkatachala, 1964).

The *Grandispora* Suite contains assemblages characterized by occurrences of *Triparites vetustus, Rotaspora knoxii, Densosporites capistratus, Grandispora spinosa, and Glomospora lucida*. The best-known localities for the *Grandispora* Suite are the United States mid-continent (Schemel, 1950; Hoffmeister et al., 1955) and Britian (Butterworth and Williams, 1958; Owens and Burgess, 1965). Various authors have also reported localities containing spores characteristic of the *Grandispora* Suite from northern Spain, Poland, and Turkey.

The Kazakhstan Suite is geographically smaller than the two suites discussed above, and the only known locality is in eastern Siberia. Spores of the Kazakhstan Suite include *Calamospora microrugosa, Punctatisporites mollis, Lycospora subtriquetra, and Vallatisporites ciliaris*. 

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Figure 34. Global miospore suites assigned by Sullivan.
(modified from Sullivan, 1967)
Sullivan (1967) reported two more detailed suites representing the Kinderhookian. The *Lophozonotriletes* Suite is indicative of Mississippian rocks in eastern Europe and western Asia and contains species of *Lophozonotriletes, Densosporites*, and *Triparites*. The *Vallatisporites* Suite, characterized by species of *Retusotriletes, Punctatisporites*, and *Raistrickia*, is indicative of Kinderhook-aged rocks in western Europe and eastern North America. The conclusions of this study are that the Lower Carboniferous (Tn2-Tn3) Borden Formation rocks reported here contain spores similar to the *Vallatisporites* Suite of Sullivan (1967), based primarily on paleogeography and the abundance of *Punctatisporites, Retusotriletes, and Raistrickia*. The fact that the suite of miospores from the Tournaisian (Tn2-Tn3) of the study area has very similar specimens is evidence to perhaps extend the *Vallatisporites* Suite of Sullivan (1967) from the Kinderhookian into the Osagean of eastern North America.

Van der Zwan (1981) established the use of palyno-regions for the Mississippian (Figure 35). Although the development of palynological differences was slow during the Tournaisian – Visean (Tn2-Vn1), three regions existed. The *Vallatisporites* Region, the *Lophozonotriletes* Region, and the *frustulentus* Region represent different paleoclimatic and geographic areas. The *Vallatisporites* Region is indicative of the dry, subtropical to tropical belt of South Euramerica, the *Lophozonotriletes* Region is representative of the tropical humid belt primarily of North Euramerica, and the *frustulentus* Region is indicative of the subtropical dry belt of Australia and Gondwana. The rocks studied in this report contain the characteristic species of the *Vallatosporites* Region. The *Vallatisporites* Region is not contemporaneous with the *Vallatisporites* Suite *sensu stricto*
Figure 35. Global palyno-regions assigned by Van der Zwan (1981).
(from Van der Zwan, 1981)
(Sullivan, 1967) discussed above. The *Vallatisporites* Region contains the characteristic species of *Vallatisporites vallatus*, *Grandispora echinata*, *Spelaeotriletes pretiosus*, *Baculatisporites fusiculus*, and *Crassispora trychera*.

The study area contains a similar microflora as the *Vallatisporites* Palyno-region of Van der Zwan (1981). The microfloral assemblage throughout the Borden Delta contains species of *Spelaeotriletes*, *Vallatisporites*, and *Grandispora*, with species of *Crassispora* and *Bacualtisporites* in the younger part of the delta.

**Paleoecological Interpretations.**

The Early Carboniferous was a time of many terrestrial innovations and changes. One of the more important innovations was the development of the first true terrestrial ecosystems. The Late Devonian landscape was dominated by *Archeopteris*, which formed dense shady forests, and *Rhacophyton*, a fern that dominated damp, lowland areas. The Frasnian – Famennian Event removed *Archeopteris* and *Rhacophyton* from the landscape (Bahensmeyer et al., 1992). The Tournaisian (Early Mississippian) landscape represented a transitional period between the massive shade producing forests of the Late Devonian and the massive coal-swamps of the Pennsylvanian (Bahensmeyer et al., 1992).

Based on the miospores collected and identified in this study, the Tournaisian landscape was dominated by marattiaceous ferns (tree-like ferns), sphenopsids, and other pteriophytes. Marattiaceous ferns are represented by specimens of *Punctatisporites* and *Retusotriletes* (Peppers, 1996). Most species of *Punctatisporites* and *Retusotriletes* are
simple, trilete, acamerate miospores, with prominent laesura extending one-half to three-quarters of the spore radius. The ambs are circular to subcircular and laevigate. These spores and related forms were dispersed as tetrahedral tetrads.

Sphenopsids are a class of pteridophytes with a segmented stalk and an arrangement of whorled leaves or sporangia. The only extant representative of the sphenopids is *Equisetum*. Pteridophytes are primitive vascular plants that reproduce by spores, including lycopsids, horsetails, scouring rushes, and ferns. In this study, specimens of *Calamospora* were representative of the sphenopsids (after Winslow, 1959).

Herbaceous lycopsids (non-woody lycopsids) were also prominent during the Lower Carboniferous. Lycopsids are pteridophytes with a dense arrangement of leaves spiraled around the stalk, with the spore producing organs situated at the base of the leaf. Club mosses are extant representatives of herbaceous lycopsids. In this study, individuals from the following genera are regarded as herbaceous lycopsids: *Cirratriradiates*, *Endosporites*, *Crassisporea*, and *Cristatisporites* (Peppers, 1996).

Specimens of *Vallatisporites* and *Verrucosisporites* are also counted due to their abundance in the rocks of the Borden Delta. Although not completely understood, these two genera are believed to have fern affinities. Not all Paleozoic miospore species have a known biological affinity; however, the representatives in this study are believed to represent a fair and somewhat concise cross-section of Early Mississippian plant life.

The oldest rocks in the study area, the Vanceburg Sequence, located in PDC-I, represented a macroflora composed of the following:
Marattiaceous ferns       57.5%  
Sphenopsids               21.4%  
Herbaceous lycopods      3.00%  
*Vallatisporites*         8.70%  
*Verrucosisporites*       6.10%  
Marine                    2.90%  

A graphic representation of these terrestrial relationships is in Figure 36. As these data indicates, after the Frasnian – Famennian Event the Early Mississippian landscape was dominated by fern-like plants. Miospores associated with marattaceous ferns (*Punctatisporites* and *Retusotriletes*) are clearly dominant. The great abundances of marattaceous fern spores in PDC-I indicates assignment to the “*Punctatisporites* Association”.

In south-central Indiana (PDC-III), the Millport Knob Sequence, sediments are much younger than those in northeastern Kentucky, and the microfloral assemblage has evidence of a slight change in the terrestrial flora.

Marattiaceous ferns       47.10%  
Sphenopsids               16.70%  
Herbaceous lycopods      2.40%  
*Vallatisporites*         31.20%  
*Verrucosisporites*       2.30%
Figure 36. Chart showing percentages of terrestrial flora throughout the Nancy Member Succession, PDC-I.
A graphic representation of these terrestrial relationships is seen in Figure 37. These younger Borden Delta sediments have a decrease in the marattiaceous ferns of approximately 10% and an increase of almost 40% in *Vallatisporites*. These changes indicate the ‘*Vallatisporites* Association’ for the outcrops in PDC-III. These changes in the terrestrial floral ecosystem could represent any number of factors including climate effects, floral evolution, or the response to niche space availability. Until the absolute biological affinities of Early Mississippian miospores are understood, the paleoecological interpretations will remain equivocal. Insufficient numbers for reliable feedback were obtainable from the areas of PDC-II in south-central Kentucky.

The fact that the miospore assemblage from the study area is not only abundant but also moderately diverse and that the lowermost Visean miospore assemblages (primarily the New Providence Shale and Spickert Knob Formation) from the study area do not match Visean assemblages from other locations (i.e. Gondwana), provides evidence for floral provincialism during the early Mississippian. A specific example involves the occurrence of *Lycospora pusilla*. Globally, the first occurrence of *L. pusilla* is correlative with the base of the Visean. In the study area, *L. pusilla* does not appear until much higher in the section. This discrepancy may be because representatives of the lycopods that produced *L. pusilla* did not migrate to this area until later in the Visean, possibly filling an open niche.
Figure 37. Chart showing the percentages of terrestrial flora throughout the Spickert Knob Formation, PDC-III.
GLOBAL CORRELATION

As discussed previously, the rocks of the Borden Delta contain miospore assemblages characteristic of the PC, CM, Pu Biozones, and three palynological assemblages; the *Schopfites claviger* Assemblage, the *Tumulispora* sp. B Assemblage, and the *Tricidarispores* sp A – *Dictylotriletes* sp B Assemblage. All the strata discussed from the study area are Osagean in age (North American Series). These Osagean rocks are equivalent to the upper Tournaisian and lower Visean of Europe (Courceyean and Chadian in Great Britian). In Belgium, the Osagean-aged rocks are equivalent to the Ivorian and Moliniacian (Tournaisian-Visean). A correlation chart of the global stages for the Lower Carboniferous can be found in Figure 38.

The PC, CM, and Pu Biozones were zones originally described from western Europe that can be used to classify and compare Lower Carboniferous occurrences globally (Figure 38). The PC Biozone (*Spleaeotriletes pretiosus – Raistrickia clavata*) is the oldest biozone of the Osagean. The base of this zone is defined by the first appearance of *S. pretiosus*. The CM Biozone (*Schopfites claviger – Auroraspora macra*)
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Figure 28: Chart showing the correlation of Fluvial/Tourmaline/Vesuvian rocks based on micropore occurrence.
is the next youngest zone in the study area, and is defined by the first appearance of *S. claviger*. The youngest zone in the study area is the Pu Biozone (*Lycospora pusilla*) and is defined by the first appearance of *L. pusilla*. The base of the Pu Biozone is considered the base of the Visean Series in Europe and in many other regions around the globe. However, in North America, the succession is different. The Borden Delta rocks in the study area are not younger than the Pu Biozone (Lower Visean).

**Great Britain.**

Great Britain is home to the most extensive research on Early Carboniferous (Mississippian) miospores. Neves et al. (1972) developed the first miospore biozonation for the British Isles. Since 1972, several papers on Lower Carboniferous miospores of Great Britain have been published, including several contributions from Clayton et al. and Higgs et al. throughout the 1980’s and 1990’s. Great Britain has rocks containing miospores of the PC biozone that are similar to those in northeastern and south-central Kentucky. The base of this zone is defined by the first appearance of *Spelaeotriletes pretiosus* and contains many diagnostic species including *Spelaeotriletes balteatus*, *Vallatisporites* sp., *Verrucosisporites nitidus*, and *Retusotriletes inhocatus*. The CM Biozone is immediately above the PC Biozone and represents the highest zone of the Tournaisian. Defined by the first appearance of *Schopfites claviger*, the CM Biozone also contains a number of diagnostic species, including *Cristatisporites menendezii*, *Puncatatisporites glaber*, and *Baculatisporites fusticulus*. These diagnostic species were recovered from the study area in Indiana and Kentucky and are also documented from
sections in the British Isles (Keegan, 1981; Higgs et al., 1988; Riley, 1993). The Pu Biozone is the youngest biozone in the study area and is defined by the first appearance of *Lycospora pusilla*. The base of the Pu Biozone in the British Isles is not as well defined as the previous two biozones, but a characterisitc miospore assemblage can be identified. The base of the Pu Biozone and the base of the Visean are not coeval on a global scale. Phillips and Clayton (1980) documented the first appearance of *L. pusilla* immediately below the early Visean limestone succession on Clare Island, Ireland. In northern England, foraminifera approximately 2 m above the first occurrence of *L. pusilla* are Chadian (= Late Osagean) in age. The base of the Pu Biozone and the base of the Visean Series in Great Britain are not equivalent, but more work has to be completed. In this study, the first occurrence of *L. pusilla* is in the Floyds Knob Bed, well above the base of the New Providence Shale, which is the base of the Visean. This discrepancy may be due to floral provincialism during the Lower Mississippian.

**North Africa.**

Tournaisian/Visean rocks have yielded miospores from various locations in across North Africa. The first well-documented work referring to Lower Carboniferous miospores was completed by Lanzoni and Magloire (1969) from the Grand Erg Occidental in Algeria. In this report, Lanzoni and Magloire (1969) defined three biozones and six subzones (M2-M7) for the Tournaisian and Visean from the Arhlad and Bahmer Formations. The Tournaisian is represented by the *Convolutispora* Biozone. Subzone M3 represents the uppermost Tournaisian and is believed to be the equivalent of
the PC and CM Biozones of Kentucky. The Visean is subdivided into the Monolete Spore 2874 Biozone and the *Densosporites – Verrucosisporites* Biozone. Subzone M4 represents the lowermost Visean (Monolete Spore 2874 Biozone) and is believed not to be present in the study area in this report. This absence is more than likely a result of floral provincialism during the Lower Mississippian, rather than an unconformity. Subzones M5 and M6 also seem to be missing from the succession in south-central Indiana. In North Africa, the first occurrence of *Lycospora pusilla* is not until the base of Subzone M7, in the upper *Densosporites – Verrucosisporites* Biozone.

In 1980, two important studies were published on the miospore biostratigraphy of North Africa. Attar et al. (1980) subdivided the Tournaisian and Visean of the Illizi Basin into three palynozones. The upper part of Palynozone III (Tournaisian) is believed to equivalent to the PC and CM Biozones in Kentucky. The basal Visean in Algeria is represented by the occurrence of Palynozone IV, however the first occurrence of *Lycospora pusilla* is not until the base of Palynozone V. Although the first occurrence of *L. pusilla* in the present study area is within the Floyds Knob Bed in south-central Indiana, Palynozone V is probably more correlative with the *S. claviger* Assemblage of Coleman (1991). Massa et al. (1980) divided the Tournaisian and Visean beds of the Rhadames Basin in Libya into four palynozones. The Tournaisian rocks of the Rhadames Basin are represented by Palynozone XII, which contains a similar assemblage to that of the PC and CM Biozones of Kentucky and Indiana. According to Massa et al. (1980), the Visean succession in Libya is marked by the base of Palynozone XIII, but the first occurrence of *Lycospora pusilla* is not until the base of Palynozone XV. The
Touraisian/Visean section in Libya contains two additional palynozones (biozones) than the Touraisian/Visean section in Kentucky and Indiana. Of all the global localities discussed in this report, North Africa probably is the most correlative with the study area.

Belgium.

Touraisian rocks of Belgium contain miospore zones comparable with those in the study area in Kentucky and Indiana. Higgs et al. (1992) reported on the palynostratigraphy of the Touraisian rocks in the Namur Synclinorium in West Flanders. The Orient Formation contains a spore assemblage with the characteristics of the PC Biozone (Higgs et al., 1992). Higgs *(personal communication, 2001)* reported that the PC Biozone is coeval with the Tn2 sub-series and is nowhere comparable to the Tn3. However, it is the belief of the author that the PC Biozone in Kentucky is at least Tn3 in age, due to the characteristics of the assemblage, the date of the underlying Sunbury Shale, and the date of the rocks across the study area.

Although miospores are present in the Touraisian – Visean transition of Belgium, the official biostratigraphic marker for the base of the Visean is the first appearance of *Eoparastaffella* (foram).

Germany.

In Germany, the Touraisian – Visean succession is somewhat similar to that in Kentucky and Indiana. The succession in Germany is termed the Rügen Zonal Scheme, proposed by Carson and Clayton (1997) and named after the succession on the Arctic
Island of Rügen, Germany. The basal Tournaisian miospore zone in Germany is the PC Biozone, defined by the first appearance of *Spelaeotriletes pretiosus*. Stratigraphically above the PC Biozone is the CM Biozone, which corresponds to the study area (Kentucky and Indiana) and the British Isles. The base of the CM Biozone in Germany is also based on the first occurrence of *Schopfites claviger*. In the present study area, the S. claviger Assemblage of Coleman (1991) is located directly above the CM Biozone. However, in the Rügen Zonal Scheme, directly above the CM Biozone is the *Gorgonispora multiplicabis – Convolutispora circumvallata* or MC Biozone. This biozone is based on the first appearance of *G. multiplicabis*. The presence of this zone indicates the transitional zone between the *Vallatisporites* Microflora of North America and western Europe from the *Lophozonotriletes* Microflora of eastern Europe (Burmann, 1975). The first appearance of *Lycospora pusilla* (Pu Biozone) occurs above the MC Biozone. In Germany, the Pu Biozone still represents the base of the Visean. Therefore, the Pu Biozone at Rügen (GER) may be closely analogous with the Pu Biozone of Indiana.

**Poland.**

In Poland, the Tournaisian-Visean succession of miospores differs markedly from the miospore succession in the study area. The basal Tournaisian succession in Poland is marked by the Cl Biozone. The Cl Biozone is marked by the first appearance of *Prolycospora claytonii*, which according to Avchimovitch and Turnau (1994) correlates with the base of the PC Biozone in western Europe and east-central North America. The
first appearance of *Spelaeotriletes pretiosus* (PC Biozone) has been reported to be both slightly younger and slightly older in several boreholes from Poland. However, the details of this boundary is beyond the scope of this paper.

In 1994, the Cl Biozone was subdivided into the “lower Cl Subzone” and the “upper Cl Subzone” by Avchimovitch and Turnau. The base of the “upper Cl Subzone” is defined by the first occurrence of *Schopfites claviger*. This definition makes this Polish biozone correlative with North America and the British Isles applicable. The difference between the CM Biozone and the “upper Cl Subzone” is in the total assemblage. The assemblage in Poland is defined by *S. claviger* and *G. multiplicabilis*, along with a high percentage of *Schopfites delicatus*.

Overlying the Cl Biozone in Poland is the Pu Biozone. The first appearance of *Lycospora pusilla* defines the base of this biozone and also defines the base of the Visean. This occurrence is coeval with the Pu Biozone in western Europe and probably with the *S. claviger* Assemblage in the study area.

Belarus.

The Tournaisian-Visean succession in Belarus is zoned quite differently than the succession in North America and the British Isles (Turnau et al., 1997). The basal Tournaisian biozone in Belarus (Pripyat Depression) is the *Colatisporites multisetus*- *Spelaeotriletes pretiosus*, or MP Biozone. The zone is defined by the first appearance of *S. pretiosus*, *C. multisetus*, and *P. claytonii* and is comparable to the base of the PC Biozone in the study area and the western Europe. The next youngest miospore zone in
Belarus is the RC (*Tumulispora rarituberculata – Schopfites claviger*) Biozone. The RC Biozone is defined by the first appearance of *Schopfites claviger*, which makes it coeval to the CM Biozone in east-central North America and western Europe. Characteristic assemblages of the RC Biozone are similar to the “upper Cl Subzone” of Poland, but *Tumulispora rarituberculata* and *Simonozonotriletes sublobatus* are present in high abundance. Overlying the RC Biozone in Belarus is the Pu Biozone, which is based on the first appearance of *Lycospora pusilla*. This occurrence marks the base of the Visean Series, and corresponds with the basal Visean (*S. claviger* Assemblage) in Indiana (North America) and the first appearance of *L. pusilla* in the British Isles.

**Turkey.**

Higgs, Finucane, and Tunbridge (2002) described the microfloras of the Upper Devonian and Lower Carboniferous rocks of Hakkari Province, southeastern Turkey. These Paleozoic rocks outcrop near the Iran and Iraq border. Higgs et al. (2002) described three palynomorph assemblages from the region: 1) *Verruciretusispora loboziakii* assemblage, 2) *Retispora lepidophyta* assemblage, and 3) *Spelaeotriletes pretiosus – Aratrisporites saharenxis* assemblage. The *Spelaeotriletes pretiosus – Aratrisporites saharenxis* assemblage is recorded from the Köprülü Formation and is believed to be equivalent to the PC Biozone of western Europe (Higgs et al., 1988). The *S. pretiosus – A. saharenxis* can also be correlated with Palynozone III from the Illizi Basin (Algeria) and the lower part of the Borden succession in Kentucky.
China.

The Tournaisian – Visean succession in China contains three miospore biozones defined by Gao (1985). The palynological succession in China was described from the Lower Carboniferous of Kansu Province. The basal Tournaisian miospore biozone is Zone II. This is based on the first appearance of *Hymenozonotriletes explanatus*. Zone II is believed to be correlative with the CM Biozone of east-central North America, which is coeval with the Tn3c, or latest Tournaisian. In the Kansu Province, Zone III is the next youngest miospore biozone. The base of Zone III is defined by the first appearance of *Lycospora pusilla* and, additionally, defines the base of the Visean. The base of the Visean in the study area is probably coeval with the *S. claviger* Assemblage of Coleman (1991), rather than the first appearance of *L. pusilla*, which is higher in the section. The microfloral assemblage indicates a composition similar to the *Lophozonotriletes* and *Monilospora* Microfloras in the British Isles and North America, as defined by Sullivan (1967).

Australia.

In Australia, the Tournaisian – Visean miospore assemblage is markedly different than the assemblage in the study area (Kentucky and Indiana) and the British Isles. Rocks of similar age to those in the present study area are present in several basins across Australia. The Bonaparte Gulf Basin in the north, the Canning Basin in the northwest, and the Drummond Basin in the east all contain rocks of Tournaisian – Visean age. Kemp et al. (1977) reviewed the palynological zonation of Australia and showed
evidence for the existence of one major microflora during the Tournaisian – Visean. The microflora, known as the *Granulatisporites frustulentus* Microflora, is subdivided into the *Grandispora spiculifera* Assemblage (Tournaisian) and the *Anapiculatisporites largus* Assemblage (Visean). The Canning Basin, the Drummond Basin, and the Bonaparte Gulf Basin all contain miospores of the *Grandispora spiculifera* Assemblage, which is upper Tournaisian in age. These rocks contain assemblages comparable to the PC and CM Biozones of east-central North America and western Europe. The base of the *Anapiculatisporites largus* Assemblage represents the lowermost Visean. The *A. largus* Assemblage is comparable to the Pu Biozone in the study area. The *Anapiculatisporites largus* Assemblage occurs in the Drummond and Bonaparte Gulf Basins, but this time is absent in the Canning Basin. There are no Carboniferous rocks younger than Tournaisian in the Canning Basin.

**Eastern Canada.**

In eastern Canada, especially in Nova Scotia and New Brunswick, miospore assemblages of Tournaisian – Visean age have been reported. The Horton, Windsor, and Canso Groups are the primary sections containing these assemblages. The miospores from the Horton Group, described by Hacquebard (1957) and Playford (1964), have assemblages comparable to the middle and late Tournaisian of western Europe and east-central North America. Miospore zones of eastern Canada were defined by Hacquebard (1972) and Utting (1980). The Horton Group contains four miospore zones. These zones are (in ascending order) the d, e, f, and g miospore zones. Utting [personal
communication with Clayton, 1983] reported *Schopfites claviger* from the Cheverie Formation. The Cheverie Formation is the uppermost formation of the Horton Group and is equal to the *Vallatisporites vallatus* – *Spelaeotriletes pretiosus*, or Miospore Zone g.

This miospore zone is comparable with the CM Biozone of the study area (Kentucky and Indiana). Thus, the underlying zone, Miospore Zone f (*Lophozonotriletes malevkensis* – *Reticulatisporites fimbriatus*), is believed to be somewhat comparable to the PC Biozone of the study area. An equivalent to the Pu Biozone, or lowermost Visean, is not represented in the rocks of western Canada.
CHAPTER 8

DISCUSSION AND CONCLUSIONS

Historically, the Borden Delta was thought to represent a classic example of a siliciclastic basin-filling succession, with sedimentation dynamics being controlled by tectonics. These tectonic controls included load emplacement and bulge migration, both away from and toward the sediment source (Ettensohn and Pashin, 1993). Because the Mississippian was supposed to have been a time of tectonic quiescence in most of North America, the factors controlling the regional sedimentation dynamics of the Borden Delta warranted further research. In this report, the Borden Delta rocks were reanalyzed using miospore biostratigraphy to gain a better understanding of the time-transgressive relationships of the lithologic boundaries. Along with the biostratigraphy, sequence stratigraphic and chemostratigraphic concepts were applied to gain a more detailed understanding of the factors affecting the deposition of the Borden Delta sediments.

The study area covers Borden outcrops from northeastern Kentucky to south-central Kentucky to southeastern Indiana. The rocks in these areas were classified into
three primary depositional centers. Primary depositional center I (PDC-I) covers the outcrops in northeastern Kentucky. Rocks in primary depositional center II (PDC-II) include all the outcrops around the Lake Cumberland area in south-central Kentucky. The outcrops in north-central Kentucky and southeastern Indiana, from the Louisville (KY) area to the Bloomington (IN) area, are assigned to primary depositional center III (PDC-III). All the strata in a given primary depositional center contain a similar succession of rocks, which are composed of characteristic depositional sequences (3rd order) and differ from the other primary depositional sequences.

Primary depositional center I encompasses all the Borden exposures in northeastern Kentucky. The Borden delta strata in PDC-I were deposited as part of the Vanceburg Sequence, which is the oldest 3rd order depositional sequence in the study. The base of the sequence is defined by the contact between the Kinderhookian and Osagean, which according to the miospores and conodonts, is in the upper one meter of the Henley Bed (basal Farmers Member). Just below the Kinderhookian – Osagean boundary, there is a massive $\delta^{13}C$ excursion (Saltzman et al., 2000; Mii et al., 1999), which is believed to have been produced by the increased weathering of carbonates, resulting from sea level drop. Recent research in Gondwana has revealed glacial deposits (Calamarca Tillite) of Tournaisian age (Lower Carboniferous). Further study indicates the stratigraphic level of these glacial deposits is coeval with the $\delta^{13}C$ excursion.

In PDC-I, the result of this sea level drop is the beginning of the deposition of the Borden Delta, and the Vanceburg Sequence. The Borden strata in PDC-I were deposited during sea level lowstand and transgressive conditions, composing the lowstand systems
tract and transgressive systems tract of the Vanceburg Sequence. The basal rocks of the Vanceburg Sequence are represented by the uppermost part of the Henley Bed, which is representative of sediment-starved conditions in the basin that formed during the initial sea level drop. The Farmers Member is composed of stacked thin-bedded turbidites, resulting from the sediment bypass during the sea level and is a true basin floor fan, the overlying Nancy Member is analogous with a slope fan, and is most widespread of all the lithologic members of the Borden Delta. The Cowbell Member represent the final stages of lowstand conditions. The Nada Member, which directly overlies the Cowbell Member and represent the youngest Borden rocks in PDC-I, was deposited during a sea level rise and subsequent delta abandonment in PDC-I.

Palynologically, the deltaic beds of the Borden Formation in PDC-I are extremely rich. The beds yield a microfloral assemblage that is comparable to the PC (pretiosus – clavata) Biozone of western Europe (Higgs et al., 1988). Analysis of the miospores, along with other faunal information, namely conodonts (Collinson et al., 1971) and ammonoids (Mason, 1981) has lead to an age assignment of early and middle Osagean, and Tn3b and possibly into the Tn3c, although this cannot be confirmed by miospores (European Series).

The Borden Formation in PDC-II (south-central Kentucky) is represented by a completely different succession of rocks. The lowermost Mississippian rocks in PDC-II are represented by the “Maury Shale”, a condensed section that spans the Kinderhookian and the lower part of the Osagean. The eastern part of PDC-II has the most distal deposits of ‘true’ Borden Delta rocks. The Nancy Member in PDC-II represents the
distal deposits of the Borden Delta during the middle Osagean (Tn3c). The Nancy Member in this part of the study area is representative of the distal slope fan sedimentation, which ended the sediment starved conditions of the underlying “Maury Shale” (Kinderhookian and early Osagean).

In the western part of PDC-II, the Kinderhookian – Osagean aged “Maury Shale” is also present; however, overlying this condensed unit is the carbonate-rich Fort Payne Formation. The Fort Payne Formation is a carbonate ramp that entered the study area from the southeast after the Borden Delta abandonment in the area. The shallow water equivalent of the Fort Payne Formation is the Muldraugh Member. This unit is present in the eastern part of PDC-II, overlying the Nancy Member. Between the towns of Nancy (KY) and Burkesville (KY) is the location of the Borden Front (Peterson and Kepferle, 1970). The Borden Front marks the boundary between the clastic Borden Delta being deposited from the northeast and the carbonate-rich Fort Payne being deposited from the south after the Borden Delta had migrated to the northwest.

Two 3rd order sequences are present in PDC-II. The Vanceburg Sequence is represented by the Nancy Member, which forms the slope fan and was deposited during the lowstand systems tract. The base of the Vanceburg Sequence in this part of the study area is within the “Maury Shale”, and is analogous with the Henley Bed in PDC-I. The top of the Vanceburg Sequence in the study area is marked by the unconformity present between the Nancy Member and the overlying Muldraugh Member.

The Cumberland Sequence is also present in PDC-II. This sequence is younger than the Vanceburg Sequence and was deposited after the Vanceburg Sequence
sediments had abandoned the area. The base of the Cumberland Sequence is within the condensed interval (“Maury Shale”) and is overlain by the Fort Payne Formation. The Fort Payne Formation is representative of the transgressive systems tract of the Cumberland Sequence. The shallow water equivalent (possibly highstand) of the Cumberland Sequence is the Muldraugh Member, visible overlying the Nancy Member in the eastern part of PDC-II.

Palynologically, the miospore succession in PDC-II is neither very abundant nor diverse; however, there is an important boundary present in the area. The “Maury Shale” contains very few miospores, and only a general biostratigraphic framework can be constructed based on miospores. The overlying Nancy Member contains a more diverse and more abundant miospore transition. Within the Nancy Member (sample 00JR8-6), precisely the upper half of the section, *Schopfites claviger* makes its first appearance. The appearance of this spore indicates the base of the CM (*claviger – macra*) Biozone. The CM Biozone is the youngest miospore biozone of the Tournaisian. More precisely, this biozone is coeval with the Tn3c (European sub-series) and the *anchoralis – latus* Conodont Zone. The stratotype of the Nancy Member contain the transition from the PC Biozone (Tn3b) to the CM Biozne (Tn3c).

The rocks in the western part of PDC-II are not very palyniferous. Several samples from the Fort Payne Formation yielded nothing but amorphous organic matter (AOM). The Muldraugh Member also yielded AOM. One sample from the upper part of the Fort Payne Formation did yield miospores. The assemblage was not very abundant or diverse but did contain specimens of Visean age.
Primary depositional center III is the most challenging part of the study area. Basin floor topography and floral provincialism are major factors in the geological history of this part of the study area. The succession of rocks in PDC-III were mostly deposited during the early Visean sea level rise, making them transgressive deposits. Two 3rd order sequences are represented by the strata in PDC-III. The oldest Mississippian deposit in PDC-III is the “Maury Shale”, which represents the maximum inundation of an unnamed, older sequence, and subsequently the base of the New Providence Sequence. The “Maury Shale” in this part of the study was probably under sediment starvation for a longer period of time than the basin in PDC-II, but more research is needed to determine the exact time discrepancy. Overlying the “Maury Shale” in PDC-III is the New Providence Shale, which was deposited during the Lower Visean sea level rise, probably resulting from the melting of Gondwanan ice. The New Providence Shale represents the transgressive systems tract of the New Providence Sequence. Locally, the New Providence Shale can be overlain by the Kenwood Siltstone, which represents brief lowstand deposits of the overlying Millport Knob Sequence. During this brief lowstand (Type II sequence boundary), sediments were transported into the basin (Kenwood Siltstone). The resulting sea level rise led to the deposition of the Spickert Knob Formation and the Edwardsville Formation, which represent the transgressive systems tract and the highstand systems tract respectively. The maximum flooding surface is present between the Spickert Knob Formation (TST) and the Edwardsville Formation (HST) and is represented by the Floyds Knob Bed. The basin was being filled during sea level rise, much like the Mississippi Delta today.
Palynologically, PDC-III is extremely complex. The rocks in PDC-III, for the most part, do not correlate with the previously described miospore biozones of western Europe. The Visean aged New Providence Shale should have *Lycopora pusilla* (Pu Biozone) present at the base; however, the assemblage does not have the characteristic features of any of the western European miospore biozones. The lower half of the New Providence Shale contains an assemblage similar to the CM Biozone, but not enough to make the correlation with western Europe. The lower part of the New Providence Shale does contain specimens of *S. claviger*. The upper half of the New Providence Shale is does not contain *S. claviger*. The assemblage is characterized by *Tumulispora* sp B. This species was not recovered by the author; however, this report will follow the classification of Coleman (1991). Coleman (1991) assigned the lower part of the New Providence Shale to the *Schopfites claviger* Assemblage and the upper part of the New Providence Shale to the middle Spickert Knob Formation to the *Tumulispora* sp. B Assemblage. The upper part of the Spickert Knob Formation was assigned to the *Tricardisporites* sp. A – *Dictylotriletes* sp. B Assemblage. This report agrees with the work of Coleman (1991) for the assignment and classification of these miospore assemblages. The basal Edwardsville Formation, specifically the Floyds Knob Bed, yields the first occurrence of *Lycospora pusilla*. This occurrence documents the base of the Pu Biozone. The Pu Biozone, at other locations globally, is coeval with the Visean; however, in the study area *L. pusilla* does not occur until much higher in the section. This discrepancy is regarded as a function of floral provincialism and provides clear evidence for the presence of floral provincialism during the Early Mississippian.
Conclusions.

With the objectives stated in the first chapter in mind, the conclusions to this study are listed below.

1) Miospores were used to construct a biostratigraphic framework for the Lower Mississippian Borden Delta. The miospore assemblages in this study covered parts of the three previously established biozones from western Europe and three assemblage zones, previously defined by Coleman (1991).

2) Sequence stratigraphic concepts were applied to the rocks of the Borden Delta. The Borden Delta in the study area (Kentucky and Indiana) contain parts of four 3rd order Vail sequences. Some of the interpretations do not necessarily agree with previous interpretations from previous authors for certain parts of the study area.

3) The glacial history of several Gondwana basins (presently South America) was researched. Several Tournaisian-aged diamictites were described in the literature; however, only one glacio-genic diamictite was discussed. The occurrence of the Calamarca Tillite is at a level that is correlative with the sea level drop identified in the study area and the associated chemostratigraphic fingerprints.

4) Glacio-eustatic signals can be identified in the study area (Kentucky and Indiana). The depositional response to the forced regression can be best observed in northeastern Kentucky, while the subsequent sea level rise can be
best observed in the younger Borden Delta deposits in north-central Kentucky and southeastern Indiana.

5) Using all the available data; including the miospore biostratigraphy, sequence stratigraphy, chemostratigraphic fingerprints, sedimentation patterns, and basin floor topography, a detailed spatial and temporal framework was produced for the Borden Delta in Kentucky and Indiana.
CHAPTER 9

SYSTEMATIC PALYNOLOGY

Many references were used in the construction of the systematics for this research. Although systematic classification of miospores is still debated, the ‘turma’ system of Potonié (1893) is the basis for the classification in this study. Eighteen plates illustrating specimens from this study can be seen in Appendix D. The distribution of stratigraphically important genera by locality is given in Appendix B, and the stratigraphic distribution of key taxa is given in Chapter 4. The coordinates for the figured specimens refer to American Scientific Products Micro-Locator slide.

Anteturma SPORITES H. Potonié, 1893

Turma TRILETES (Reinsch) Dettman, 1963

Suprasubturma ACAMERATITRILETES Neves & Owens, 1966

Subturma AZONOTRILETES (Luber) Dettman, 1963

Infraturma LAEVIGATI (Bennie & Kidston) R. Potonié, 1956

Genus CALAMOSPORA Schopf, Wilson & Bentall, 1944
Calamospora liquida Kosanke, 1950

Plate I, figure 1

Description. Amb round to sub-round, acamerate, and trilete, however trilete mark is not prominent. The exine is folded in the polar region, with additional folding distally in the equatorial region. Miospores are laevigate to slightly granulate.

Occurrence. PC - CM Biozones.

Calamospora microrugosa (Ibrahim, 1932)
Schopf, Wilson & Bentall, 1944

Plate I, figure 2

1932 Sporonites microrugosa Ibrahim in Potonié, Ibrahim & Loose p. 447, pl. 14, fig. 9.
1933 Laevigato – sporites microrugosus (Ibrahim). Ibrahim, p. 18, pl. 1, fig. 9.
1938 Azonotriletes microrugosus (Ibrahim). Waltz in Luber and Waltz, p. 10, pl. 1, fig. 1; pl. A, fig. 1.
1944 Calamospora microrugosus (Ibrahim). Schopf, Wilson & Bentall, p. 52

Description. Miospores acamerate and trilete, with an amb round to subround. Exine is heavily folded in the polar region. Spores of microrugosa are larger than the other species of Calamospora (72µm to 100µm).

Discussion. All the species of Calamospora, including C. liquida, C. pallida, C. microrugosa, and C. nigrata are heavily folded. One of the distinguishing characteristics is the size of the amb.
Occurrence.  PC - CM Biozones.

Genus PLICATISPORA Higgs, Clayton, and Keegan, 1988


Plate I, figure 3

1973 Cyclogranisporites sp. Warg & Traverse, pl. 1, fig. 11.
1975 Pulvinispora quasilabrata Higgs, p. 394, p. 1, figs. 5, 6, 8.
1988 Plicatispora quasilabrata Higgs, Clayton, and Keegan, pl. 1, figs. 11-12.

Description.  Miospores acamerate and trilete with sub-round to sub-triangular ambs with straight sides.  Trilete mark not prominent in observed speciemens.  Exine folding exhibits characteristic folding pattern.  Folds are large and prominent; a single medial fold with two distal folds branching equatorially.  Exine laevigate or granulate.

Occurrence.  PC - CM Biozones.

Genus PUNCTATISPORITES Ibrahim emend Potonié & Kremp, 1954

Punctatitsporites minitus Kosanke, 1950

Plate I, figures 4, 5, 6

Description.  Miospores acamerate and trilete with circular ambs.  Trilete mark simple and prominent; with laesura extending ½ to ¾ spore radius.  Thin exine observed equatorially with laevigate sculpture.
Discussion. *P. minitus* differs from *P. planus* based on the length of the laesura and the width of the suture. *P. planus* occasionally exhibits some small scabrate sculpture and slight folding equatorially.


*Punctatisporites planus* Hacquebard, 1957

Plate II, figure 1, 2

Description. Miospores acamerate and trilete with circular ambs. Trilete mark simple and prominent, with laesura extending ¾ spore radius, and suture somewhat open. Sculpture laevigate or sometimes slightly scabrate, with slight folding equatorially.

Occurrence. PC - CM Biozones, *S. claviger* Assemblage

Remarks. All the species of the *Punctatisporites* genus are extremely similar. All the species are trilete, acamerate miospores, with a simple but prominent trilete mark present. The defining characteristics for identification to the species level include length of laesura, width of suture, and width of identifiable exine in the equatorial region. Transport, preservation, and diagenetic effects can play a significant role in the identification process.

Genus RETUSOTRILETES Naumova emend Streel, 1964

*Retusotriletes cf. coniferus* Kedo, 1963

Plate II, figures 3
**Description.** Miospores acamerate and trilete. Amb round with possible equatorial thickening (dark areas). Trilete mark prominent, with laesura straight (or slightly sinuous) and of even width from the pole to the equator, and are terminated with curvature perfectae. Distally, the area where the laesura intersects the equatorial margin is slightly darkened. Miospores are laevigate to slightly granulate.

**Occurrence.** PC Biozone.

*Retusotriletes famenensis* Naumova, 1963

Plate II, figure 4, 5

**Description.** Amb round and acamerate with prominent trilete mark. Laesura sinuous and is terminated equatorially with curvature perfectae. Equatorial thickening prominent and visible.

**Occurrence.** PC Biozone.

*Retusotriletes planus* Dolby & Neves 1970

Plate II, figure 6

1964 c.f. *Punctatisporites irrasus* Hacquebard; Streel, p. 81, pl. 2, fig. 26.

1969 *Punctatisporites irrasus* Hacquebardx; Streel in Bouckeart et al., pl. 93, fig. 5.

1970 *Retusotriletes planus* Dolby & Neves p. 635, pl. 1, fig., 2.
Description. Miospores trilete and acamerate, round ambs with prominent trilet mark. Suturae extending ½ to ¾ spore radius. An extension of the suture to the equatorial region exhibits a curvature along the margin, a defining characteristic of the genus.

Discussion. Specimens of *R. planus* are extremely similar to *Punctatisporites irrassus*. Hacquebard, and Dolby and Neves (1970, p. 635) regarded *R. planus* as “*P. irrassus*” with curvaturae.


Infraturma APICULATI (Bennie & Kidston) R. Potonié, 1954
Genus BACULATISPORITES Thompson & Phufg, 1953

*Baculatisporites fusiculus* Sullivan, 1968
Plate III, figures 1, 2

Description. Miospores are acamerate and trilete with sub-circular ambs. Trilete mark not prominent. Characteristic massive folds observed in the exine, circumpolar pattern. Sculpture is dominated by closely spaced baculi, with occasional coni and grana.

Discussion. Two primary defining characteristics of this species is the dense bacculate sculpture and the massive circumpolar folding. According to Higgs et al.
(1988), the Irish specimens exhibit a coarser baculate sculpture and a wider size range than the original material described by Sullivan (1968).


Genus CAMPTOTRILETEDES Naumova emend Potonié & Kremp, 1954

*Camptotriletes prionotus* Higgs, 1975

Plate III, figure 3

**Description.** Miospores acamerate and trilete; amb sub-circular to circular. Trilete mark not visible. Exine moderately thick, with equatorially thickening. Surface heavily sculpted with dense conate elements, with spinose elements rare but present.

**Occurrence.** PC Biozone.

Genus GRANULATISPORITES Ibrahim emend Potonié and Kremp, 1954

*Granulatisporites microgranifer* Ibrahim, 1933

Plate III, figures 4, 5

**Description.** Miospores acamerate and trilete; amb triangular with rounded apices, and sides slightly concave. Laesura distinct and straight, extending ½ to ¾ the spore radius. Surface sculptured with grana, with varying density but same size.

**Discussion.** This species is important in the PC Biozone because it represents one of the earliest occurrences of concavo-triangular miospores.
Occurrence. PC – CM Biozones.

Genus NEORAISTRICKIA Potonié, 1956


Plate III, figure 6


1981 *Neoraistrickia logani* (Winslow). Coleman and Clayton, pl. 4, figs. 7-8, 12.

**Description.** Miospores are acamerate and trilete, with ambs ranging from triangular to sub-triangular, with sides either being straight, convex, or concave. Trilete mark not prominent. Surface sculpted with coni and or bacculi, ranging from narrow-based to broad-based, and concentrated near the corners, but also present along the sides.

**Discussion.** Although these spores are present in North America they are rare outside of Europe. The American species of Clayton and Coleman (1987) were classified as *Neoraistrickia* based on triangular amb shape and presence of coni/baculi. In the study area, the only specimens of *N. logani* are described from the Cowbell Member, northeastern Kentucky.

Occurrence. PC Biozone (rare).


*Raistrickia clavata* Hacquebard emend Palyford, 1964

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Plate IV, figure 1, 2, 3, 4

1957 *Raistrickia clavata* Hacquebard, p. 310, pl. 1, fig. 25.

1957 *Raistrickia pistillata* Hacquebard, pp. 310-311, pl. 2, fig. 2.

1964 *Raistrickia clavata* Hacquebard; emend Playford, pp. 24-25, pl. 6, figs. 5-10.

**Description.** Miospores are acamerate and trilete, ambs circular to sub-rounded (convexly triangular). Trilete mark not very prominent. Surface densely packed with conate elements. Individual elements are small, no longer than 3.5µm and are distally terminated with a point or a rounded surface.

**Discussion.** *Raistrickia clavata* represents one of the two zone palynomorphs defining the PC (*pretiosus – clavata*) Biozone. Although not extremely common in the study area, *R. clavata* does appear in the PC Biozone. *R. clavata* differs from *R. conylosa* and other species of *Raistrickia* based on the type of and length of ornamentation.

**Occurrence.** PC – CM Biozones, *S. claviger* Assemblage

*Raistrickia conylosa* Higgs, 1975

Plate IV, figure 5

**Description.** Miospores are trilete and acamerate, with ambs round to sub-round (ovate). Trilete mark not prominent in observed species. The exine surface is moderately ornamented with conate/pilate sculpture. Each individual coni is narrow and elongate,
with an even width from base to top. The distal part of each coni are rounded, and the distal part of each individual pila are rounded and slightly bulbous.

**Occurrence.** PC Biozone

**Remarks and Comparison.** All species of *Raistrickia* contain rounded ambs, and are trilete and acamerate. Defining specimens to the species level include a detailed identification and description of the ornamentation. These parameters include number, size, length, and type of the sculpture elements.

Genus SCHOPFITES Kosanke, 1950

*Schopfites claviger* Sullivan, 1968

Plate V, figures 1, 2, 3, 4

1968 *Schopfites claviger* Sullivan, p. 121, pl. 25, figs. 1-10.

**Description.** Miospores trilete and acamerate (possibly camerate), with circular to sub-circular ambs. Trilete mark not prominent, but suture can be observed. Laesura extending ¾ spore radius and terminates distally. Exine moderately thick and occasionally folded equatorially. The surface is moderately ornamented with pila or baccula, rarely coni or verrucae. Each individual element short, terminally rounded. Some sculptures may terminate in a point.

**Discussion.** The appearance of *Schopfites claviger* denotes the presence of the CM Biozone, which also marks the base of the Tn3c. The specimens of *S. claviger* in the study area are found in south-central Indiana, primarily in the Millport Knob section.
When originally described, species of Schopfites claviger were only known from northern Ireland.


Subinfraturma NODATI Dybova et Jachowicz, 1957

Genus *Umbonatisporites* Hibbert et Lacey, 1969

*Umbonatisporites abstrusus* Clayon, 1971

Plate V, figure 5

*Description.* Miospores are acamerate and trilete, with a triangular amb. Laesura is simple and straight, extends approximately 1/3 spore radius, and is not always prominent. Slight equatorial thickening present.

*Occurrence.* PC Biozone.

*Umbonatisporites distinctus* Clayton, 1971

Plate V, figure 6

1960 *Apiculatisporites* sp. Balme, p. 28, pl. 4, figs. 10,11.

1971 *Umbonatisporites distinctus* Clayton, pp. 591-592, pl. 4, figs. 4-6.

*Description.* Miospores trilete and acamerate. Amb circular to subcircular with laesura prominent and extending ¾ to entire spore radius. The amb is ornamented with heavy and closely spaced coni or spinae.

*Occurrence.* PC - CM Biozone.
Subinfraturna VERRUCATI Dybova et Jachowicz, 1957

Genus VERRUCOSISPORITES Ibrahim & Smith, 1971


Plate VI, figure 1

1957 *Raistrickia? gibberosa* Hacquebard, p. 310, pl. 2, fig. 10.

1964 *Pustulatisporites gibberosus* (Hacquebard). emend Playford, pl. 3, figs. 18-20.

1968 *Verrucosisporites scoticus* Sullivan, p. 121, pl. 25, figs. 11-12.

1988 *Verrucosisporites gibberosus* Higgs, Clayton, and Keegan, pl. 6, fig. 5.

*Description.* Miospores are trilete and acamerate, with amb rounded to sub triangular. Laesura distinct; however, obscured by ornamentation. Heavy verrucae ornamentation on distal face, with rounded tops (rarely truncated).


*Verrucosisporites nitidus* (Naumova) Playford, 1964

Plate VI, figures 2, 3, 4, 5, 6


1956 *Lophotriletes aff. grumosus* (Naumova). Ishchenko, p. 40, pl. 7, fig. 74.


1963 *Converrucosisporites parvinodusus*, Playford, p. 15, pl. 3, figs. 7-9.


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1964 *Verrucosisporites nitidus* (Naumova). Playford, 1964

*Description.* Miospores are acamerate and trilete, with amb subs-circular to triangularly convex. Trilete mark not prominent. The surface of the specimens are heavily ornamented with verrucae, non-overlapping equatorially, forming polygonal to circular ornaments along the edge. The verrucae form a ‘recticulate’ sculpture.

*Discussion.* Species of *Verrucosisporites* are some of the longest ranging spores in the study area. *Verrucosisporites nitidus* ranges from the Fammenian (Devonian) to the upper Tournaisian (Mississippian), seemingly unaffected by the multiple extinctions and floral turnovers during this time. *Verrucosisporites* specimens do not have a known biological affinity, however it is believed they are related to the ferns.


Infraturma MURORNATI Potonié & Kremp, 1954

Genus CONVOLUTISPORA Hoffmeister, Staplin and Malloy, 1955

*Convolutispora caliginosa* Clayton & Keegan In Clayton et al., 1982

Plate VII, figure 1

1967 *Convolutispora* sp. Neves and Dolby pl. 2, fig. 7.

1977 *Convolutispora* sp. Clayton et al. pl. 5, figs. 17-18.

1977 *Convolutispora* sp. A. Keegan p. 548, pl. 2, figs. 6-9.

1982 *Convolutispora caliginosa* Clayton and Keegan In Clayton et al., pl. 6, figs. 9-11.
*Description.* Miospores are trilete and acamerate, with subcircular to circular ambs. Laesura distinct however are obscured by heavy ornamentation. Verrucae ornamentation, heavy ridges separated by sinuous channels. Ornamentation can be observed along equatorial fringe.

*Occurrence.* PC - CM Biozones.

*Convolutispora vermiformis* Hughes and Playford, 1961
Plate VII, figure 2

1957 *Convolutispora flexuosa* forma minor Hacquebard, p. 312, pl. 2, fig. 10.
1961 *Convolutispora vermiformis* Hughes and Playford, p. 30, pl. 1, fig. 2.

*Description.* Miospores are acamerate and trilete, with sub-round to ovate ambs. Trilete mark is not prominent. The species are characterized by wide, irregular rugulae. This sculpture gives the equatorial outline a distinct pattern. The miospores are laevigate.

*Discussion.* Higgs et al. (1988) document the occurrence of *C. vermiformis* in western Europe as ranging from the LL-CM Biozones. The specimens in this study are reported from the Fort Payne Formation, which has been assigned to be equivalent to the Pu Biozone.

*Occurrence.* PC - CM Biozones and Fort Payne Formation.

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Genus DICTYLOTRILETES Naumova emend
Smith & Butterworth, 1967

Dictylotriletes trivialis Naumova in litt. in Kedo, 1963

Plate VII, figure 3

**Description.** Miospores are acamerate and trilete, with a circular amb. Exine exhibits distinct reticulate sculpture of muri. These muri protrude the equatorial margin and produce an uneven outline.

**Discussion.** This species of Dictylotriletes is distinguished from others by the presence of the muri produce the uneven equatorial outline.

**Occurrence.** PC - CM Biozones.

Genus MICRORETTICULATISPORITES Knox emend
Potonié & Kremp, 1954

Microreticulatisporites araneum Higgs, Clayton, and Keegan, 1988

Plate VII, figure 4


1978 Dictylotriletes sp. B, Playford, p. 128, pl. 8, figs. 8-10.

1988 Microreticulatisporites araneum Higgs, Clayton, and Keegan, pl. 7, figs. 6, 9-10.

**Description.** Trilete, acamerate spores with rounded to subrounded ambs. Laesura distinct and simple, extending to the spore margin. Reticulate sculpture visible on the exine surface.
 occurrence. PC Biozones.

Genus EMPHANISPORITES McGregor 1960

Emphanisporites rotatus (McGregor) McGregor 1973

Plate VII, figure 5, 6

1961 Emphanisporites robustus McGregor p. 3, pl. 1, fig. 13.
1962 Radforthia robustus Winslow p. 72, pl. 16, figs. 15, 15a, pl. 2, fig. 17.
1964 Emphanisporites sp. aff. rotatus McGregor in Cousminer pl. 15, fig. 36.
1965 Emphanisporites sp. Herner p. 14, fig. 1.
1967 Emphanisporites cf. rotatus McGregor in Richardson pl. 2, fig. E.
1967 Emphanisporites cf. robustus McGregor in Richardson pl. 2, fig. F.
1967 Emphanisporites cf. radiatus (Winslow). Menedez & Pothe de Baldis pl. 2, figs. F-H.
1967 Emphanisporites robustus McGregor in Beju pl. 1, fig. 19.
1968 Emphanisporites robustus McGregor in Lanniger pl. 24, fig. 1.
1968 Emphanisporites robustus McGregor in Schultz pl. 3, figs. 6, 6a.
1968 Emphanizonosporites radiatus Schultz p. 30, pl. 3, fig. 16.
1968 Emphanisporites sp. no. 2514 Lanzoni & Magloire pl. 7, figs. 6-7.
1969 Emphanisporites cf. rotatus McGregor in Downie & Lister pl. 1, figs. A-C.
1969 Emphanisporites robustus McGregor in Cramer pl. 1, fig. 11.
1972 Emphanisporites spp. Kemp pl. 4, figs. 1-3.

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1974 *Emphanisporites* sp. Clayton, Higgs, Guienn, and Van Gelder pl. 6, fig. 2.

1976 *Emphanisporites rotatus* McGregor *in* Massa and Moreau-Benoit pl. 1, fig. 10.

**Description.** Miospores acamerate and trilete; amb round to sub-round. Trilete mark prominent, extending from the pole to the equator. Numerous radial ribs present on the proximal side, extending ¾ to entire spore radius. Exine surface laevigate to slightly granulate.

**Discussion.** Species of *Emphanisporites rotatus* are defined by the presence of radial ribs on the proximal surface, starting near the pole and terminating distally near the equator. McGregor and Camfield (1976) reported multiple variations within the species including size, wall thickness, and prominence of the ribs. Taxonomic subdivision of the species is not practical.

**Occurrence.** PC Biozone.

Infraturma TRICRASSITI Dettman, 1963

Genus ROTASPORA Schemel, 1950

*Rotaspora fracta* Schemel, 1950

Plate VIII, figure 1

**Description.** Spores are trilete and radial, with a sub-circular to circular amb. Central part of the amb is subequilaterally triangular, with rounded corners and slightly concave
sides. Equatorial flange widest at inter-radial regions and narrow at the corners. The flange is thickened at the edge forming a rim.

**Discussion.** The specimen illustrated in this report from the Fort Payne Formation is smashed. The flange and the equatorial rim are somewhat visible, and the trilete mark is also visible.

**Occurrence.** Pu Biozone (Visean), Fort Payne Formation.

Infraturma CINGULATI (Potonié & Klaus) Dettman, 1963

Genus KNOXISPORITES Potonié and Kremp, 1954

*Knosisporites* sp. A.

Plate VIII, figure 2

**Description.** Amb sub-round to triangular, acamerate and trilete. Laesura not prominent. Sculpture includes broad low labra, densely packed, and extending distal to equatorial margin, resulting in uneven amb outline.

**Occurrence.** Fort Payne Formation, (Visean).

Genus SECARISPORITES Neves, 1961

*Secarisportes* sp. A.

Plate VIII, figure 3
Description. Amb trilete, acamerate, and sub-round to triangular. Laesura not prominent. Distal surface is covered by dense, thick globulose rugulae and the proximal surface is covered with sinuous rugulae. The outline of the amb is uneven due to the extent of the sculpture.

Occurrence. PC Biozone.

Suprasubturma CAMERATITRILETES Neves & Owens, 1966
Subturma SOLUTITRILETES Neves & Owens, 1966
Infraturma PLANATI Neves & Owens, 1966
Genus AURORASPORA Hoffmeister, Staplin, and Malloy Emend Richardson, 1960

Auroraspora macra Sullivan, 1968
Plate VIII, figure 5

Description. Miospores are camerate and trilete, with amb sub-circular to triangularly convex. Trilete mark prominent and extends ¾ spore radius, trilete rays straight. Intexine laevigate to scabrate. Exoexine thin and irregularly folded, often torn, slightly darkened where the trilete rays extend.

Discussion. Auroraspora macra is one of the zone fossils for the CM (claviger – macra) Biozone. Not confined to the CM Biozone, A. macra occurrences with Schopfites claviger identifies the CM Biozone. Although the species is not numerous, specimens do occur in the study area.
**Occurrence.** CM Biozone, *S. claviger* Assemblage.

*Auroraspora solisortis* Hoffmeister, Staplin, and Malloy, 1955

Plate VIII, figure 6

1955 *Auroraspora solisortis* Hoffmeister, Staplin & Malloy, pl. 37, fig. 3.


**Description.** Miospores are trilete and camerate with circular ambs. The laesura is present but not prominent, simple and straight. Intxine laevigate and extending 2/3 to 3/4 spore radius. Exoexine conformable with exine and very prominent, characterized by slight folding.

**Occurrence.** PC - CM Biozones.

Infraturma *DECORATI* Neves & Owens, 1966

Genus *GRANDISPORA* Hoffmeister, Staplin & Malloy emend Neves & Owens, 1966

*Grandispora corunata* Higgs, 1975

Plate IX, figure 1, 2, 3

**Description.** Miospores trilete and camerate, amb sub-round to triangularly convex. Trilete mark not prominent. Intxine sculpted with irregularly spaced spinae and/or
galae. Each element short with a broad base, and terminates distally to point or curve. Exoexine thin and seems to follow the outline of the amb.

Occurrence. PC Biozones.

Grandispora echinata Hacquebard, 1957

Plate IX, figure 4

Description. Ambs sub-round to triangularly convex, camerate and trilete. Trilete mark present but not prominent. Trilete rays straight to slightly sinuous, extending at least ¾ spore radius. Intexine thin and laevigate encompassing up to 2/3 total spore radius. Exoexine ornamented with coni and grana, terminated distally to an extended point.

Occurrence. PC - CM Biozones.

Genus RUGOSPORA Neves & Owens, 1966

Rugospora flexuosa (Jushko) Streel, 1974

Plate X, figure 1

1960 Trachytriletes flexuosus Jushko table 1, fig 4.
1967 Hymenozonotriletes famensis Kedo; Neves & Dolby, pl. 2, fig 3.
1974 Rugospora flexuosa (Jushko). Streel in Becker et al., p. 27, pl. 21, figs. 8-11.

Description. Triletes, camerate miospores with a convexly triangular amb. Laesura prominent with slightly sinuous to straight sutures and extending to the spore margin.
Intexine laevigate and conformable with amb. Exoexine has dense ornamentation of regulae.

**Occurrence.** VI – BP Biozones (Chattanooga Shale in this study).

**Genus SPELAEOTRILETES Neves & Owens, 1966**

*Spelaeotriletes obustus* Higgs, 1975

Plate X, figure 2

*Description.* Amb sub-round to slightly triangular. Trilete mark indistinct. Amb sculptured with densely packed bacula and pila. Clayton et al. (1988) suggests the specimens recovered outside Hook Head are quite similar.

**Occurrence.** VI – BP Biozones (“Maury Shale”).

*Spelaeotriletes pretiosus* (Playford) Neves & Belt, 1970

Plate X, figures 3, 4

1964 *Pustulatisporites pretiosus* Playford p. 19, pl. 4, figs. 7-9; pl. 5, fig. 1, text fig 1a.


1970 *Spelaeotriletes pretiosus* (Playford). Neves and Belt, pl. 13, figs. 16-18.

*Description.* Miospores trilete and camerate, ambs sub-round to triangularly convex with rounded apices. Trilete mark visible but not prominent; rays straight to slightly
sinuous and extending ¼ to entire length of spore radius. Exoexine ornamented with broad-based spinose verrucae, irregularly distributed, more often around the polar area then the equator. Intexine not readily observed.

Discussion. The occurrence of *Spelaeotriletes pretiosus* marks the base of the oldest Osagean biozone, the *pretiosus –clavata*, or PC Biozone. The PC Biozone in the study area overlies the VI Biozone, which is the oldest Kinderhookian biozone. In the study area, there are two spore zones missing (HD and BP) between the VI and PC Biozones. In western Europe, the missing zones are present. The first occurrence of *S. pretiosus* in the study area occurs in the Farmers Member in northeastern Kentucky, and the Maury Shale in south-central Kentucky.

Occurrence. PC – CM Biozones.

Subturma MEMBRANITRILETES Neves & Owens, 1966

Infraturma CONTINUATI Neves & Owens, 1966

Genus DISCERNISPORITES Neves & Owens, 1966

*Discernisporites micromanifestus* (Hacquebard) Sabry & Neves, 1971

Plate X, figure 5; Plate XI, figure 1

1957 *Endosporites micromanifestus* Hacquebard p. 317, pl. 3, fig. 16.

1958 *Discernisporites concentrus* Neves p. 5, pl. 3, fig. 7.


1971 *Discernisporites micrmanifestus* (Hacquebard). Sabry & Neves, pl. 3, fig. 11.
Description. Specimens of *D. micromanifestus* are trilete and camerate, with a trianually convex amb shape; well rounded apices. Trilete mark very prominent with laesura rays straight to slightly sinuous distally; length of rays is \(\frac{3}{4}\) spore radius. Intexine large, 2/3 to 4/5 spore radius, laevigate, and conformable with the outline of the amb. Exoexine thin and laevigate.

Discussion. Specimens of *D. micromanifestus* differ from *D. macromanifestus* only in form size.

Occurrence. PC – CM Biozones.

Genus GEMINOSPORA Balme, 1962

*Geminospora spongiata* Higgs, Clayton, and Keegan, 1988

Plate XI, figure 2

1975a *Geminospora* cf. *lemurata* Higgs p. 400, pl. 6, fig. 17.


Description. Miospores camerate and trilete, with amb subround to convexly triangular. Laesura prominent and sometimes slightly gaping, straight to slightly sinuous, and extending \(\frac{3}{4}\) spore radius and terminate with slight curvature. Exoexine prominent, with inner margin somewhat sponge-like. Intexine extending approximately 4/5 spore radius, laevigate.
Discussion. The species is most common in the HD Biozone, and rare in the LE and LN Biozones.

Occurrence. PC Biozone.

Genus SPINOZONOTRILETES Hacquebard emend Neves & Owens, 1966

Spinozonotriletes uncutus Hacquebard, 1957
Plate XI, figures 3, 4

Description. Miospores are camerate and trilete, with amb shape convexly triangular. Trilete mark is present but not prominent, rays straight to slightly sinuous. Intexine distinct, laevigate, and extending ¾ spore radius. Exoexine distinct rarely granulate. Equitorially, the exoexine ornamented with prominent spines, wide at the base and tapering distally to a point.

Discussion. Although species of S. uncutus are present throughout the upper Devonian and lower Mississippian, the species is most common to the PC Biozone. Most of the specimens from the study area were recovered from the Nancy Member, northeastern Kentucky.

Occurrence. PC – CM Biozones.

Turma ZONALES (Bennie & Kidston) R. Potonié, 1956
Subturma ZONOTRILETES Waltz, 1935
Infraturma CINGULICAMERATI Neves & Owens, 1966

Genus CRISTATISPORITES Potonié & Kremp emend But...
Genus KRAEUSELISPORITES Leschik and Jansonius, 1962

*Kraeuselisporites mitratus* Higgs, 1975

Plate XII, figure 2, 3

*Description.* Specimens of *K. mitratus* are trilete and camerate, with round to triangular ambs. Sides of the amb can be straight or slightly convex. Trilete mark present but not prominent. Suturae rays straight to slightly sinuous and extending ½ to ¾ spore radius. Intexine laevigate, extending ¾ spore radius, and conformable with general shape of the amb. Exoexine narrow and extending equatorially to form a zona. Zona thickest near the exoexine and thins distally, often fibrous on the outer edge. Exoexine and zona ornamented with spinae. Each element broad based tapering distally.

*Occurrence.* PC Biozone.

Genus VALLATISPORITES Hacquebard, 1957 emend Sullivan, 1964

*Vallatisporites microspinus*

Plate XIII, figures 1, 2

*Description.* Specimens of are trilete and cinguli-camerate, with triangularly convex ambs. Trilete mark visible but not prominent; suture rays straight, and extending to true spore margin. Intexine laevigate to granulate, extending approximately ½ spore radius. Exoexine thins distally to form thin cingulum. Cingulum containing several radially-aligned, cross-cutting vacuoles.

*Vallatisporites vallatus* Hacquebard, 1957

Plate XIII, figure 3, 4, 5

**Description.** Specimens of *V. vallatus* are trilete and camerate, with amb triangularly convex. Trilete mark visible but not prominent; rays straight and extending to the spore margin but mostly obstructed by sculpture. Intexine granulate and extends ½ to ¾ spore radius. Exoexine narrow, infrapunctate, and forms a thinning cingulum equatorially. Exoexine sculpted with broad-based conate and bacculate ornaments. Individual ornaments taper distally into a point or a rounded surface.

**Discussion.** *Vallatisporites vallatus* is an extremely long ranging species, present in the VI through CM Biozones, but usually absent in the HD Biozone. The sections in south-central Indiana contain a distinctive increase in the amount of *Vallatisporites* specimens.

**Remarks and Comments.** The *Vallatisporites* genus has been the center of many taxonomic debates over the years. Most of the species of *Vallatisporites* are extremely similar, with subtle morphologic variations defining each species. A review of the
morbidity and taxonomy of the group is needed and possibly the assignment of a morphon status.

*Vallatisporites verrucosus* Hacquebard, 1957

Plate XIII, figure 6

*Discussion.* *V. verrucosus* differs from other species of *Vallatisporites*, mainly *V. vallatus* by ornamentation only. *Vallatisporites verrucosus* is sculpted with verrucae that sometimes fuse and form sinuous rugulae.


Suprasubturm LAMINATITRILETES Smith & Butterworth, 1967

*Genus Lycospora* (Schopf, Wilson, and Bentall) Potonié and Kremp, 1965

*Lycospora pusilla* (Ibrahim) Schopf, Wilson, and Bentall, 1944

Plate XIV, figures 1, 2, 3

1932 *Sporonites pusillus* Ibrahim in Potonié, Ibrahim, and Loose, p. 448, pl. 15, fig. 19.

1933 *Zonales-sporites pusillus* Ibrahim, p. 32, pl. 2, fig. 20.


1938 *Zonotriletes pusillus* (Ibrahim); Waltz in Luber and Waltz, pl. 3, fig. 33, & pl. 8, fig. 105.

1944 *Lycospora pusilla* (Ibrahim); Schopf, Wilson, and Bentall, p. 54.
Description. Species of *L. pusilla* are trilete and camerate; amb shape is triangularly convex. The sides of the amb range from straight to slightly convex. Trilete mark very prominent, extending total width of spore; trilete rays straight with an even width. Intexine and exoexine division not easily identified; outer margins of exoexine conformable to general spore shape. Exine laevigate, granulate, and reticulate. Distally, exine forms cingulum; the equatorial cingulum reticulate, similar to the main body of the spore.

Discussion. The first occurrence of *L. pusilla* in most localities globally indicates the base of the Visean. In the study area, the first occurrence of *L. pusilla* is in the Floyds Knob Bed, which is a small transgressive surface in northwestern Kentucky and Indiana. The transgression associated with the Floyds Knob Bed may be coeval with the transgression associated with the Ft. Payne Formation.

Occurrence. Pu Biozone.

Turma MONOLETES Ibrahim
Subturma AZONOMONOLETES Luber
Infraturma PSILOMONOLETI van der Hammen
Genus LATOSPORITES Potonié & Kremp, 1954

*Latosporites* sp. A sensu Owens, 1971

Plate XIV, figure 4
Description. Miospores monolete and bilateral; with round to ovate shaped amb. Laesura distinct, straight and simple; total length of suture approximately \( \frac{3}{4} \) spore length and terminating in curvaturaee perfectae.

Discussion. This species of spores is closely related to the species described by Owens (1971) from the Devonian of Arctic Canada. *Retusotrtiletes digressus* is a closely related form, however it is a trilete taxon.

Occurrence. PC Biozone.

Division CHLOROPHYTA Pascher, 1914
Class PRASINOPHYCEAE Christensen, 1962
Order HALOSPHAERALES
Family PTEROSPERMATACEAE
Genus CYMATIOSPHAERA O. Wetzel ex Deflandre, 1954
*Cymatiosphaera rhacomba* Wicander, 1974
Plate XV, figure 1

Description. Vesicle circular in shape and laevigate. The surface is subdivided into 12-14 polygonal fields on both the proximal and distal surfaces. Each field is separated by laevigate ridges forming a reticulate-type pattern. Excystment structure is formed by splitting of the wall.
Discussion. The presence of this species of prasinophyte is indicative of deep water. Dorning (1981), in his model of morphologic variation across the Welsh Basin, described three assemblages. The third (distal) assemblage is the deep water assemblage containing low diversity. The deep water assemblage contains species of *Cymatosphaera* and *Pterospermella*.

Occurrence. Nancy Member and Maury Shale.

Genus PTEROSPERMELLA Eisenack, 1972

*Pterospermella captiana* Wicander, 1974

Plate XV, figure 2

Description. The vesicle is spherical and surrounded by an equatorial flange. The vesicle wall is relatively thick and scabrate; the flange is thinner than the vesicle wall and laevigate. The flange is characteristically folded, giving the appearance of supporting rods. The folding extends from the vesicle wall to the distal edge of the flange.

Discussion. The presence of this species of prasinophyte is indicative of deep water. Dorning (1981), in his model of morphologic variation across the Welsh Basin, described three assemblages. The third (distal) assemblage is the deep water assemblage containing low diversity. The deep water assemblage contains species of *Cymatosphaera* and *Pterospermella*.

Occurrence. Nancy Member.
ALGAE INCERTAE SEDIS

ACRITARCHA Evitt, 1961

Genus DORSENNIDIMUM Wicander, 1974

*Dorsennidium patulum* Wicander, 1974

Plate XV, figure 3

*Description.* Ovate to sub-round vesicle, with straight to slightly convex margins. Vesicle walls moderately thick and laevigate. Processes laevigate, with a slight widening at the base and tapering to a point distally. Each process open freely with the vesicle. Two of the primary process arranged at the elongate end of the vesicle.

*Occurrence.* Nancy Member, Osagean (Lower Mississippian).

Genus GUTTATISPHAERIDIUM Wicnader, 1974

*Guttatisphaeridium pandum* Wicander, 1974

Plate XV, figure 4

*Description.* Vesicle sub-round to slightly oblong, wall thick and slightly granulate; 10 – 12 flexible processes, with length approximately equivalent to diameter of the vesicle. Each process wide at the base and tapering to a point distally, and open freely with the vesicle.

*Occurrence.* Nancy Member, Osagean (Lower Mississippian).

Genus MICRHYSTRIDIUM Deflandre, 1957

*Micrhystridium erugatum* Wicander, 1974
Plate XV, figures 5, 6; Plate XVI figure 1

Description. Vesicle sphaerical, with straight to slightly convex margins. Vesicle ornamented with 15-20 processes. Each process laevigate, flexible and in open contact with the vesicle. Each process slightly widened at the base and tapers to a point distally.

Occurrence. Nancy Member, Osagean (Lower Mississippian).

Micrhystridium flexible Wicander, 1974

Plate XVI, figure 2

Description. Vesicle sphaerical with straight margins. Vesicle ornamented with relatively short, simple processes, averaging 15-25 processes per individual. Each process in open communication with vesicle and is slightly widened at the base and tapers distally.

Occurrence. Nancy Member, Osagean (Lower Mississippian).

Genus SOLISPHAERIDIUM Staplin, Jansonius, & Pocock, 1965

Solisphaeridium astrum Wicander, 1974

Plate XVI, figure 3, 4

Description. Polygonal vesicle, some margins slightly concave, walls moderately thick and laevigate; processes laevigate, slight widening at the base and tapering to a point distally, open to vesicle interior, numbering 8 – 12.

Occurrence. Nancy Member, Osagean (Lower Mississippian).
Genus STELLINIUM Jardiné, Combaz, Magloire, Peniguel, and Vachey, 1974

Stellinium inflatum Wicander, 1974

Plate XVI, figure 5

Description. Sub-circular vesicle with thin walls, slightly granulate to laevigate. Five to seven processes observed with broad bases, and tapering to a point distally. Each process hollow and in open communication with the vesicle.

Occurrence. Nancy Member, Osagean (Lower Mississippian).

PALYNOS INCERTAE SEDIS

Unknown Palyno-debris

Plate XVII, figure 1

Description. Specimens are elongate, open at one end and sealed at the other. The sealed end tapers to a rounded point. Length is approximately 10X to 15X width. These organisms may be a type of algal sack or possible a chitinozoan type organism.

Occurrence. PC Biozne, Nancy Member.

Plant vascular tissue

Plate XVII, figures 2, 3, 4
Description. All specimens elongate, with some type of vesicles or protrusions present. It is believed these specimens represent some part of the early water conducting tissue in the terrestrial flora.

Discussion. Specimens similar to the three figured occur throughout the Borden Delta succession. These occurrences allow suggestions on the morphology of Early Mississippian land plants and also give insight into the amount of sediment being transported into the basin.

Occurrence. Entire Borden succession.

Scolecodont Fragment
Plate XVIII, figure 1

Description. Specimen showing simple dentition of scolecodont apparatus. ‘Simple’ dentition was assigned due to the presence of only a single ridge of cones. Very few genera were present during the Mississippian, therefore with more research, this may be identifiable.

Occurrence. Fort Payne Formation.

Fungal Spore A
Plate XVIII, figure 2
Description. Spore is muriform, with each individual head well rounded. Seven to ten individual bulbs. Dark brown color.

Occurrence. Farmers Member.

Fungal Spore B

Plate XVIII, figure 3

Description. Spore is tetracellate – like in shape. Four individual heads, each consecutively smaller than the previous. Three of the heads form a straight form; however, the four (presumably) and newest is formed to the side of the middle head.

Occurrence. Nancy Member.


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APPENDIX A.

This section contains detailed descriptions of all the outcrops observed and sampled for this study. Each locality was assigned a letter code, which will be used in Appendix B.
The section measured at Evans Chapel is located 100 m west of the junction of Kentucky Highway 546 and Kentucky State Route 1149. At this exposure, the lower members of the Borden Delta are exposed. The succession extends for about 1.1 km along Kentucky Highway 546 east of Vanceburg, Kentucky.

**Description.**

**Henley Bed**

0 m – 11 m  
Mudstone, poorly consolidated, maroon with beds of alternating gray mudstones; poorly fossiliferous. Continuous siltstone layers prominent in the upper 5.0m. These siltstone layers are turbiditic in origin. The Kinderhookian-Osagean boundary lies within the Henley Bed.

*Important Genera: None recovered.*

**Farmers Member**

11 m – 47.2 m  
Siltstones, predominantly thinly bedded, continuous, poorly fossiliferous, turbiditic in origin. Each turbidite has sharp basal contacts, biosturbed tops, and grade upward into thinly-bedded, pelagic, gray shales. Turbidites vary in thickness from 1.3 m to
greater than 7.0 m. The siltstone layers as a whole seem to exhibit several thickening upward packages.

*Important Genera:* *Geminospora, Neoraistrickia, Punctatisporites, Retusotriletes, Spelaeotrilets, Umbonatisporites.*

Nancy Member

47.2 m – 74.7 m  Shale; gray to green-gray, mud-rich, interbedded with fine, continuous siltstone layers (turbidites). Each siltstone layer has a sharp basal contact, and bioturbated tops. The amount of turbidite occurrences decreases from the Farmers Member to the Nancy Member. Sideritic nodules abundant near the base, sometimes fossiliferous. A transition zone is believed to exist between the Farmers Member and the Nancy Member. The transition zone contains the transformation from the turbidite-dominated deposits of the Farmers Member to the pelagic-dominated Nancy Member.

*Important Genera:* *Calamospora, Punctatisporites, Retusotriletes, Spelaeotriletes, Verrucosisporites.*

**LOCAL #2 (L2)**

**GRIFFEN HOLLOW SECTION,**

**NORTHEASTERN KENTUCKY (PDC-I)**
The succession exposed at Griffen Hollow exposes a more complete section of the Borden Delta sediments, including the Farmers Member, Nancy Member, and Cowbell Member. The exposure is located approximately 3.1 km east of the Evans Chapel exposures along Kentucky State Road 546.

**Description.**

**Farmers Member**

0 m – 41.2 m Siltstone, fine to medium grained, tabular and continuous, interbedded with thinly bedded, pelagic-shales. Siltstones layers are turbiditic in origin. Each turbidite has a sharp basal contact, and a bioturbated top. Vertical burrows present throughout, some burrows penetrate the entire bed, some do not. Turbidites vary in thickness from 0.5 m to greater than 7.0 m.

*Important Genera: Geminospora, Punctatisporites, Retusotriletes, Spelaeotriletes, Umbonatisporites.*

**Nancy Member**

41.2 m – 61.7 m Silty shale, gray to greenish gray, interbedded with thinly bedded, continuous siltstone layers of turbiditic origin. Each turbidite has a sharp basal contact and bioturbated tops. Sideritic concretions throughout the silty shale, more abundant basally.

*Important Genera: Calamospora, Punctatisporites, Spelaeotrieletes, Micrhystridium, Pterospermella, Solisphaeridium.*
Cowbell Member

61.7 m – 79.7 m

Siltstone, gray to bluish-gray, resistant with massive appearance. Bioturbation throughout, cross-bedding throughout but not prominent. Fossils rare but present, and iron concretions present throughout.

*Important Genera:* Neoraistrickia, Punctatisporites, Retusotruletes, Spelaeotruletes.

LOCASE #3 (L3)

MOREHEAD, KENTUCKY

(PDC-I)

The area around Morehead, Kentucky yields several Borden Delta exposures. The northwest side of the intersection Interstate 64 and Kentucky State Route 801 has an exposure of the Farmers Member, which represents the western most occurrence of the strata in this report. This exposure of Borden rocks exposes the distal deposits of the delta.

Description.

Sunbury Shale

0 m – 4.5 m Shale, black, fissile, and poorly fossiliferous. Thin bedding at certain intervals. Pyrite nodules present and staining present throughout, ‘rusting’ the outcrop.
*Important Genera:* None recovered.

**Henley Bed**

4.5 m – 5.5 m Shaly mudstone, red, and poorly consolidated; interbedded with gray shale. Poorly fossiliferous. The Kinderhookian – Osagean boundary lies within this interval.

*Important Genera:* None recovered, amorphous organic matter.

**Farmers Member**

5.5 m – 11.08 m Siltstone, predominantly thinly bedded, continuous, poorly fossiliferous, turbiditic in origin. Each individual turbidite has a sharp base and a bioturbated top. Vertical burrow throughout.

Thicknesses of individual turbidites vary from .25 m to .90 m.

The succession as a whole exhibits thickening upwards packages.

Nine turbidites are present in this succession. Each turbidite separated by deposits of gray, thin pelagic shales.

*Important Genera:* *Punctatisporites, Retusotriletes, Spelaeotrilites.*

**Locale #4 (L4)**

MP146, I-64

Near Morehead, Kentucky
The succession observed along westbound Interstate 64, at milepost 146.0, contains the youngest deposits of the Borden Delta. The Nada Member, which composes the delta-top deposits, is the main interval exposed at this locality. Overlying the Nada Member is the Renfro Member, which is easily recognizable due to differential weathering.

Description.

**Nada Member**

- **0 m – 2.0 m** Shales, greenish-gray interbedded with thin discontinuous carbonate lenses. Carbonate lenses fossiliferous, fragments of crinoids, brachiopods, and bryozoa dominant.
- **2.0 m – 15.5 m** Shales, greenish-gray interbedded with reddish layers. Discontinuous siltstones lenses near the base and discontinuous carbonate lenses near the top. Glauconite occurs basally with phosphatic nodules in the upper 9.0 m. Fossils common in the nodules and rare in the shale.

*Important Genera: None recovered.*

**Renfro Member**

- **15.5 m – 17.8 m** Dolomite, yellowish-gray, argillaceous. Easily recognizable due to resistant nature.

*Important Genera: None recovered.*
The section is located along Kentucky State Route 36, south of Frenchburg, Kentucky. The exposure at Frenchburg yields the younger parts of the Borden Delta. The Cowbell Member, representative of the deltaic foreset beds, is seen at the base of the section. The Nada Member (delta top) comprises the bulk of the section, and is overlain by a small exposure of the Renfro Member.

**Description.**

**Cowbell Member**

0 m – 4.5 m  Siltstones, greenish-gray, massively bedded, interbedded with greenish shales. Phosphatic nodules abundant near the top and glauconite present throughout.

*Important Genera: None recovered.*

**Nada Member**

4.5 m – 16.0 m  Shale, green, interbedded with thin, discontinuous lenses of siltstone and carbonate. Carbonate lenses contain high amount of fossils and fossil fragments including crinoids, brachiopods, and bryozoans. Phosphatic nodules and red shales are present near the top of the unit.

*Important Genera: None recovered.*
Renfro Member

16.0 m – 18.0 m  Dolomite, yellowish-brown, resistant, and interbedded with greenish-gray silty shales.

*Important Genera:* None recovered.

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**LOCATE #6 (L6)**

PULASKI COUNTY STATE PARK,

STATE ROUTE 3189,

NANCY, KENTUCKY

(PDC-II)

The section measured in Pulaski County State Park is the stratotype of the Nancy Member. This exposure is located primarily along the east side on the road, however the base of the section can be seen in the small valley along the west side of the road. The base of the section yields the Devonian Chattanooga Shale, which is overlain by a thin exposure of the Maury Shale, the Nancy Member, and topped by an exposure of the Muldraugh Member.

**Description.**

**Chattanooga Shale**

0 m – 1.5 m  Shale, black, fissile and thinly bedded. Pyrite staining throughout the succession. Poorly fossiliferous.

*Important Genera:* Rugospora.
Maury Shale

1.5 m – 1.8 m
Shale, tan to gray, argillaceous, and poorly consolidated.

Glaucoritone present throughout but more abundant towards the top.

Important Genera: None recovered.

Poorly fossiliferous. Condensed section.

Nancy Member

1.8 m – 37.2 m
Shale, gray to grayish green, poorly consolidated. Interbedded continuous, thinly bedded siltstones, turbiditic in origin. Fossils present throughout, rare in the base and more abundant near the top. Shales and mudstones dominate the basal deposits but grade to silty-shales near the top of the exposure. Turbidites more abundant in the basal deposits.

Important Genera: Auroraspora, Convolutispora, Plicatispora, Punctatisporites, Retusotriletes, Schopfites, Verrucosisporites, Vallatisporites.

Muldraugh Member

37.2 m – 42.0 m
Silty limestones, brown to light-brown, well consolidated, fossil fragments present, mostly crinoids and bryozoans. Interbedded with discontinuous lenses of siltstone.
Important Genera: None recovered.

LOCALSE #7 (L7)

BURKESVILLE, KENTUCKY

(PDC-II)

The section is located along Kentucky State Route 61, approximately 8 km south of Burkesville, Kentucky. The section, although approximately 80 km southwest of the section discussed from Pulaski County State Park, is strikingly different. In this part of the study area, the Maury Shale sits directly atop the Devonian Chattanooga Shale, but the Nancy Member is not present. South of Burkesville, carbonates of the Ft. Payne Formation sit atop the Maury Shale. The area between Nancy and Burkesville is the location of the Borden Delta front, which represents the southwestern most progradation of the clastics.

Description.

Maury Shale

0 m – 0.30 m  Shale, gray to green-gray, argillaceous, with phosphatic nodules throughout. Glauconite prominent, especially in the upper 25 cm. Poorly fossiliferous. Condensed section containing the Kinderhookian-Osagean boundary.

Important Genera: Spelaeotritites, Verrucosisporites, Pterospermella.
The area surrounding Lake Cumberland in south-central Kentucky yields several exposures of the Ft. Payne Formation. In the fall when the lake level is low, several ‘seasonal’ outcrops appear. Many of these exposures show occurrence of carbonate mud-mounds. The exact origin of these mud-mounds is still under debate. At the mouth of Indian Creek, a massive turbidite is exposed, which can be observed in 3-dimensions, and is laterally quite extensive.

**Description.**

**Ft. Payne Formation**

0 m – 4.0 m Siltstone, gray, moderately consolidated and poorly fossiliferous. Interbedded with discontinuous gray shale-rich intervals.
4.0 m – 5.6 m Limey-siltstone, brown, moderately consolidated, fossil fragments throughout. Rip-ups of underlying silty-shale are common in the base. Graded beds are present throughout the turbidite, along with minor cross-bedding and roll-over structures. The turbidite and the underlying sediment share a sharp contact.

*Important Genera: None recovered.*

**LOCAL #9 (L9)**

RT. 61

NORTH OF BURKESVILLE, KY

PDC-II

This locality is near the top of the Fort Payne Formation in PDC-II. The siltstone sampled at this locality was deposited during the late stages of the transgressive systems tract or the earliest stages of the highstand systems tract of the Cumberland Sequence.

**Description.**

Fort Payne Formation

0 m – 4.5 m Gray, moderately cemented, carbonate-rich siltstone. Poorly fossiliferous; however local sedimentary structures can be very prominent.

*Important Genera: Convolutispora, Knoxisporites, Rotaspora.*
The exposure studied at Dale Hollow Dam is located approximately 5 km east of Celina, Tennessee and is located adjacent to the parking lot on the south side of the dam. The section here includes the Chattanooga Shale (Devonian) at the base, a small exposure of the Maury Shale, and a massive section of the Ft. Payne Formation. The exact thickness of the Ft. Payne Formation was not measured due to the inaccessibility and height of the outcrop.

**Description.**

Maury Shale

0 m – 0.30 m  Shale, brown to greenish-gray, argillaceous, poorly consolidated, poorly fossiliferous. Phosphatic nodules present throughout, with glauconite present and more abundant in the upper 20 cm. Condensed section believed to contain the Kinderhook-Osage boundary.

*Important Genera: None recovered, amorphous organic matter.*

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**LOCALE #11 (L11)**

**BUTTON MOLD KNOB**

**BROOKS, KENTUCKY**

**PDC-III**
The exposure at Button Mold Knob is the location of the classic fauna described in detail by Kammer (1982). The section exposes 24 m of the New Providence Shale and is located off of Kentucky State Route 1020, north of Brooks, Kentucky. The section is easiest to access from the Whispering Oaks Trailer Court, and is located in a glade on the northwest side of Button Mold Knob.

**Description.**

**New Providence Shale**

0 m – 24 m  Shale, gray, poorly consolidated, very fossiliferous. Interbedded with discontinuous limestone lenses in the lower 10 m. Siderite nodules common in the upper 14 m. Fossil fauna is classic Button Mold Knob fauna, abundant with crionoids.

*Important Genera: Auroraspora, Calamospora, Grandispora, Retusotriletes, Vallatisporites, Verrucosisporites.*

**LOCALE #12 (L12)**

**BROOKS CRUSHED STONE QUARRY**

**BULLITT COUNTY, KENTUCKY**

**PDC-III**

The exposure at the Brooks Crushed Stone Quarry is an excellent section of that is important because it exposes the base of the New Providence Shale. The main part of the quarry is located on the southwest side of Button Mold Knob. The quarry can be accessed by driving north on State Route 1020 from Shepardsville, Kentucky.
**Description.**

**New Albany Shale**

0 m – 24.0 m  Black, thinly bedded, fissile shale. Base of this unit is not exposed in the quarry, but the upper contact has a sharp contact with the overlying New Providence Shale.

*Important Genera: Rugospora flexuosa.*

**“Maury Shale”**

24.0 m – 24.5 m  Tan, nodular, glauconite-rich shale. Condensed section. The unit is observable between the underlying New Albany Shale and the overlying New Providence Shale. This unit represents an area of maximum flooding and this quarry is the one of the only places where the base of the New Providence Shale is observable.

*Important Genera: None recovered.*

**New Providence Shale**

24.5 m – 45.0 m  Gray, fissile, thinly-bedded shale. Poorly fossiliferous; however some horizons can be extremely fossiliferous. The shale is more compressed near the bottom of the section and becomes badly weathered near the top of the section.

*Important Genera: Schopfites, Vallatisporites, Verrucosisporites.*
LOCALE #13 (L13)

RT. 61

BULLITT COUNTY, KENTUCKY

PDC-III

This roadside locality, albeit mostly covered, does yield a small exposure of the base of the New Providence Shale. The outcrop is located on the north side of State Route 61, approximately 1.5 km east of State Route 44, 0.1 km before the State Route 61 – State Route 1020 intersection.

Description.

New Albany Shale

0 m – 0.5 m Black, fissile, poorly fossiliferous shale. The exposure requires a small amount of digging.

Important Genera: None recovered.

“Maury Shale”

0.5 m – 0.75 m Tan, fissile, nodular shale. Some glauconite is present especially near the top. Condensed section.

Important Genera: None recovered.

New Providence Shale

0.75 m – 1.0 m Gray, poorly consolidated, poorly fossiliferous shale. The remainder of the section is badly weathered and mostly covered
with vegetation.

*Important Genera: None recovered.*

LOCALE #14 (L14)

FINLEY HILL,

(IROQUOIS PARK) LOUISVILLE, KENTUCKY

PDC-III

The section at Finley Hill exposes the New Providence Shale and the Kenwood Siltstone. The outcrop is located on the northwestern side of Finley Hill, approximately 2.0 km south of Iroquois Park, on the west side of New Cut Road (KY State Route 1865), on the south-side of Louisville. The section at Finley Hill was originally described by Kepferle (1972).

**Description.**

New Providence Shale

0 m – 18.0 m Shale, gray, poorly consolidated, fossiliferous. Fossil fauna is representative of the classic Button Mold Knob fauna, named for the Button Mold Knob locality described above.

18.0 m – 26.9 m Siltstone, brown to light-brown, poorly consolidated, and poorly fossiliferous, tubidites. Interbedded with thinly bedded, gray, pelagic shales.

*Important Genera: None recovered.*
The exposure is located along the north side of Indiana State Route 211, approximately 15 km south of New Albany, Indiana. The section exposes the upper part of the Carwood Member (Spickett Knob Fm.) and the Floyds Knob Bed. The Borden Delta members exposed here represent the latest part of the lowstand systems tract, and the true transgressive surface (Floyds Knob Bed), and the early parts of the transgressive systems tract (Edwardsville Formation). The outcrop is topped by the transgressive systems tract, the carbonates of the middle Mississippian (Salem Ls, St. Louis Ls, and Ste, Genevieve).

**Description.**

**Carwood Formation**

0 m – 18 m Siltstone, gray, argillaceous, moderately cemented, poorly fossiliferous. Some cross-bedding present. Interbedded with discontinuous carbonate lenses. Sideritic nodules present in the base of the section and absent near the top.

*Important Genera:* *Baculatisporites, Cristatisporites, Grandispora, Granulatisporites, Retusotriletes, Vallatisporites, Verrucosisporites.*
Floyds Knob Bed

18 m – 19 m  Limestone, brown to reddish-brown, well-cemented, packed with crinoid fragments. Unit grades to a silty-limestone upwards. This unit represents the first transgressive event after the initial drop at the beginning of the Osagean.

Important Genera: None recovered.

Edwardsville Formation

19 m – 23.5 m  Shale, brown to gray, interbedded with discontinuous layers of siltstone and carbonate. Fossils rare but present throughout. This unit is believed to represent the early stages of the transgressive systems tract.

*Important Genera: None recovered.*

LOCALE #16 (L16)

MILLPORT KNOB SECTION,

MILLPORT, INDIANA

PDC-III

The section exposed at Millport Knob is located Indiana State Route 135, just north of Millport, Indiana. The section exposes the Spickert Knob Formation, the Floyds Knob Member, and the Edwardsville Formation. The base of the section is located along west side of the State Route 135, just south of the intersection of Indiana State Route 135
and Delany Port Road. The remainder of the section is located on the east side of the road, on the north side of the intersection.

**Description.**

**Spickert Knob Formation**

**Locust Point Member**

0 m – 27.0 m Siltstone, gray to blue-gray, interbedded with thinly bedded shale lenses. Sideritic concretions abundant in the base of the section and the top of the unit, but barren in the middle. Fossils present throughout, but not abundant. Trace fossils, “curly worm marks”, visible throughout the section. Geodes present in the ironstone concretions.

**Covered Interval**

27.0 m – 42.0 m Covered interval across the intersection.

**Carwood Member**

42.0 m – 57.8 m Siltstone, gray to bluish-gray, fairly resistant. Interbedded with discontinuous layers of bioclastic debris, well-sorted. Several sedimentary structures present through the unit. Trace fossils, “curly worm marks”, present throughout the section.

*Important Genera: Auroraspora, Baculatisporites, Cristatisporites, Vallatisporites, Verrucosisporites.*
Floyds Knob Bed
57.8 m – 59.5 m  Dolomite, brown to reddish-brown, fine-grained, resistant.
Poorly fossiliferous. Small occurrence of glauconite in the base.
This unit represents the first transgressive surface since the sea-level drop at the end of the Kinderhook.

*Important Genera:* *Lycospora, Vallatisporites.*

Edwardsville Formation
59.5 m – 76.9 m  Siltstone, gray-brown to reddish-brown, soft. Poorly fossiliferous.
trace fossils, “curly worm marks”, present. This unit represents
The early stages of the transgressive systems tract.

*Important Genera:* *Lycospora.*

LOCALE #17 (L17)
WALDRIP LOCALITY, MONROE COUNTY RESERVOIR, BLOOMINGTON, INDIANA
PDC-III

The exposures at the Waldrip Site are located along the south shore Monroe County Reservoir, 16 km south of Bloomington, Indiana. The outcrop is a clastic dominated sequence with a well-preserved and diverse crinoid fauna, believed to deposited as part of a submarine channel and levee system. The Edwardsville Formation
represents the early stages of the transgressive systems tract. The submarine channel-fill deposits are easily observable at this locality.

**Description.**

**Edwardsville Formation**

0 m – 5.0 m  Shales, brown to gray, soft, very fossiliferous. Crinoids dominate the fauna. Lensoid shaped siltstone present protruding form the shale. The siltstone lenses are submarine channel fill deposits. Fossils are present in the channel fill deposits, but are rare.

*Important Genera: None recovered.*
APPENDIX B

This section includes an alphabetical list of palynomorph species and the locality where each is present. The locality names correspond to the descriptions in Appendix A.
Table 1. List of miospore taxa at each locality. The locality descriptions can be found in Appendix A.

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Table 2. List of miospore taxa at each locality (continued).
The locality descriptions can be found in Appendix A.
APPENDIX C

This section includes the statistical data used to construct the macrofloral environments for the Nancy Member in PDC-I and the Spickert Knob Formation in PDC-III.
Table 3. Statistical listing used to calculate macrofloral composition for the Succession of the Nancy Member in PDC-I, northeastern Kentucky.

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<th>Sphenops.</th>
<th>HerbLycos</th>
<th>Vallatisp.</th>
<th>Verrucosi</th>
<th>Marine</th>
<th>TOTAL</th>
</tr>
</thead>
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<tr>
<td>99JR6-1</td>
<td>177</td>
<td>58</td>
<td>5</td>
<td>26</td>
<td>23</td>
<td>11</td>
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<tr>
<td>99JR6-3</td>
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<td>72</td>
<td>21</td>
<td>25</td>
<td>15</td>
<td>2</td>
<td>300</td>
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Table 4. Statistical listing used to calculate macrofloral composition for the succession of the Spickert Knob Formation at Millport Knob, PDC-III, southeastern Indiana.

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<th>SAMPLE #</th>
<th>Mar. Ferns</th>
<th>Sphenops.</th>
<th>HerbLycos</th>
<th>Vallatisp.</th>
<th>Verrucosi</th>
<th>Marine</th>
<th>TOTAL</th>
</tr>
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<tr>
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<td>3</td>
<td>95</td>
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<td>00JR14-9</td>
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<td>24</td>
<td>54</td>
<td>6</td>
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<td>300</td>
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APPENDIX D

This section contains eighteen plates containing the palynomorph specimens identified in this study. For detailed descriptions, see Chapter 9, Systematic Palynology.
PLATE 1

Figure 1, *Calamospora liquida*, 61µm, specimen recovered from Nancy Member, OSU 51726, 99JR6-1, nwR35.

Figure 2. *Calamospora microrugosa*, 48µm, specimen recovered from Nancy Member, OSU 51727, 99JR6-3, seP26.

Figure 3. *Plicatispora quasilabrata*, 56µm, specimen recovered from Spickert Knob Formation, OSU 51728, 00JR14-1, neM11.

Figures 4, 5, 6. 4, *Punctatisporites minitus*, 31µm, specimen recovered from Farmers Member, OSU 51729, 99JR1-6, seJ29; 5, 38µm, specimen from the Nancy Member, OSU 51730, 99JR6-1, swP28; 6, 35µm, specimen from Nancy Member, OSU 51731, 99JR6-3, nQ25.
PLATE 2

Figures 1, 2. *Punctatisporites planus*, 1, 47µm, specimen recovered from the Nancy Member, OSU 51732, 99JR6-1, seM17; 2, 52µm, specimen recovered from Nancy Member, OSU 51733, 99JR6-2, nwR12.

Figure 3. *Retusotriletes cf. coniferus*, 68µm, specimen recovered from the Farmers Member, OSU 51734, 99JR1-4, nwL34.

Figure 4, 5. *Retusotriletes famenensis*, 4, 50µm, specimen recovered from the Cowbell Member, OSU 51735, 01JR2-3, seJ13; 5, 52µm, specimen recovered from the Nancy Member, OSU 51736, 99JR6-1, neT25.

Figure 6. *Retusotriletes planus*, 65µm, specimen recovered from the Nancy Member, OSU 51736, 99JR6-3, neU23.
PLATE 3

Figure 1, 2. *Baculatisporites fustinulus*, 1, 57μm, specimen recovered from the Spickert Knob Formation, OSU 51737, 00JR14-5, eM34; 2, 56μm, specimen recovered from the Spickert Knob Formation, OSU 51738, 00JR14-4, seP35.

Figure 3. *Camptotribletes prionotus*, 63μm, specimen recovered from the Cowbell Member, OSU 51739, 01JR2-4, eR34.

Figure 4, 5. *Granulatisporites microgranifer*, 4, 31μm, specimen recovered from the Farmers Member, OSU 51740, 99JR1-5, seK34; 5, 28μm, specimen recovered from the Nancy Member, OSU 51741, 99JR6-1, neN34.

Figure 6. *Neoraistrickia logani*, 55μm, specimen recovered from the Cowbell Member, OSU 51742, 01JR2-3, nwJ7.
Figure 1, 2, 3, 4. *Raistrickia clavata*, 1, 59µm, specimen recovered from Farmers Member, OSU 51743, 99JR1-5, neT15; 2, 60µm, specimen recovered from the Nancy Member, OSU 51744, 99JR6-2, neS17; 3, 64µm, specimen recovered from the Nancy Member, OSU 51745, 99JR6-1, seH26; 4, 59µm, specimen recovered from the Cowbell Member, OSU 51746, wR12.

Figure 5. *Raistrickia condylosa*, 5, 68µm, specimen recovered from the Nancy Member, OSU 51747, 99JR6-1, seV23.
PLATE 5

Figures 1-4, *Schopfites claviger*, 1, 49µm, specimen recovered from the Nancy Member, OSU 51748, 00JR8-6, swT12; 2, 56µm, specimen recovered from the Nancy Member, OSU 51749, 00JR8-7, nR12; 3, 48µm, specimen recovered from the New Providence Shale, OSU 51750, 99JR12-1, neK18; 4, 50µm, specimen recovered from the New Providence Shale, OSU 51751, 99JR12-1, swT34.

Figure 5. *Umbonatisporites abrurstus*, 55µm, specimen recovered the Nancy Member, OSU 51752, 99JR6-1, sW24.

Figures 6. *Umbonatisporites distinctus*, 5, 71µm, specimen recovered from the Farmers Member, OSU 51753, 99JR1-5, sT17.
PLATE 6

Figure 1, *Verrucosisporites gibberosus*, 33µm, specimen recovered from the Nancy Member, OSU 51754, 99JR6-1, wU17.

Figure 2, 3, 4, 5, 6. *Verrucosisporites nitidus*, 2, 49µm, specimen recovered from the Cowbell Member, OSU 51755, 01JR2-4, seT34; 3, 53µm, specimen recovered from the Spickert Knob Formation, OSU 51756, 99JR14-3, swJ28; 4, 44µm, specimen recovered from the Farmers Member, OSU 51757, 99JR1-7, seH23; 5, 52µm, specimen from the Nancy Member, OSU 51758, 99JR6-2, nT24; 6, 55µm, specimen from the Nancy Member, OSU 51759, 99JR6-3, swG34.
PLATE 7

Figure 1. *Convolutispora caliginosa*, 57µm, specimen recovered from the Spickert Knob Formation, OSU 51759, 00JR14-9, sH17.

Figure 2. *Convolutispora vermiformis*, 50µm, specimen recovered from the Fort Payne Formation, OSU 51760, 02FP-90a, seQ29.

Figure 3. *Dictyotriletes trivialis*, 62µm, specimen recovered from the Spickert Knob Formation, OSU 51761, 00JR14-3, seT20.

Figure 4. *Microreticulatisporites araneum*, 31µm, specimen recovered from the Nancy Member, OSU 51762, 00JR8-3, swR35.

Figures 5, 6. *Emphanisporites rotatus*, 5, 42µm, specimen recovered from the Nancy Member, OSU 51763, 99JR6-3, nT39; 6, 48µm, specimen recovered from the Nancy Member, OSU 51764, neU16.
Figure 1. *Rotaspora fracta*, 30µm, specimen (smashed) recovered from the Fort Payne Formation, OSU 51765, 01FP-90a, nwT20.

Figure 2. *Knoxisporites* sp. A, 50µm, specimen recovered from the Fort Payne Formation, OSU 51766, 01FP-90a, nwJ23.

Figure 3. *Secarisporites* sp. A, 52µm, specimen recovered from the Farmers Member (possibly reworked), OSU 51767, 99JR1-5, swJ34.

Figure 4. *Auroraspora macra*, 57µm, specimen recovered from the Nancy Member, OSU 51768, 99JR-6-3, neU24.

Figure 5. *Auroraspora solisortus*, 58µm, specimen recovered from the Cowbell Member, OSU 51769, 00JR2-3, sR34.
PLATE 9

Figure 1, 2, 3. *Grandispora corunata*, 1, 71\(\mu\)m, specimen recovered from the Nancy Member, OSU 51770, 99JR6-1, seW12; 2, 49\(\mu\)m, specimen recovered from the Cowbell Member, OSU 51771, 00JR2-4, nwJ24; 3, 54\(\mu\)m, specimen recovered from the Nancy Member, OSU 51772, 99JR6-3, nR35.

Figure 4. *Grandispora echinata*, 61\(\mu\)m, specimen recovered from the Nancy Member, OSU 51773, 99JR6-1, seT45.
PLATE 10

Figure 1. *Rugospora flexuosa*, 63µm, specimen recovered from the Chattanooga Shale, OSU 51774, 00JR8-1, seT25.

Figure 2. *Spelaeotriletes obustus*, 55µm, specimen recovered from the “Maury Shale”, OSU 51775, 99JR7-1, seU35.

Figure 3, 4. *Spelaeotriletes pretiosus*, 3, 69µm, specimen recovered from the Nancy Member, OSU 51776, 99JR6-2, nR12; 4, 62µm, specimen recovered from the Cowbell Member, OSU 51777, seG33.
PLATE 11

Figure 1. Discernisporites micromanifestus, 60µm, specimen recovered from the Farmers Member, OSU 51778, 99JR1-5, seK23.

Figure 2. Geminospora spongiata, 55µm, specimen recovered from the Farmers Member, OSU 51779, 99JR1-6, seU20.

Figure 3, 4. Spinozonotriletes uncatus, 3, 70µm, specimen recovered from Nancy Member, OSU 51780, 00JR6-1, nK19; 4, 89µm, specimen recovered from the Nancy Member, OSU 51781, 99JR6-3, swH34.

Figure 5. Cristatisporites menendezii, 49µm, recovered from the Spickert Knob Formation, OSU 51782, 00JR14-9, sH17.
PLATE 12

Figure 1. *Cristatisporites menendezii*, 74µm, specimen recovered from the Spickert Knob Formation, OSU 51783, 00JR14-5, sQ23.

Figure 2, 3. *Krauselisporites mitratus*, 2, 52µm, specimen recovered from the Nancy Member, OSU 51784, 99JR6-1, sH37; 3, 69µm, specimen recovered from the Nancy Member, OSU 51785, 99JR6-3, swT34.
Figure 1, 2. *Vallatisporites microspinous*, 1, 43µm, specimen recovered from the Spickert Knob Formation, OSU 51786, 00JR14-5, neH39; 2, 45µm, specimen recovered from the Spickert Knob Formation, OSU 51787, 00JR14-2, neL30.

Figure 3, 4, 5. *Vallatisporites vallatus*, 3, 68µm, specimen recovered from the Spickert Knob Formation, OSU 51788, 00JR14-1, seL14; 4, 62µm, specimen recovered from the Spickert Knob Formation, OSU 51789, 00JR14-1, neU12; 5, 72µm, specimen recovered from the Nancy Member, OSU 51790, 99JR6-2, seR27.

Figure 6. *Vallatisporites verrucosus*, 55µm, specimen recovered from the Nancy Member, OSU 51791, 99JR6-3, neU34.
Figures, 1, 2, 3. *Lycospora pusilla*, 1, 41µm, specimen recovered from the Edwardsville Formation, OSU 51792, 00JR14-9, swK14; 2, 38µm, specimen recovered from the Edwardsville Formation, OSU 51793, 00JR14-9, wP14; 3, 40µm, specimen recovered from the Edwardsville Formation, OSU 51794, 00JR20-1, seG34.

Figure 4. *Latosporites* sp. A, 72µm, specimen recovered from Nancy Member, OSU 51795, 99JR6-1, seF14.
PLATE 15

Figure 1. *Cymatiosphaera rhacomba*, 31µm, specimen recovered from the Nancy Member, OSU 51610, 99JR6-1, neH4.

Figure 2. *Pterospermella captiana*, 75µm, specimen recovered from the Nancy Member, OSU 51611, 99JR6-1, neJ23.

Figure 3. *Dorsennidium patulum*, 35µm, specimen recovered from the Nancy Member, OSU 51612, 99JR6-3, nS30.

Figure 4. *Guttatisphaeridium pandum*, 31µm, specimen recovered from the Nancy Member, OSU 51613, 99JR6-3, seK17.

Figure 5, 6. *Micrhystridium erugatum*, 5, 41µm, specimen recovered from the Nancy Member, OSU 51614, 99JR6-3, nwL34; 6, 40µm, specimen recovered from the Nancy Member, OSU 51615, 99JR6-1, sU24.
PLATE 16

Figure 1. *Micrhystridium erugatum*, 38µm, specimen recovered from the Nancy Member, OSU 51616, 99JR6-3, no data.

Figure 2. *Micrhystridium flexible*, 42µm, specimen recovered from the Nancy Member, OSU 51617, 99JR6-2, sH5.

Figure 3, 4. *Solisphaeridium astrum*, 3, 44µm, specimen recovered from the Nancy Member, OSU 51618, 99JR6-2, seU41; 4, 45µm, specimen recovered from the Nancy Member, OSU 51619, 99JR6-1, eT15.

Figure 5. *Stellinium inflatum*, 32µm, specimen recovered from the Nancy Member, OSU 51620, 99JR6-3, seL29.
Figure 1. Unknown palyno-debris, specimen recovered from the Farmers Member, OSU 51796, 99JR1-5, neT34.

Figure 2, 3, 4. Plant vascular tissue, 2, specimen recovered from the Nancy Member; OSU 51797 99JR6-2, nH24; 3, specimen recovered from the Farmers Member (possibly stomata), OSU 51798 99JR1-5, neG25; 4, specimen recovered from the Cowbell Member; OSU 51799, 01JR2-4, sw K34.
PLATE 18

Figure 1. Scolecodont, fragment recovered from the Fort Payne Formation. OSU 51800, 01FP-90a, nwT20.

Figure 2. Unknown fungal spore, 45 µm, specimen recovered from the Farmers Member, OSU 51801, 99JR1-6, nwJ45.

Figure 3. Unknown fungal spore, 54 µm, specimen recovered from the Nancy Member, OSU 51802, 00JR8-4, neH4.