SPORES ALONG A TIME-LINE

The second biostratigraphic study involved spores which are commonly preserved independently (to a large extent) of environment. According to the Barrier-Shoreline hypothesis, spore assemblages along a time line ought to be the same, although differences in abundance should be expected because of differences in proximity to the site of deposition of various plant species and because of different modes of transportation. These differences in abundance and diversity show up, for example, when spore assemblages from a coal bed are examined from place to place.

The coal-bearing rocks of the Central Appalachian basin represent sediment and peat swamps deposited near sea level in coastal lowlands. Given the great mobility of spores, spore assemblages from an area the size of this study area should be similar even though abundances and diversity may be different. Therefore, in the rock record, spore assemblages from coal beds and associated rocks along a time line ought to show nearly the same species. The spore occurrences in the shallow-water marine rocks ought to be nearly the same as the spores from coastal plants (Haq and Boersma, 1978, p. 335). For example, spore assemblages from a coal bed and associated marine and non-marine shales at site 3 (Pennington Formation, northeastern Kentucky) should be similar to spore assemblages from similar lowland coals at site 4 (Gilbert and Cedar Grove coal beds, southern West Virginia) along the same Barrier-Shoreline time line (Fig. 34). A time line extending from the Gilbert coal bed in the deeper part of the basin to the Pennington and Slade (Newman Limestone) along the basin margin is readily inferred from the Barrier-Shoreline cross section of Ferm and Cavaroc (1969; Fig. 4). However, the taxonomic make-up of these beds is quite different (Ettensohn and Peppers, 1979: Kosanke, 1984). The lowest Pennington Formation assemblage, sample 2087 (Ettensohn and Peppers, 1979), indicates a Late Visean age (Fig. 36), whereas the assemblages from the Gilbert (Grundy formation) and Cedar Grove (Pikeville formation) coal beds indicate deposition near the Westphalian A-B boundary.

AMMONOIDS ALONG A TIME-LINE

Ammonoids occurring along the same Barrier-Shoreline time-line discussed above, also should be the same. The distribution of ammonoids is commonly independant of environment because they are pelagic in part, and after death the shells become flotant which drift into a variety of marine environments. Their distribution is generally widespread. Abundant marine fossils were collected from the Kendrick Shale (Hyden formation) which overlies the Cedar Grove and other coal beds (site 5, Harlan County, Kentucky:

Figure 36. Spore and ammonoid biostratigraphic-determinations. Information from Ettensohn and Peppers (1979), Kosanke (1984), and Gordon and Mason (personal communication, 1986).

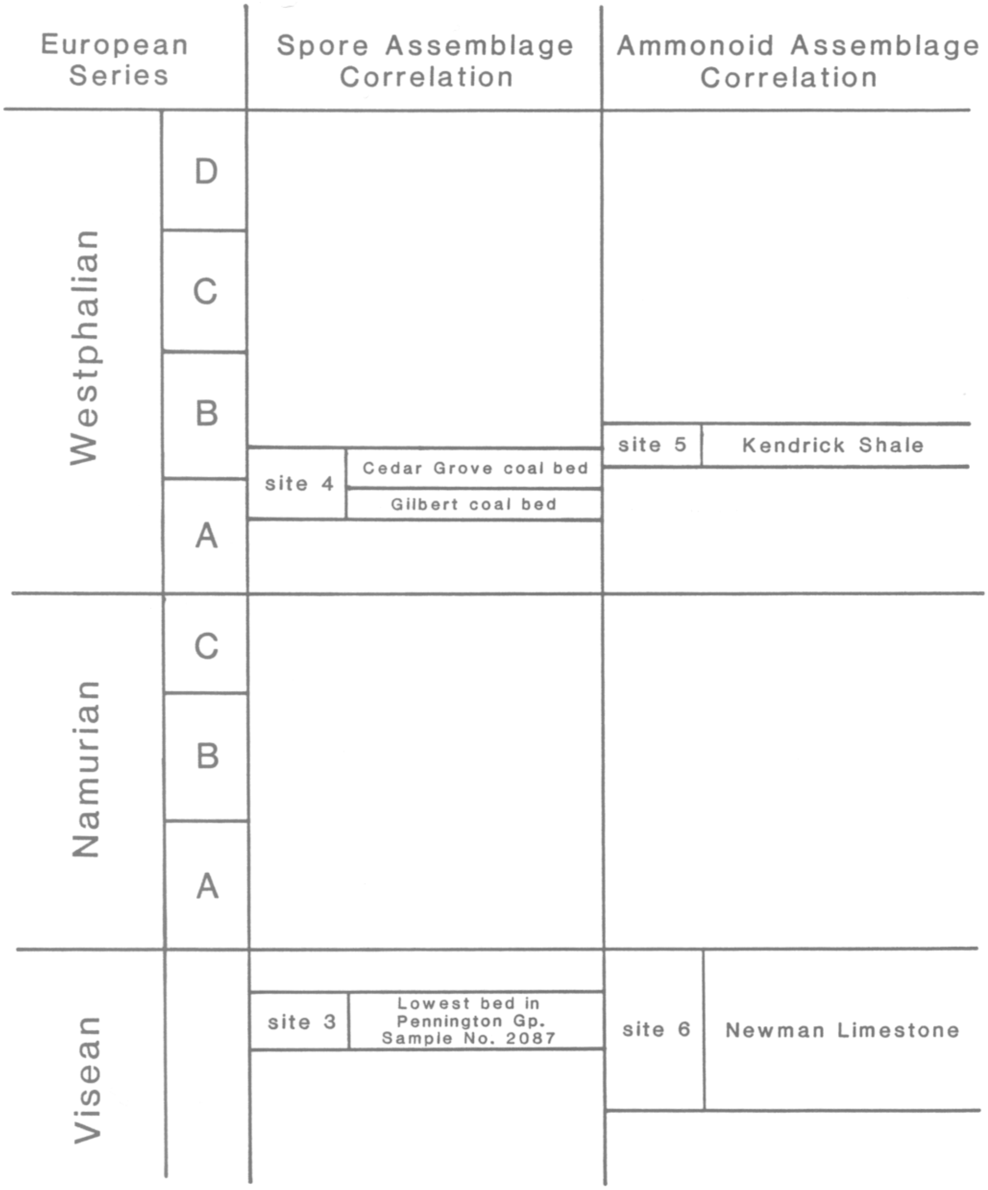

European Series
Spore Assemblage Correlation
Ammonoid Assemblage Correlation
Westphalian
D
C
B
A
Namurian
C
B
A
Visean
site 4
Cedar Grove coal bed
Gilbert coal bed
site 5
Kendrick Shale
site 3
Lowest bed in Pennington Gp. Sample No. 2087
site 6
Newman Limestone

Fig. 36). Ammonoids collected from this unit include Gastrioceras occidentale (Miller and Faber) and Dimorphoceratoides campbellae Furnish and Knapp, which are Early to Middle Pennsylvanian ammonoids. The occurrence of Dimorphoceratoides campbellae is correlated with the Diaboloceras neumeieri Ammonoid Zone in Arkansas and with the Westphalian B of Europe (Fig. 36)(Saunders and others, 1977, p. 124).

Goniatites from the Slade Formation in northeastern Kentucky (site 6, Fig. 34) were collected and identified by Charles Mason as Goniatites spp., Lusitanites sp., and prolotenitids, of no later than Chesterian age in the United States and the Upper Visean of Europe (Fig. 36) (Charles Mason and MacKenzie Gordon, Jr., personal communication, 1986). These two assemblages indicate a gap of tens of millions of years between the deposition of the Kendrick Shale and the Slade Formation, demonstrating that the former cannot be a facies equivalent of the latter.

The possibility exists that the worldwide biostratigraphic successions are incorrect because the zonations actually represent facies controlled associations. The accepted sequence of biostratigraphic zones could actually represent facies changes from marine to terrestrial, as in the Carboniferous of the Appalachians.

Thus the worldwide occurrence of the "biostratigraphic" sequences may actually represent similar tectonic events occurring in the late Paleozoic around the world, not necessarily coeval. Therefore, the resulting biostratigraphic succession would be useless for biostratigraphic-age determinations. However, cases exist where the tectonic events and resulting lithologic sequences are different from the marine to terrestrial transition above, yet the biostratigraphic sequences are the same. For example, in some areas of the Yangtze terrane in southern China most of the strata from the Devonian through Triassic are shallow, open-marine limestones. Even though the environment remained much the same through time, the biostratigraphic zones occur in the proper sequence (Wei and others, 1987). In north-central China, on the Sino-Korean terrane, the Carboniferous and Permian are dominated by coal-bearing clastic rocks and yet the same biostratigraphic sequences are recognized (Xu and others, 1987) even though the tectonic histories of these terranes are different. These examples support the use of recognized biostratigraphic successions in age determination.

Overlap Onto The Erosional Surface

Recognition of the regional unconformity in this study and sequential overlap of Pennsylvanian sediments onto the unconformity toward the Cincinnati Arch imply a period of subaerial exposure and denudation of the underlying Mississippian rocks along the northwestern margin of the Appalachian Basin. This period of subaerial exposure is compared to the periods of subaqueous erosion of the Barrier-Shoreline hypothesis.

The overlap constrains the duration of the unconformity and the controls of Early Pennsylvanian deposition. The area beyond each overlapping unit at the time of overlap may have been the product of three possible conditions: 1.) subaerial erosion, 2.) subaequeous erosion, or 3.) deposition followed by erosion. Subaerial exposure on the unconformity surface in many exposures along the western belt of outcrop can be interpreted from the soil profiles. Leached and rooted underclays are common at the unconformity. Moreover, the occurrence of coal beds directly on the unconformity surface indicates that no widespread deposition beyond the coal beds took place (For example, Cobb and others, 1981, plate 1). Thus, the most likely choice from the possible conditions above is subaerial exposure beyond the overlapping units.

The surface of unconformity was first covered by sediments in distal areas to the southeast of the Cincinnati arch and later by sediments encroaching toward the arch. Therefore, the origin and duration of the time-stratigraphic break along the unconformity was variable from place to place: areas closest to the Cincinnati Arch were exposed and eroded for the longest time.

In contrast to the few million years of time-stratigraphic break indicated by the Tabular-Erosion model, the Barrier-Shoreline model must reflect a substantially larger duration for the sum of all possible time-stratigraphic breaks. The large-scale progradational continuum of the Barrier-Shoreline model includes many local channel unconformities which become younger toward the Cincinnati arch. Collectively, the duration of all the erosional events is on the scale of the whole Carboniferous Period. Hence, the series of physically connected local-channel unconformities could be interpreted as one unconformity surface which formed over a period of tens of millions of years.

The Central Appalachian Tabular-Erosion Model

The results of this study, including evidence for the truncation of beds below a regional unconformity and overlap of units on the unconformity, supplemented by biostratigraphic arguments, support the Tabular-Erosion model. This model is here applied to the Central Appalachian Basin.

The term "Mississippian-Pennsylvanian unconformity," as cited in the literature, is a misnomer in the Central Appalachian Basin. This and past studies (Miller, 1974; Englund and others, 1985) indicate that the unconformity represents Early Pennsylvanian erosion at a horizon between the Pocahontas and Lee formations, although the unconformity separates Mississippian and Pennsylvanian strata over most of the basin. Therefore, the unconformity should be properly referred to as the Early Pennsylvanian unconformity.

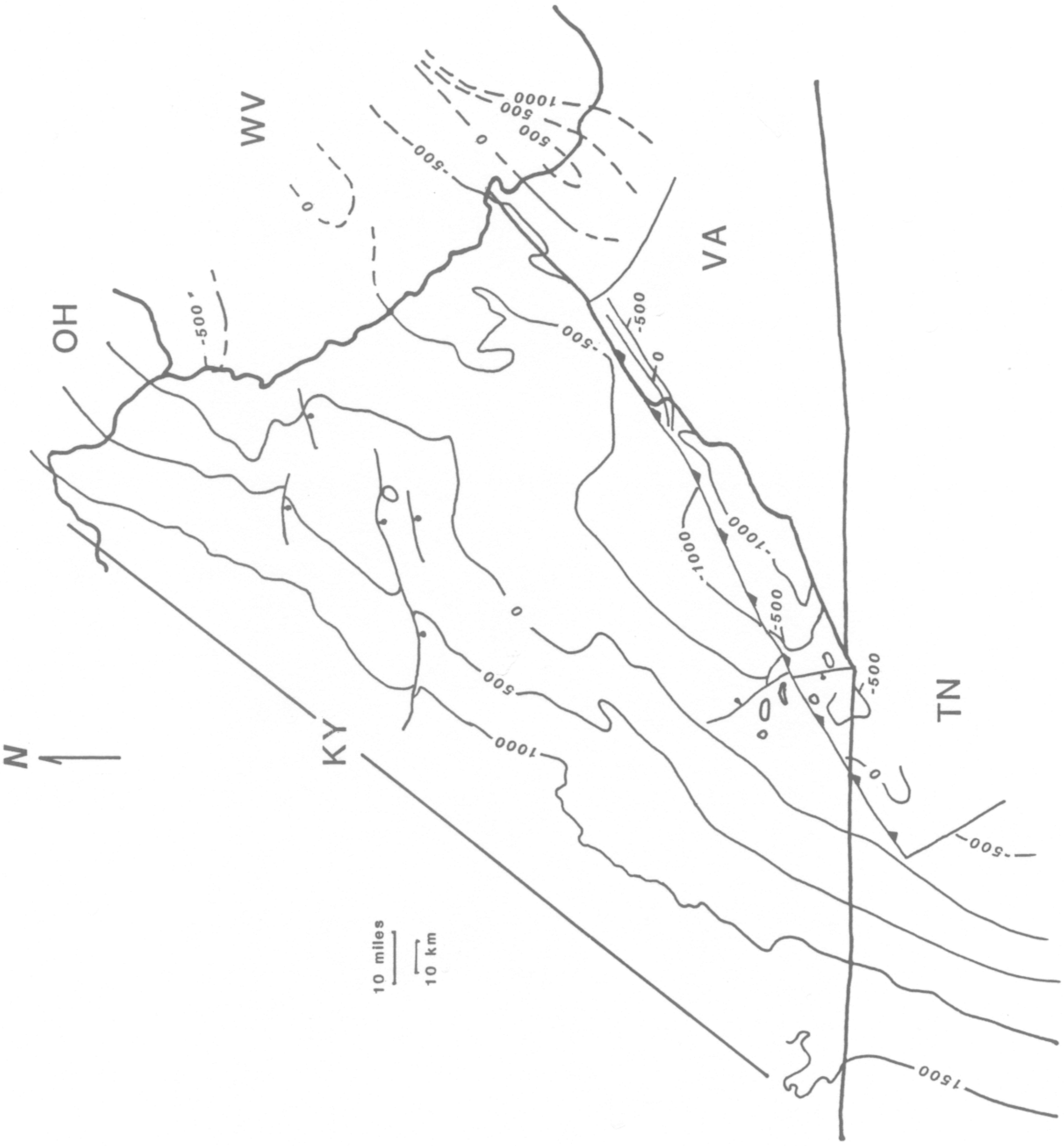
A geologic map of the subcrop at the Early Pennsylvanian unconformity was projected from the cross sections of the study area (Fig. 37). The Pocahontas Formation is preserved only in Virginia and in the southern part of West Virginia. Throughout the rest of the area, older units of Mississippian age are present below the unconformity. The Pennington Group occurs at this position throughout most of this area, but in the northwestern part of the study area, the Slade Formation and outliers of Pennington Group occur directly below the unconformity. In the northernmost part of the study area, the Borden Formation and outliers of the Slade Formation are present below the unconformity.

The present surface of the Early Pennsylvanian unconformity is illustrated by the structure-contour map (Fig. 38). A general southwest-northeast trend of the

Figure 37. Subcrop geology at the Early Pennsylvanian unconformity. Information from the cross sections of this study, as well as from Rice (1984, fig. 4) for the western outcrop belt and from Miller (1974, fig. 17) for Virginia. The data were plotted on a palinspastic base map. Contour lines represent the depth to the unconformity at the end of Lee Formation deposition.


OH
WV
KY
VA
TN
N
10 miles
16 km
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
eastern outcrop belt
western outcrop belt
Borden Fm., Slade outliers
Slade Fm., Pennington outliers
Pennington Gp., lower part
Pennington Gp., upper part
Pocahontas Fm.

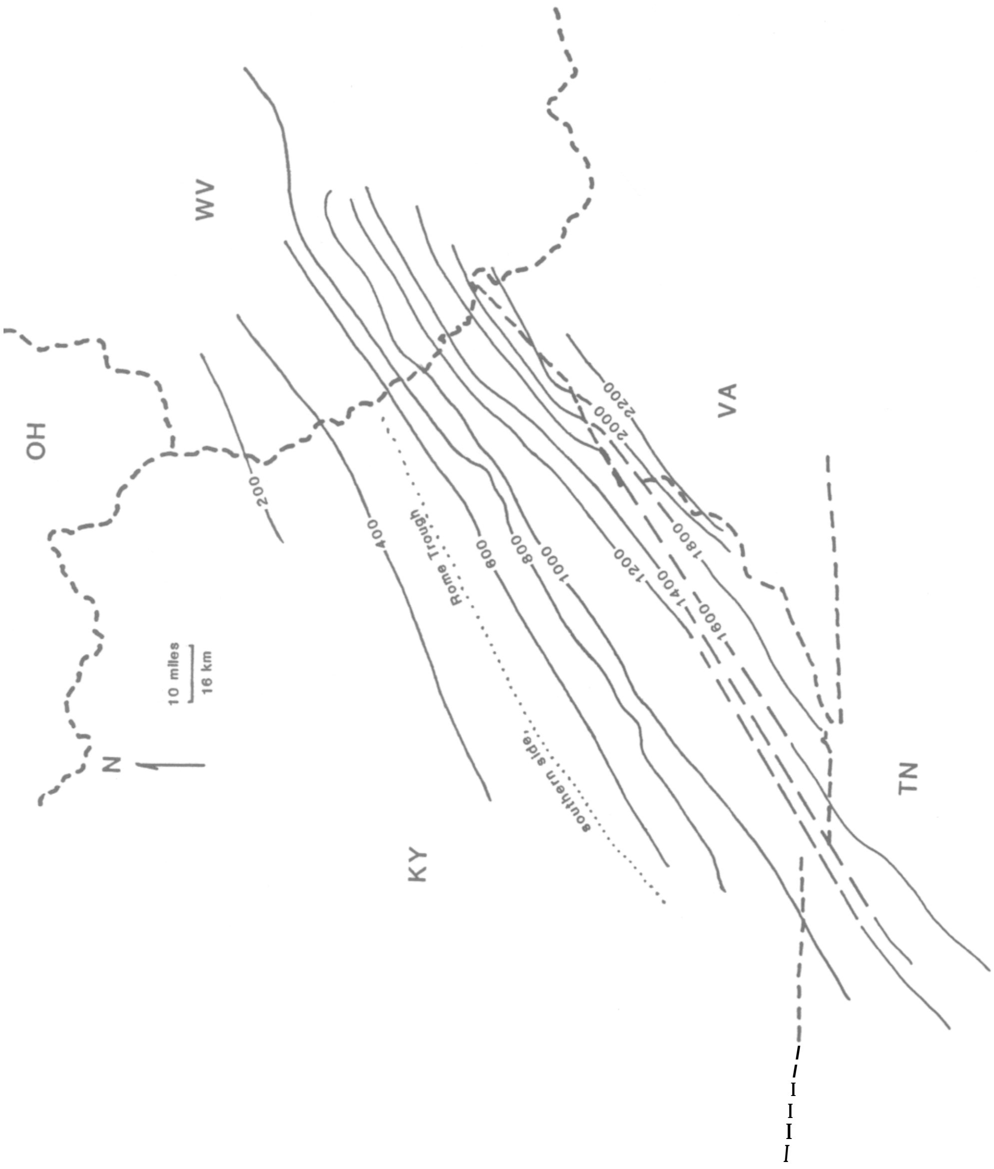
Figure 38. Contour map of the present surface of the Early Pennsylvanian unconformity. Contours for eastern Kentucky were taken from Coskren and Rice (1979); their map was generated from the analysis of over 2,000 oil and gas logs. Detailed checking of the Grundy dip section from this study indicates close agreement with the map of Coskren and Rice. Based on information in the cross sections, the 500-foot contour intervals were projected into Tennessee, Virginia, West Virginia, and Ohio. Data were too sparse for reliable projections in Virginia and West Virginia. Down.-thrown sides of faults indicated by ball-and-bar.


N
OH
WV
VA
KY
TN
10 miles
10 km
1000
500
500
0
-500
0
-500
-500
-500
0
-1000
1000
-500
-500
0
500
1000
0
-500
1500

contours is obvious. The unconformity surface dips to the southeast toward the Kentucky-Virginia border, where it crosses the axial plane of a NE-SW-trending syncline. South of the syncline's axial plane in Virginia and in the southern part of West Virginia, the beds dip toward the northwest. In contrast, the contours on the Pine Mountain thrust sheet reflect the structure of the Middlesboro syncline.

Data from the cross sections were also used to construct an isopach map (Fig. 39) of the interval between the base of the Betsie Shale and the Early Pennsylvanian unconformity. Because the Betsie Shale, the stratigraphically lowest extensive marker bed, overlies the stratigraphic highest part of the Lee Formation, this map also shows the approximate depth to the unconformity, uncorrected for compaction, at the end of Lee deposition. The data used to make this figure are too general to reflect paleotopography on the erosion surface, but other features can be recognized. First, the contours trend northeast-southwest, suggesting that the slope of the erosion surface during Lee deposition was to the southeast. The implications of this slope will be discussed later. Another feature is the change in slope: contours 600 through 2200 feet reflect a steeper dip than do 600 through 200 feet. This change in dip may indicate that a syndepositional structural hingeline

Figure 39. Isopach map of interval between the base of the Betsie Shale and the Early Pennsylvanian unconformity. Data for the construction of this map were from cross sections. This map also represents the depth to the unconformity, uncorrected for compaction, at the end of Lee Formation deposition. The Pine Mountain overthrust is palinspastically replaced. The southern side of the Rome Trough, from Sutton (1981), is represented by the dotted line.


OH
WV
VA
KY
TN
N
10 miles
16 km
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Rome Trough
southern side
I
I
I
I

was located somewhere between contours 400 and 600 feet. The southern side of the Rome Trough (Fig. 39), a basement graben active in the Early Paleozoic, coincides with this hingeline and may indicate reverse reactivation of this graben fault during the Early Pennsylvanian.

A generalized supercrop map above the Early Pennsylvanian unconformity is illustrated in Figure 40. Data used to construct this map were projected from the cross sections. The map shows that the supercrop is represented by formational belts trending NE-SW. These belts sequentially overlap the unconformity surface from the southeast to the northwest.

The seven cross sections (Figs. 12-18) have also been used to construct a fence diagram (Fig. 41). The fence diagram illustrates the three-dimensional stratigraphic framework of Pennsylvanian rocks. The base of the Betsie Shale at the base of the Pikeville formation and overlying the highest stratigraphic level of the Lee Formation, was used as the datum. The upper line of each cross section in the diagram represents the maximum preservation of Pennsylvanian rocks. Stratigraphically deep erosion occurring along the eastern ends of Catlettsburg, Pineville and Harlan sections (Fig. 41) resulted from the Allegheny Front Uplift represented by the Kentucky-Virginia Monocline (Fig. 24). In addition, the notch near the middle of the

Figure 40. Map illustrating the supercrop geology on the Early Pennsylvanian unconformity, projected from the cross sections. (A) Warren Point and its lateral equivalents in the Breathitt Group, (B) Sewanee and its lateral equivalents, (C) Bee Rock and its lateral equivalents, and (D) Corbin and lateral equivalents. Plotted on palinspastic base map.

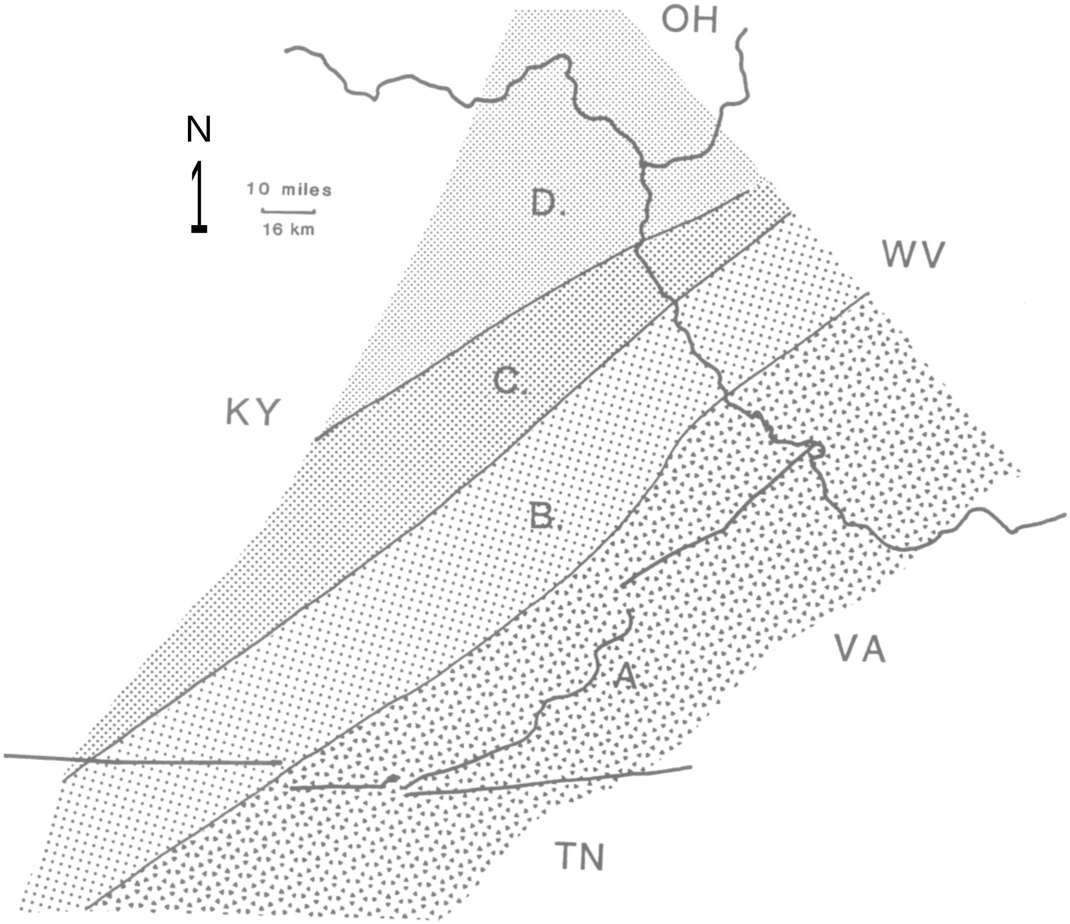

OH
N
10 miles
16 km
D.
WV
C.
KY
B.
VA
A.
TN

Figure 41. Fence diagram of Pennsylvanian-age units. Datum is on the base of the Betsie Shale at the base of the Pikeville formation and the top of the Grundy formation.

See dissertoversize334.pdf

Harlan section (Fig. 41) represents deep erosion associated with the Rocky Face Fault (Fig. 22). The presence of stratigraphically deep erosion can also be observed along the western ends of the dip sections and of the Hazard and Pineville sections (Fig. 41).

Unconformity and Basin Development

Three important large-scale features recognized in this study are: 1). the regional Early Pennsylvanian unconformity, 2). the onlap of Early Pennsylvanian rocks (Warren Point, Sewanee, Bee Rock and Corbin members) to the northwest, and 3),. the apparent successive migration of increasingly smaller depositional basins away from the orogenic areas (Fig. 24). These features have important implications regarding basin development.

The major causes of unconformities include: A). eustatic lowering of sea level, B). uplifts throughout a depositional basin, or C). major aggradation throughout a basin. The origin of the regional Early Pennsylvanian unconformity may have been caused by any or a combination of these processes. Early Carboniferous rocks which were deposited before Late Carboniferous basin development are eroded at the unconformity; therefore, aggradation throughout the basin cannot have been a major cause of erosion at the unconformity.

EUSTATIC ORIGIN FOR UNCONFORMITY

Saunders and Ramsbottom (1986) provided biostratigraphic arguements that mid-Carboniferous unconformities around the world reflect a world-wide sea-level lowering that occurred at the Mississippian-Pennsylvanian boundary. They suggested that the Mississippian-Pennsylvanian unconformity in North America reflects this event.

Eustatic drops in sea level are caused by a decrease in volume of available water or an increase in holding capacity of the ocean basins (see Table 3). Large-scale glaciation results in eustatic changes in sea level, and Carboniferous glaciations from Gondwanan continents are reported (Caputo and Crowell, 1985; Veevers and Powell, 1987). Sequences of Carboniferous transgressive-regressive cycles (Busch and Rollins,1984; Ross and Ross 1985; and Heckel, 1986) are interpreted by Busch and Rollins and by Heckel to record glacial events that lasted less than half a million years. Saunders and Ramsbottom (1986) adduce a 1.9 m.y. duration to the mid-Carboniferous eustatic event. This, however, is about four times as long as the Carboniferous glacial cycles.

An increase in holding capacity of the ocean basins would have caused an eustatic sea-level decrease. Such an increase in capacity could have been caused by the formation of a new oceanic trench or the destruction of a mid-oceanic

Table 3. Causes for eustatic decreases.

Causes for eustatic lowering of sea level

I. Decrease in volume of available ocean water:
Climatic cause– Glaciation

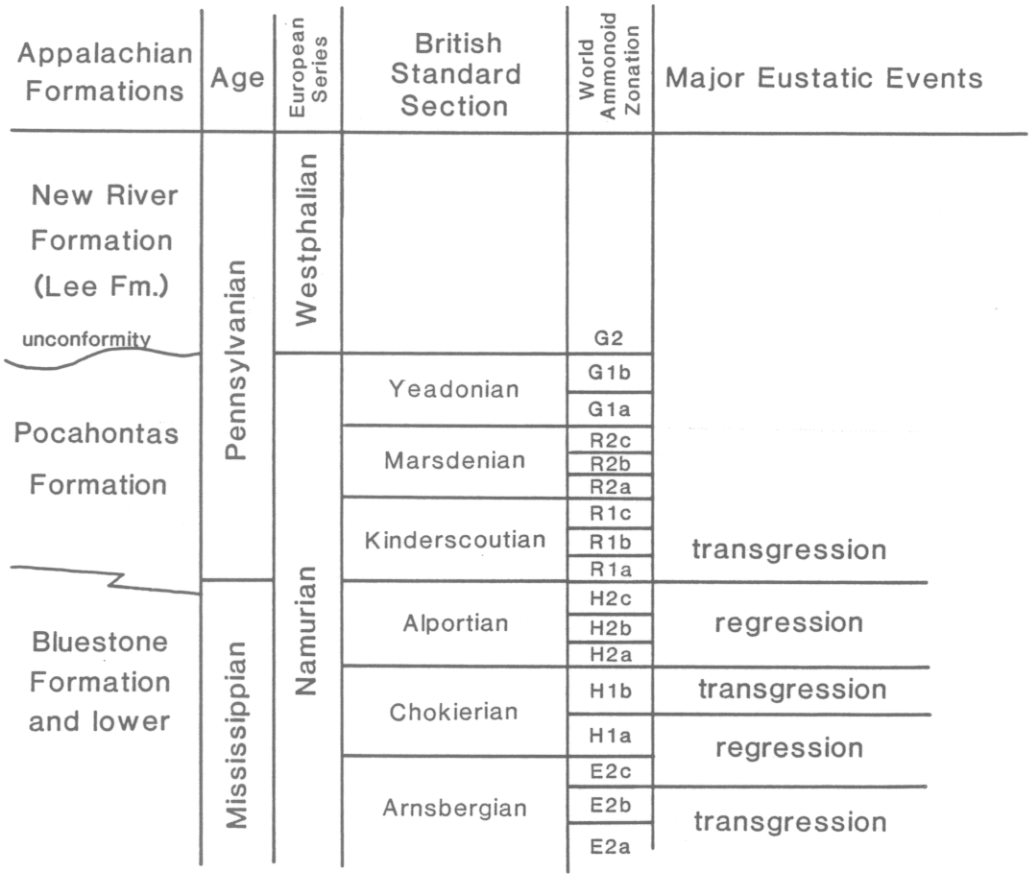
II. Increase in holding capacity of ocean basins:
Tectonic causes
    A. Formation of new trenches
    B. Destruction of mid–oceanic ridges

ridge. Any mid-oceanic ridge between Laurasia and Gondwana would have been destroyed by relative motions of these two supercontinents as they approached one another, although no evidence has been found which supports the destruction of a trench during the Carboniferous. New trenches might have been expected along some edges of a newly formed Pangea. Actual continent-continent collision between Gondwana and Laurasia probably did not occur until much later (Late Pennsylvanian and Permian)(Rast, in press), and therefore new trench development around Pangea would probably have occurred much later than this mid-Carboniferous event. Formation of trenches or destruction of mid-oceanic ridges would have had an effect on sea level that would have lasted tens or hundreds of millions of years, not 2 million years, as suggested for this event. If this event is truly a worldwide lowering of sea level, then some unknown phenomenon other than those mentioned above must have caused it.

TECTONIC ORIGIN OF UNCONFORMITY

As already indicated, the so-called Mississippian-Pennsylvanian unconformity in the Central Appalachian Basin formed during the Early Pennsylvanian, not at the Mississippian-Pennsylvanian boundary. Figure 42 shows the relationship between the Bluestone, Pocahontas, and Bottom

Figure 42. Mid-Carboniferous eustatic events, adapted from information in Gillespie and Pfefferkorn (1979), **Wagner (1982), and Saunders and Ramsbottom (1986).**



Appalachian Formations	Age	European Series	British Standard Section	World Ammonoid Zonation	Major Eustatic Events
New River Formation (Lee Fm.) unconformity	Pennsylvanian	Westphalian		G2	
Pocahontas Formation		Namurian	Yeadonian	G1b	
				G1a	
			Marsdenian	R2c	
				R2b	
				R2a	
			Kinderscoutian	R1c	
				R1b	transgression
				R1a	
Bluestone Formation and lower	Mississippian		Alportian	H2c	regression
				H2b	
				H2a	
			Chokierian	H1b	transgression
				H1a	regression
			Arnsbergian	E2c	
				E2b	transgression
				E2a	

Creek formations and the equivalent European Series and British Standard Section determined by plant fossils (Gillespie and Pfefferkorn, 1979; Wagner, 1982). The eustatic events were correlated through world-wide ammonoid zonation by Saunders and Ramsbottom (1986). The eustatic event described by Saunders and Ramsbottom, therefore, occurred very near the Pocahontas-Bluestone contact approximately coinciding with the Mississippian-Pennsylvanian boundary. The unconformity in the Central Appalachian basin truncates rocks as young as the uppermost Pocahontas, and cannot have been caused by the eustatic events suggested by Saunders and Ramsbottom. A change in lithology between the Bluestone and Pocahontas formations representing a change from shallow marine to paludal and deltaic environments (Miller, 1974) occurs in Virginia and West Virginia. This change has been interpreted in the past to represent a transition between facies in a prograding clastic wedge. However, this change in lithology may also be explained by a drop in sea level, or by a surge of coarser clastics caused by the formation of new highlands to the east.

It seems unlikely that regional tectonics in such separated areas as North America, Europe, North Africa, Spain, Turkey, southern Urals, southeastern China, Japan, and elsewhere (as reported by Saunders and Ramsbottom, 1986) could have all been connected and have occurred at the same time in a single worldwide event. Many of these areas were on widely separated plates. Orogeny along the Variscan-Allegheny belt can be used to relate the geographic occurrence of some of these areas, but synchroneity of the orogeny is not likely even along this belt (Rast, in press).

Some of the many regional tectonic processes which are capable of producing unconformities include: 1.) thickening of the crust due to compression, 2.) formation of a peripheral bulge, 3.) isostatic rebound due to relaxation of crustal stresses or unloading of the crust, 4.) heating of the crust, 5.) faulting, and 6.) overriding of plates. Two of these processes have recently been used to explain the Early Pennsylvanian unconformity.

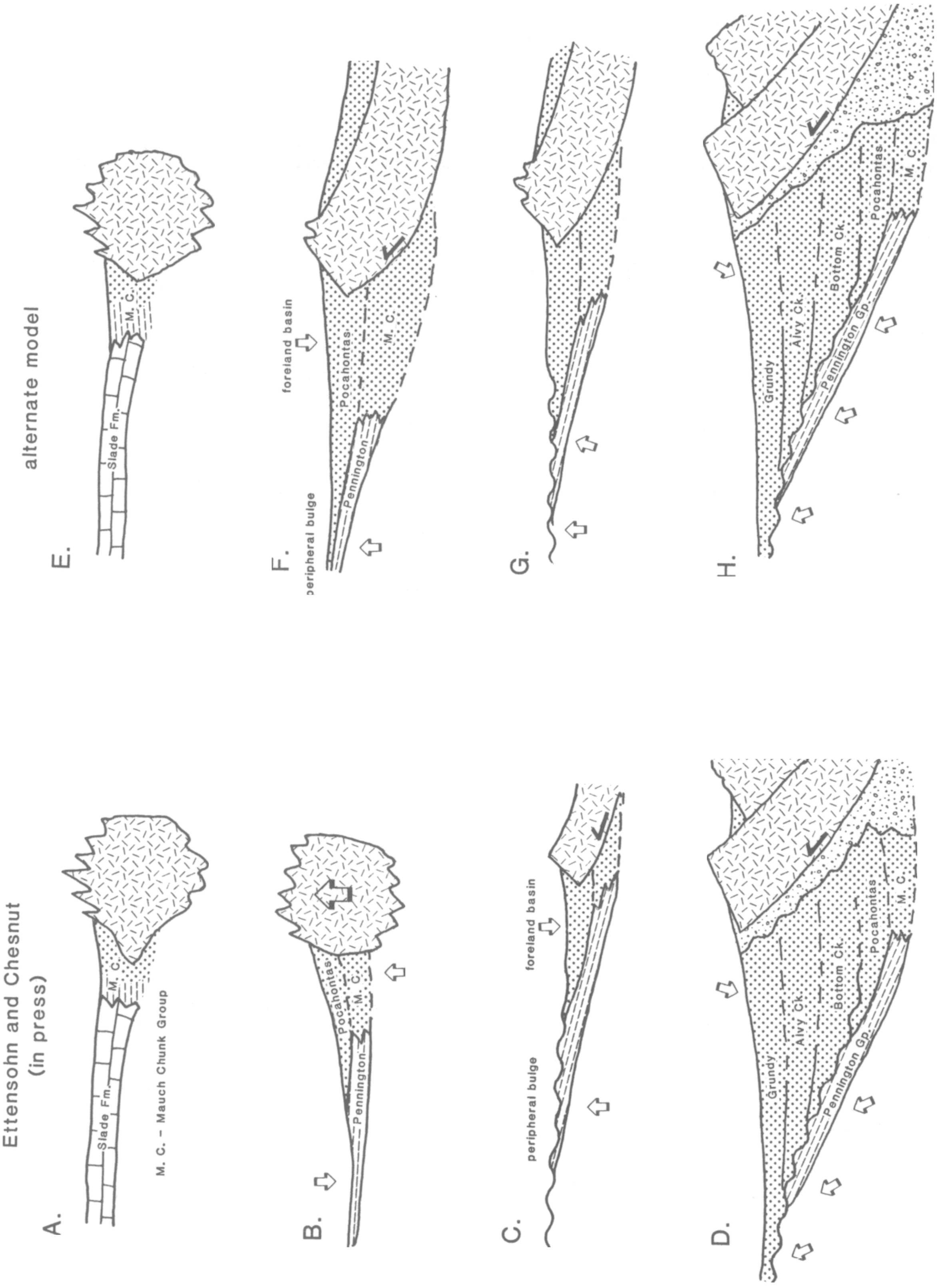
A scenario describing both the origin of basin migration and the regional unconformity has been suggested by Quinlan and Beaumont (1984), who related Appalachian thrusting, development of foreland basins, and movement of the peripheral bulge during the Paleozoic. Their model is incorporated with the Tabular-Erosion model of this study in the following scenario.

The Borden and Ft. Payne formations in the Central Appalachian basin are a clastic wedge derived from the erosion of highlands to the northeast. The basin apparently experienced minimal subsidence during deposition of this wedge. Therefore, the highlands at the source were probably being constantly uplifted by isostatic rebound as they were eroded. Such uplift without concomitant basin subsidence on the craton probably marks the final stages of the Acadian orogeny.

The Slade Formation, part of an extensive carbonate bank in eastern North America represents a stable, quiescent period (Fig. 43a). Although some clastic sedimentation continued in Maryland, eastern West Virginia and in parts of Alabama and Mississippi, clastic sedimentation and subsidence on the craton was minimal. Many of the same processes that existed during the deposition of the Borden and Ft. Payne must have continued during the deposition of the Slade, but at a much reduced rate.

Following the carbonate-platform deposition of the Slade Formation, a southeastward-thickening wedge of Pennington and Pocahontas clastics was deposited (Fig. 43b). According to Rast (1984), an eastern source for these clastics reflects new thrust faulting. If this were the case, then the weight of the thrust block would have loaded the viscoelastic lithosphere. Moreover, the downwarping of the crust due to the weight of the thrust block would have resulted in a foreland basin on the craton adjacent to the thrust. This basin would have received the sediments from the newly produced uplands on the thrust block. In

Figure 43. Comparison of tectonic scenarios for the mid- and Late Carboniferous development of the Central Appalachian basin. (A) Late Mississippian carbonate-platform development. (B) Pennington (Late Mississippian) and Pocahontas (Early Pennsylvanian) deposition. (C) Early Pennsylvanian unconformity. (D) Lee and Breathitt (Early to Late Pennsylvanian) deposition.


Ettensohn and Chesnut
(in press)
alternate model
A.
Slade Fm.
M. C.
M. C. - Mauch Chunk Group
B.
Pennington
Pocahontas
M. C.
C.
peripheral bulge
foreland basin
D.
Grundy
Alvy Ck.
Bottom Ck.
Pocahontas
M. C.
Pennington Gp.
E.
Slade Fm.
M. C.
F.
peripheral bulge
foreland basin
Pennington
Pocahontas
M. C.
G.
H.
Grundy
Alvy Ck.
Bottom Ck.
Pocahontas
M. C.
Pennington Gp.

addition, a peripheral bulge would have been formed cratonward of the foreland basin because of the eastward downwarping of the stiff crust. The position of the peripheral bulge was controlled by the position of the Eastern Interior (Illinois) Basin, by either reinforcing or cancelling the peripheral bulge (Quinlan and Beaumont, 1984); by the interference of stress conditions imposed by the Appalachian and Ouachita systems (Nicholas Rast, personal communication, 1986); or by reactivation of basement structural features. The foreland basin and peripheral bulge, together, would have migrated northwestward as the thrust block moved cratonward. The Pennington Group thins toward the Cincinnati Arch, which may have been the peripheral bulge. The bulge apparently was not sufficiently positive, however, to cause an unconformity within the Pennington Group, the Pocahontas Formation, or between the Pennington and the Slade Formation in the rocks that were preserved marginal to the Cincinnati Arch.

A different scenario for the Pennington and Pocahontas deposition proposed by Ettensohn (personal communication, 1987; Ettensohn and Chesnut, in press) suggests that highlands were not produced by thrust faulting, but by isostatic rebound following deloading (Fig. 43b). Deloading was caused by the erosion of old highlands to the east, and the rebound of the highlands produced a source for the

Pennington-Pocahontas clastics. In this scenario the edge of the craton would have raised along with the highlands, instead of subsiding as a basin. However, the results of this study indicate that basin development was an active process during the deposition of the Pennington and Pocahontas (Fig. 24), and therefore, isostatic rebound was probably not a process controlling deposition of these clastics.

At the end of Pennington and Pocahontas deposition, widespread uplift of the Appalachian foreland basin occurred and erosion created the Early Pennsylvanian unconformity. The uplift of this foreland basin could have been a new peripheral bulge or may have represented relaxation of the crust.

In Ettensohn's model, the Early Pennsylvanian unconformity was formed by northwestward migration of a peripheral bulge produced by the successive emplacement toward the craton of a new load upon the crust (Fig. 43c)(Ettensohn, personal communication, 1987). If the Pennington and Pocahontas peripheral bulge existed at the Cincinnati Arch, as suggested by this study, then the peripheral bulge which formed the Early Pennsylvanian unconformity must have been located in the former Pennington and Pocahontas foreland basin. A peripheral bulge in a former foreland basin could be formed by either reversal in the order of thrusting, or perhaps by emplacement of a new, large load on the crust. Except for the relaxation of stress, peripheral bulges normally migrate away from the area of tectonism, not toward it. Initial thrusts normally occur close to the orogen; subsequent thrusting carries the earlier thrust blocks "piggyback" successively away from the core of the orogen. The creation of a new thrust fault would produce a new peripheral bulge at the locus of the old one or to the west rather than east of it, unless a reverse in the order of thrusting were to occur. A reverse in order of thrust faulting is not likely, and would be indicated by a new foreland basin farther southeast than the locus of the Pennington-Pocahontas basin.

Ettensohn (personal communication, 1987) suggests that the emplacement of a new, larger load would have produced a peripheral bulge within the former foreland basin, which would then migrate toward the craton in conjunction with the emplaced load. The new peripheral bulge would be accompanied by a new foreland basin located farther to the southeast.

Evidence supporting either a reverse in order of thrusting or the emplacement of a new, large load would be the occurrence of a foreland basin farther to the southeast from the locus of the previous Pennington-Pocahontas foreland basin. However, no such basin is recognized in this study. Rather, the Breathitt-Lee foreland basin succeeds the Pennington-Pocahontas basin, but is located farther northwest (Fig. 24). In addition, the fillings of both basins are conformable in parts of Virginia and West Virginia, indicating that normal basin migration was from southeast to northwest. This migration was interupted, but not by another peripheral bulge and foreland basin. Instead, this interuption, represented by the Early Pennsylvanian unconformity, may be explained by relaxation of the crust.

Perhaps because of erosional unloading and time-dependent relaxation of stress in the viscoelastic lithosphere, part of the lithosphere isostatically rebounded (Fig. 43c). The relaxation (Quinlan and Beaumont, 1984) may have raised the lithosphere in part of the foreland basin. This uplift of the lithosphere caused erosion of the Pocahontas, Pennington, and older units, hence creating the regional Early Pennsylvanian unconformity which extended into the foreland basin. A new foreland basin is not produced when relaxation occurs, and indeed, a new foreland basin is not recognized between the Lee and Pocahontas formations.

The actual cause of the unconformity is unknown. Two scenarios based on crustal loading, unloading and relaxation have been decribed above. However, no conclusive evidence is recognized which proves either of these or any of the many other scenarios for formation of the unconformity. Basinal development for the sequence above the unconformity is more easily explained.

Emplacement of a new thrust fault, cratonward of a previous fault, once again would have depressed the lithosphere, this time generating a Lee-Breathitt foreland basin to the northwest of the Pennington-Pocahontas foreland basin (Fig. 43d). Most of the Breathitt and Lee were deposited in this basin. Because younger units overlap the unconformity northwestward (previously described), some migration of the peripheral bulge may have occurred within the vicinity of the Cincinnati Arch.

The emplacement of yet another thrust fault may have led to the formation of yet another foreland basin, the Allegheny Synclinorum. This foreland basin was much smaller than the previous two and formed just northwest of them (Fig. 24). Sediments eroded from the up-thrust highlands and deposited in this basin are represented by the uppermost Breathitt, Conemaugh, and Monongahela and the Permian Dunkard in West Virginia. Erosion of the underlying Breathitt is not known to have occurred, hence the location of the peripheral bulge is not known.

Each of these foreland basins is apparently smaller than the preceding basin (Fig. 24). The position and size of the last basin can be explained, in part, through control by the reactivation of basement structural features such as the Rome Trough and the Irvine-Paint Creek Fault zone (Fig. 22). which restricted the basin to an area between these features. The size of the basins may also be explained, however, by the progressive thinning of the telescoping thrust sheets and the increased spreading of this thrust load on an ever larger area of the lithosphere, thereby causing less loading per area of lithosphere, and therefore producing smaller basins.

During the very Late Pennsylvanian or Permian (Rast, in press) the collision between Gondwana and Laurasia produced a variety of deformational features in the Central Appalachian Basin, including the Allegheny Uplift and the Pine Mountain Fault. The Allegheny Uplift is seen as the progressive uplift of the proximal (to orogen) foreland basinal rocks. The uplift brought an end to the Appalachian foreland basin.

In conclusion, the origin of the migrations of the foreland basins can be attributed to progressive fault-block movement and consequent loading of the lithosphere. The eustatic event at the Mississippian-Pennsylvanian boundary, as inferred by Saunders and Ramsbottom (1986), is not supported by the data in this study because, an intersystemic unconformity between the Pocahontas and

Bluestone Formations is not recognized. The Early Pennsylvanian unconformity either represents an eustatic event caused by a poorly understood mechanism or more likely, by regional tectonic events such as relaxation of lithospheric stress.

Depositional Environments

In the following sections, brief descriptions of the depositional environments of most of the Carboniferous formations, based on previous work, are summarized. More detailed descriptions are given for Pennsylvanian Lee and Breathitt sequences because this study has provided new information useful in the interpretation of depositional environments.

Mississippian Depositional Environments

CHATTANOOGA SHALE

Most of the Chattanooga Shale was deposited during Late Devonian time, while the upper members (Sunbury, Berea, and most of the Bedford) may have been deposited during earliest Mississippian time (Chaplin and Mason, 1979a). The Chattanooga Shale represents deposition within basinal equivalents of the Catskill Delta during the Acadian Orogeny (Ettensohn, 1985a). The black-shale members of the Chattanooga were deposited in anaerobic conditions and represent a phase of rapid subsidence and transgression. The gray-shale and sandstone members were deposited in poorly oxygenated to well oxygenated bottom conditions and represent rapid deltaic progradation and regression (Ettensohn, 1985a). The basic tectonic and paleoclimatic conditions which influenced this deposition are described in Ettensohn and Barron (1982) and Ettensohn (1985a,b). Basinal communities that are preserved in the Chattanooga are described by Kammer and others (1986). The Berea Sandstone and Bedford Shale represent sediments from a subaqueous delta prograding to the south from Ohio and from deltas prograding westward from West Virginia.

The cross sections give little information about Chattanooga environments except that they confirm eastern and northern source areas for the clastics. The gray shales thin and eventually pinch out to the west and southwest, but thicken and become more numerous to the east and north. Sandstone content of the Berea-Bedford interval also increases to the east and north, indicating proximity to the deltas.

BORDEN FORMATION

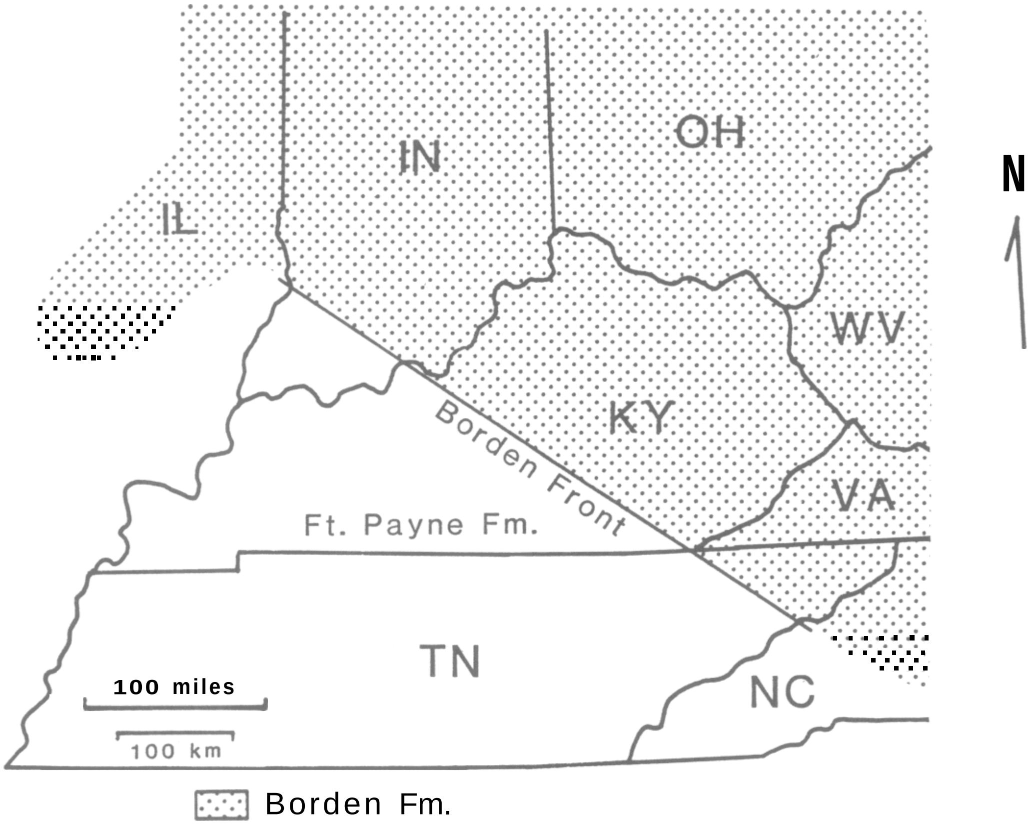
In outcrop, the Borden Formation contains certain diagnostic lithologies. These include turbiditic beds such as the Farmers Siltstone, the "Rockcastle Freestone," and the Kenwood Siltstone (Kepferle, 1977). These turbidite members, plus the prodelta shales of the Nancy Member and the delta-front siltstones and sandstones of the Cowbell Member, make up the southwestly prograding subaqueous Borden Delta. The orientation of the Borden Delta front, as indicated by Lewis and Potter (1978), is shown in Figure 44. Changes in thickness of the Borden Formation observed in the cross sections of this study support the occurrence of the Borden Delta front as indicated in Lewis and Potter (1978).

Recent studies in paleontology of the Borden include Chaplin and Mason (1979a,b), Mason and Chaplin (1979), and Chaplin (1980). Most of these describe the ichnofauna associated with the various delta environments. Gordon and Mason (1983) demonstrated biostratigraphically by employing ammonoids, the time-transgressive progradation of this delta. In recent paleoecological studies by Ausich and others (1979) and Kammer and Cox (1985) the Borden Delta communities have been analyzed and described. In addition, Gutschick and Sandberg (1983) described the paleogeography, paleotectonics, and oceanography of the Early Mississippian formations in North America.

FORT PAYNE FORMATION

In the cross sections constructed in this study, the Fort Payne occurs in the southwestern part of the study area in parts of Tennessee and Kentucky, and thins at the Borden Delta front (Fig. 44). This heterogenous and poorly understood formation needs further study. It is composed of cherty, dolomitic mudstones; cherty dolostones; cherty, geodiferous limestones; and other lithologies, including

Figure 44. Location of the Borden Front, adapted from Lewis and Potter (1978, fig. 8).


N
OH
IN
IL
WV
KY
Borden Front
VA
Ft. Payne Fm.
TN
NC
100 miles
100 km
Borden Fm.

isolated bodies of sandstone, crinoid-bearing biohermal limestones, and "Waulsortian"-type mounds (Lewis and Potter, 1978; MacQuown and Perkins, 1982). The Fort Payne is thought to represent deposition that filled the basin forward of the Borden Delta front. Various types of carbonate mounds were built up marginal to the Borden Delta.

SLADE FORMATION

The Slade represents deposition on a carbonate platform formed by the Borden Delta and Fort Payne Formation. The carbonates were deposited during a tectonically quiescent period. The members of the Slade were deposited in a variety of environments representing shallow open-marine, carbonate-shoal, and subtidal through supratidal conditions. These environments are treated in greater detail in Dever and others (1977), Dever (1980), and Ettensohn (1980, 1981). Paleoecological interpretations for the uppermost Poppin Rock Limestone Member are discussed in Chesnut and Ettensohn (1988).

The additional information obtained from this study concerning this formation is the local presence of Poppin Rock-type limestone beds above the Poppin Rock in the lower part of the Pennington Group. This occurrence indicates that in small, isolated areas carbonate deposition continued while clastics were being deposited in surrounding areas.

PENNINGTON GROUP

Only recently has much work been done on the Pennington Group. The Pennington represents a variety of environments, including shallow open-marine, protected marine, carbonate and clastic shoals, beach-barrier bars, tidal-channel and tidal-flat environments, and fluvial and deltaic environments. A thorough treatment of this complex group cannot be given here, but discussions concerning the paleontology, paleoecology, and depositional environments can be found in many studies, including Wilpolt and Marden (1959), Miller (1974), Englund and others (1979b), Fisher (1981), Chesnut (1983a). Kamm and Heald (1983), Hines and Thomas (1984), Schalla (1984), Close (1985), Ettensohn and Chesnut (1985), and Englund and others (1985).

Cross sections constructed in this study revealed sandstone bodies in the Pennington could apparently be traced over large distances, and a few proved to be helpful in correlation. Some of the sandstones appear to be very clean, indicating either reworking or a clean source. Miller (1974) attributed these sandstones to represent barrier-bar deposition. Because the Pennington is largely confined to the subsurface over most of the basin, no new information suggesting depositional environments for the sandstones was discovered.

The Little Stone Gap Member of the Hinton Formation was observed in Virginia and West Virginia, indicating a marine transgression: this has also been noted by other authors (Wilpolt and Marden, 1959; Miller, 1974). This marine transgression separates two northwest prograding sequences of the Pennington composed of shallow protected-marine, beach-barrier bar, lagoonal and deltaic facies (Ettensohn and Chesnut, 1985).

Pennsylvanian Depositional Environments

LEE AND LOWER BREATHITT FORMATIONS

A widely accepted model for the deposition of the Appalachian Carboniferous rocks hinges on a conformable relationship between the major lithologies. Because the occurrence of a regional unconformity environmentally decouples the Lee Formation and Breathitt Group from the Mississippian formations, the components of Early Pennsylvanian depositional models must be re-examined. In fact, the unconformity surface was probably an influential factor governing Early Pennsylvanian deposition.

The Lee and Breathitt formations onlap the unconformity surface to the northwest. Many of the shale beds throughout the Breathitt Group are marine (Chesnut, 1981). The lithologies of the Breathitt Formation are generally thought to represent shallow restricted-marine and coastal lowland environments including distributary and fluvial systems as well as swamps. Sandstone-body orientation (Breathitt Group), cross-bed orientations, parting lineations, and many other features indicate that the Breathitt represents many cycles of west, northwest, or southwest clastic progradation, followed by peat-swamp development, which in turn is commonly followed by east or northeast marine transgression (Rice and others, 1979). In the lower part of the Breathitt Group, the progradations built westward toward sandstone belts of the Lee Formation.

The Lee Formation occurs in two forms: a.) as channel-fills along the unconformity, and b.) as large sandstone belts. Several deep channels into the regional unconformity surface filled with sandstones of the Lee Formation have been mapped by Rice (1984). Rice indicated a southern direction of flow for these channels. However, most of these paleovalleys did not intersect the lines of cross section so that only a few channels were recorded in this study (see section on topographic relief).

The largest volume of Lee sandstones, however, occurs as four large belt-shaped lenses within the lower part of the Breathitt Group (Figs. 45-48).These belts trend southwest and average about 70 miles (110 kilometers) in width. The belts are composed of a number of sandstones most of which are 65 to 130 feet (20 to 40 meters) thick. Thicker beds

Figure 45. Location of the Warren Point sandstone belt and laterally equivalent lithologies of the Breathitt Group. The blank area northwest of these lithologies represents the unconformity surface exposed during Warren Point deposition. All data were plotted on a palinspastic base map. Contours indicate the depth to the unconformity at the end of Lee deposition.