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SEDIMENTOLOGICAL ASPECTS OF MIDDLE CARBONIFEROUS SANDSTONES ON THE CUMBERLAND OVERTHRUST SHEET

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I hereby recommend that the thesis prepared under my supervision by W. Owen BeMent

entitled Sedimentological Aspects of Middle Carboniferous Sandstones on the Cumberland Overthrust Sheet

be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

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INTRODUCTION

Purpose

This study is concerned primarily with middle Carboniferous molasse sediments in the Central Appalachian Basin exposed on the Cumberland overthrust sheet in southeastern Kentucky (Fig. 1 and 2). In this portion of the basin, shelf carbonates of Mississippian age are separated from terrigenous sediments of Pennsylvanian age by a sequence of thin limestones, varicolored shales, siltstones and sandstones ranging from sublitharenites and quartzwackes to quartzarenites (Fig. 3). The lower part of the sequence, which contains these thin limestones, varicolored shales and siltstones has been named the Pennington Formation (Campbell, 1893, p. 37). The upper part is known as the Lee Formation (Campbell, 1893, p.39), and consists mostly of quartzarenites with minor amounts of siltstone, shale and coal. More recently, the lower three members of the Lee Formation, which are present only in the northeast end of the overthrust sheet, are thought to be correlative with the Pocahontas Formation of West Virginia (Englund and Delaney, 1966, p. 49).

The objectives of this study are to:

1. Establish the depositional environments of this clastic sequence which records the transition from marine shelf carbonates (Mississippian) to fluvial-deltaic, coal bearing sediments (Pennsylvanian).
2. Locate, if possible, the position and determine the character of the Mississippian-Pennsylvanian systemic boundary.

3. Investigate the paleohydraulics of sand deposition in the Pennington and Lee Formations.
4. Develop a comprehensive regional model for middle Carboniferous sedimentation in the Central Appalachian Basin.
5. Characterize the middle Carboniferous molasse of the Appalachian Basin on the basis of provenance and sediment dispersal; and find some modern examples similar in size and sediment dispersal.
6. Explain, where possible, the relationship of the middle Carboniferous sediments in the Appalachian Basin to middle Carboniferous sediments in other Carboniferous Basins in eastern North America in terms of modern plate-tectonic models.

Background For Objectives

In this section, the background and motivation for each of this study's six objectives are briefly discusses.

Objective 1 - Establish the depositional environments of the clastic sequence which records the transition from marine shelf carbonates (Mississippian) to fluvial-deltaic coal bearing sediments (Pennsylvanian).

The first geologists to study the middle Carboniferous sediments of the Cumberland overthrust sheet were employed by state surveys to do field mapping primarily to determine the distribution of the Pennsylvanian coal bearing formations (Table 1). These geologic maps and reports were made for several counties, some of the more notable having been prepared by Harnsberger (1919), Giles (1921) and Eby (1923). Similar reports were made by Campbell (1893) and Ashley and Glenn (1906). Regional correlations in the Central Appalachian Basin based on the data of these early workers were made by Butts (1940) and Wanless (1939).

These first maps and basin-wide correlations were the starting point of a geologic mapping program conducted by state surveys and the U.S. Geological Survey. To date, almost all of the Cumberland overthrust sheet has been mapped on 7-1/2' geologic quadrangles by the U.S. Geological Survey.

For the most part, the middle Carboniferous sediments are economically unimportant, lacking well-developed limestones and coals, and have not received much attention from industry. Studies conducted for economic reasons are those of Wilpolt and Marden (1959), McGrain and Crawford (1959), Froelich (1973) and M. Miller (1974).

Three sedimentological investigations have been completed: Vail (1959) studied the Pennington Formation, Mitchum (1954) studied the Lee Formation, and Miller (1974) studied both the Pennington and Lee Formations and demonstrated the interfingering of these two lithologies in the subsurface. These three workers interpreted the Pennington Formation to represent deposition in various marine, shoreface and tidal environments. Mitchum (1954) and Miller (1974) interpreted the sandstones of the Lee Formation to represent deposition in predominantly marine and shoreface environments. Paleocurrent studies published over the last 20 years for the sandstones of the Lee Formation, or their equivalents throughout the Appalachian Basin, suggest both fluvial and littoral transport environments (Table 1). Several studies have been published in the last few years describing sandstones and criteria for determining their depositional environments; for example: Klein (1970), Le Blanc (1972), Pettijohn, et al. (1972, Ch. 11), and Shelton (1973). To date, comparatively little of this methodology has been applied to the sandstones of the Lee Formation.

Objective 2 - Locate, if possible, the position and determine the character of the Mississippian-Pennsylvanian systemic boundary.

An erosional unconformity separates much of the Pennsylvanian section from underlying strata in the United States (Wanless, 1962, p. 13). This erosional unconformity represents the systemic boundary, is identified by contrasting lithologies and is extensively exposed in the Illinois Basin and along the northwestern (Ohio) and northern (Pennsylvania) margins of the Appalachian Basin. In the Central Appalachian Basin, between Mississippian strata at the base, determined from faunal associations in the carbonates, and Pennsylvanian strata at the top, as determined from spore-pollen floras in coals, is a long sequence of variable but predominantly siliciclastic lithologies which, along the Cumberland overthrust sheet, range in total thickness from 480 to 950 meters. Within this sedimentary sequence is the Mississippian-Pennsylvanian boundary. Regional maps, and subsurface cross-sections perpendicular to the basin axis, show a lithologic boundary which may or may not be the systemic boundary; it is at best a feature difficult to observe in the field in outcrops of the Cumberland overthrust sheet (Englund, 1968, Pl. 5; Miller, 1974, Pl. 2).

Early workers thought the systemic boundary was identified as an erosional unconformity, recorded by a sharp change in lithology (White, 1886, p. 22). This hypothesis has much merit and can be demonstrated along portions of the western margin of the Basin (Sheppard, 1964). Others think the boundary is not lithologic, but rather crosses several lithologies and depositional environments (Englund, 1969, p. 21; Miller, 1974, p. 110). The interbedding of the Pennington and Lee lithologies, which would argue against the boundary being lithologic in character, has been demonstrated along both the western (Sheppard and Dobrovolny, 1962, p.45) and eastern margins of the basin (Englund, 1968, p. 14; Miller, 1974, p. 110). A few think there is no systemic boundary between the Mississippian and Pennsylvanian and that observed paleontological differences are the result of the flora and fauna being restricted to particular depositional environments (Ferm, 1974, p. 94; Horne et al, 1974, p. 98)(Fig. 4).

Objective 3 - Investigate the paleohydraulics of sand deposition in the Pennington and Lee Formations.

Physical processes of sedimentation have been studied by numerous workers, two reviews being those of Allen (1970a) and Pettijohn et al. (1972, Ch. 9). Numerous flume studies have investigated the relationship between grain-size, water depth, velocity, slope and sedimentary structures (Middleton, 1965). Extensive work on modern rivers has resulted in the derivation of empirical relationships between channel depth, width, sinuosity, discharge, channel length and drainage basin area (Schum, 1968; Allen, 1970a; and Joering, 1972).

Thus far, only a few attempts have been made to interpret paleo-hydraulic conditions of sandstone deposition from outcrop data, these being the studies of Cotter (1971), Friend and Moody-Stewart (1972), Leeder (1973), Derr (1974) and Miall (in press).

Objective 4 - Develop a comprehensive regional model for middle Carboniferous sedimentation in the Central Appalachian Basin.

Present regional sedimentation models for the middle Carboniferous of the Central Appalachian Basin reflect the different interpretation for the depositional environments of the Lee Formation sandstones. After completing a detailed analysis of the Lee sandstones on the Cumberland overthrust sheet, and visiting several localities throughout the Appalachian Basin described by earlier workers, it should be possible to synthesize these works, with perhaps some reinterpretation, into a consistent regional sedimentation model.

Objective 5 - Characterize the middle Carboniferous molasse of the Appalachian Basin on the basis of provenance and sediment dispersal; and find, if possible, some modern examples similar in size and sediment dispersal.

Molasse basins can be characterized by size, setting, fill, and various sediment dispersal patterns, which include longitudinal, lateral from predominantly one or both sides, and radial. Additional paleo-current data, a synthesis of the published studies (Table 2) and accomplishment of objectives 1 and 4 should lead to a characterization of middle Carboniferous molasse sediments in the Appalachian Basin. It is also likely that some modern molasse basins are similar in size, setting and dispersal system to that of the Appalachian Basin during the middle Carboniferous, and can be subsequently used as modern analogues.

Objective 6 - Explain, if possible, the relationship of the middle Carboniferous sediments in the Appalachian Basin to middle Carboniferous sediments in other Carboniferous basins in eastern North America in terms of modern plate-tectonic models.

The relationship between tectonics and sedimentation, and the development of present day plate-tectonic theory, lead to discussing the relationship of several sedimentary basins to one another. Middle Carboniferous sediments are found in the preserved portion of several Carboniferous molasse basins in eastern North America (Fig. 1). A review of the literature indicates that these basins can be characterized by differences in their fill, sediment dispersal, interpreted depositional environments and tectonic setting.

Methodology

The sandstones of the Pennington and Lee Formations are well exposed, forming resistent hogbacks on Pine and Cumberland Mountains. Fieldwork consisted of collecting data at stations spaced 6 to 10 kilometers apart along Pine and Cumberland Mountains. Data collected included paleocurrent information; vertical profiles of bedding type, grainsize and clay mineralogy. Samples were collected for petrology and paleontology studies. The combination of poor siltstone and shale exposures, except in some highway and railroad cuts, and limited subsurface data restrict the construction of lithologic and facies maps. Only in the extreme northeast portion of the overthrust, where the Lee Formation overlies the coal bearing Pocahontas Formation, are there sufficient subsurface core data for construction of lithofacies maps (Miller, 1974; Englund, 1974).

Analysis of the samples in the laboratory was conducted simultaneously with the construction of cross sections using data obtained from fieldwork, drillers logs, cutting descriptions and published sections (Fig. 5). Conodonts were separated from limestones and calcareous shales and sent to Dr. Carl Rexroad, Indiana Geological Survey, for identification. Macerations were made of the coals for the determination of spore-pollen assemblages by Dr. Russell Peppers, Illinois State Geological Survey, and Dr. Robert Kosanke, U.S. Geological Survey.

These data were used to determine the internal stratigraphy, petrology and depositional environments of the sandstones.

TABLE 1

PREVIOUS INVESTIGATIONS OF
MIDDLE CARBONIFEROUS SEDIMENTS
ON THE CUMBERLAND OVERTHRUST

County Reports

Crandall (1889)
Butts (1914)
Harnsberger (1919)
Giles (1921, 1925)
Wentworth (1922)
Eby (1923)

Coal Field Reports

Campbell (1893)
Ashley and Glenn (1906)

Sedimentologic

Mitchum (1954)
Vail (1959)
Miller (1974)

Stratigraphic Correlation

Butts (1940)
Wanless (1946)
Wilpolt and Marden (1959)
Englund (1964, 1968, 1969)
Englund and Delaney (1966)
Miller (1969)
Miller (1974)

Economic

McGrain and Crawford (1955) Silica Sands
Wilpolt and Marden (1959) Oil and Gas
Froelich (1973) Oil and Gas
Miller (1974) Coal

TABLE 2

PALEOCURRENT STUDIES OF
LOWER PENNSYLVANIAN SANDSTONES
IN THE APPALACHIAN BASIN

NORTHEAST → SOUTHWEST

Study Area	Author	Depositional Environment
Pennsylvania Ohio	Meckel (1967)	Fluvial
Ohio	Mrkovich and Coogan (1974)	Fluvial
Ohio, Kentucky Tennessee	Potter and Siever (1956)	Fluvial
Kentucky Tennessee	Mitchum (1954)	Littoral
Tennessee, Georgia Alabama	Schlee (1963)	Fluvial
Tennessee	Jones (1972)	Littoral
Tennessee	Ferm, et. al. (1972)	Littoral
Alabama, Georgia	Chen and Godell (1964)	Fluvial
Alabama	Metzger (1965)	Littoral
Alabama	Hobday (1969)	Littoral

FIGURE 1. Middle Carboniferous basins in the eastern United States. The Appalachian Basin has been divided into three sub-basins (Wanless, 1967, Fig. 2). Maximum thickness of middle Carboniferous sediments in the Central Appalachian Basin is 1100 meters. The smaller Woonsocket and Scituate basins, west of the Narragansett Basin are not shown.

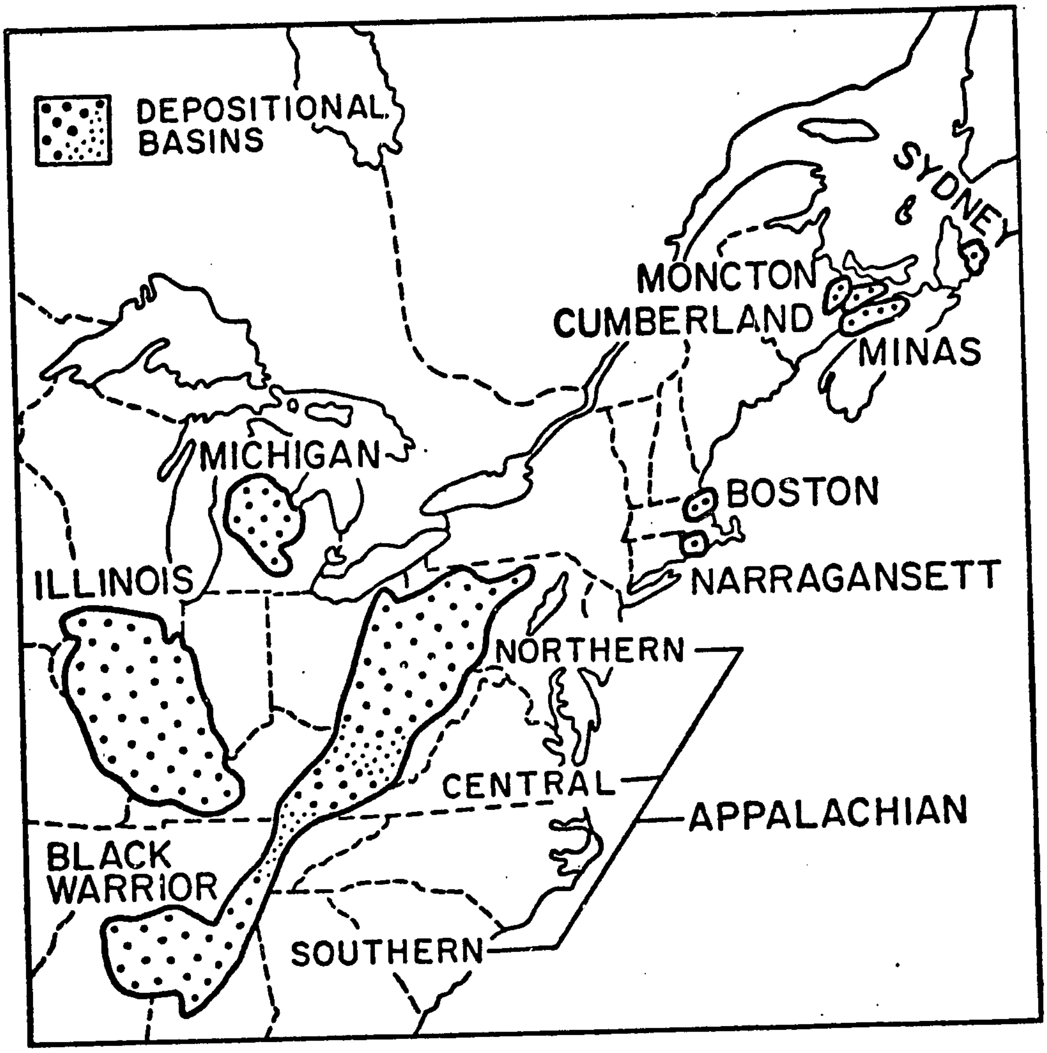
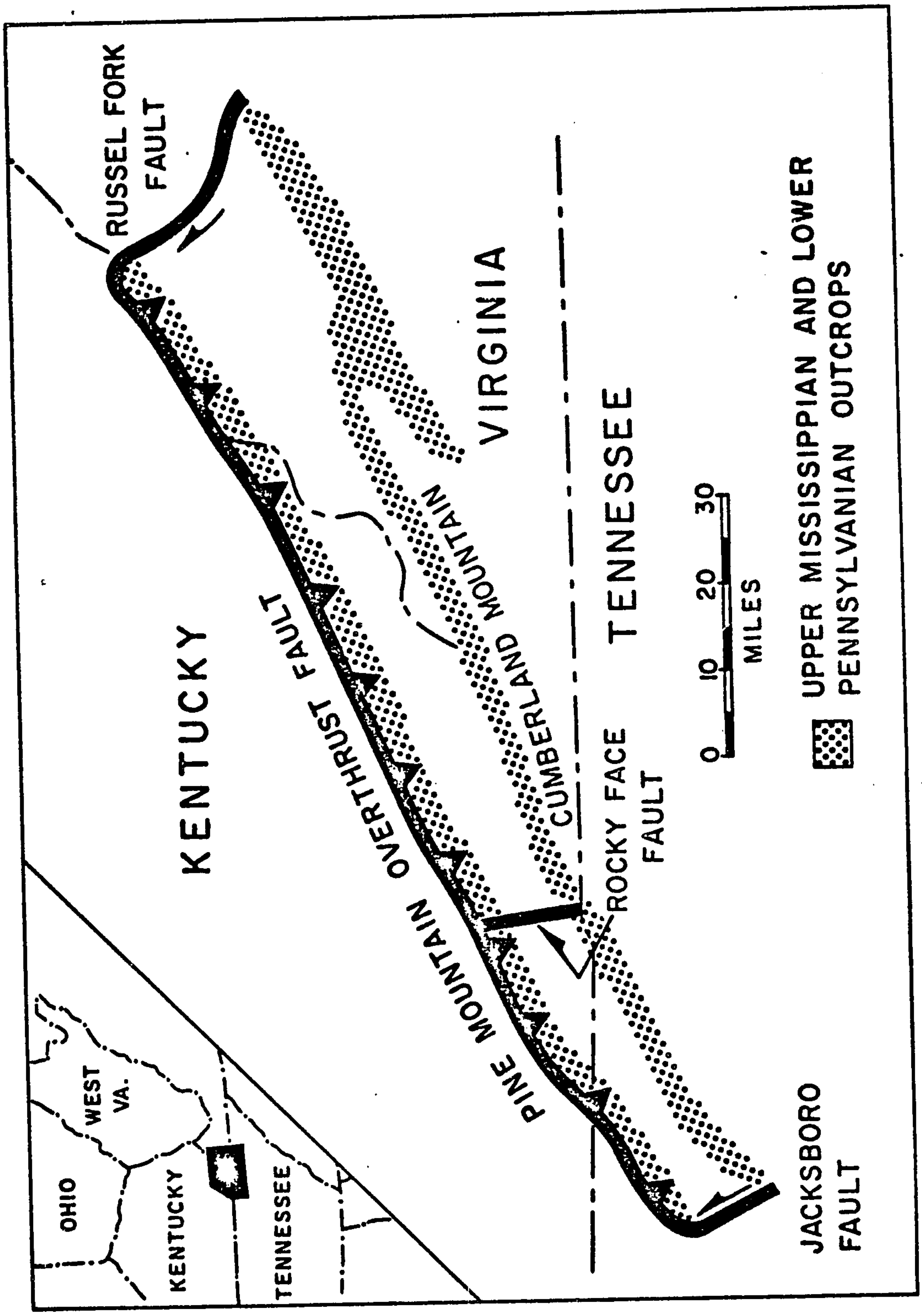

DEPOSITIONAL BASINS
SYDNEY
MONCTON
CUMBERLAND
MINAS
MICHIGAN
BOSTON
NARRAGANSETT
ILLINOIS
NORTHERN
CENTRAL
APPALACHIAN
BLACK WARRIOR
SOUTHERN

FIGURE 2. Location of the Cumberland overthrust sheet and the Pine Mountain overthrust fault, which is considered to have a lateral displacement to the northwest ranging from 6.4 kilometers along the Russell Fork Fault to 17.6 kilometers along the Jacksboro Fault. (Englund, 1968, p. 30; Miller, 1974, p. 15)



RUSSEL FORK FAULT
VIRGINIA
KENTUCKY
PINE MOUNTAIN OVERTHRUST FAULT
CUMBERLAND MOUNTAIN
TENNESSEE
ROCKY FACE FAULT
JACKSBORO FAULT
0 10 20 30
MILES
UPPER MISSISSIPPIAN AND LOWER PENNSYLVANIAN OUTCROPS
OHIO
WEST VA.
KENTUCKY
TENNESSEE

FIGURE 3. Generalized stratigraphic section of middle Carboniferous sediments on the Cumberland overthrust sheet. Thickness varies from 480 meters at Jellico, Campbell Co., Tennessee, to over 950 meters at Little Stone Gap, Wise Co., Virginia.

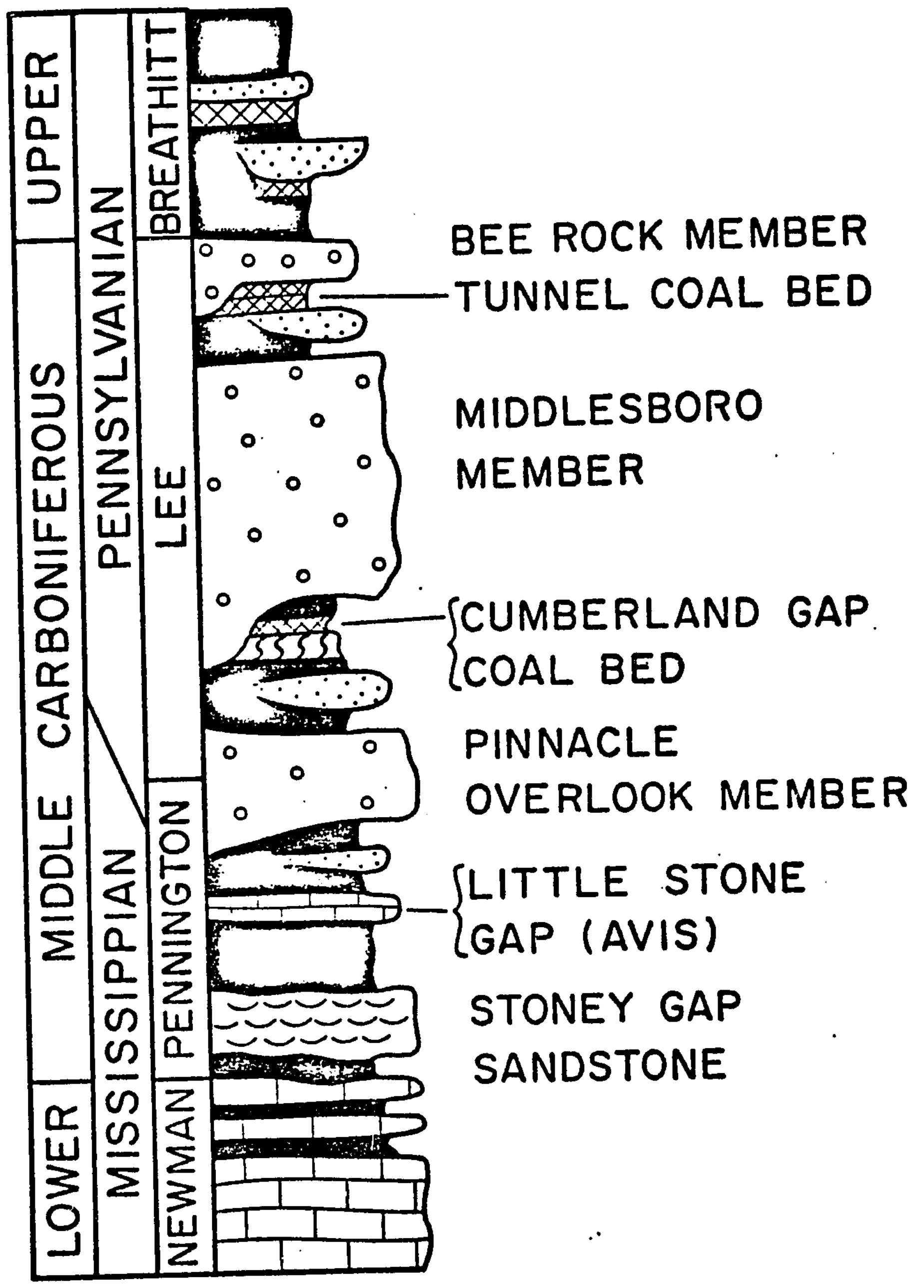

UPPER
MIDDLE CARBONIFEROUS
LOWER
PENNSYLVANIAN
MISSISSIPPIAN
BREATHITT
LEE
PENNINGTON
NEWMAN
BEE ROCK MEMBER
TUNNEL COAL BED
MIDDLESBORO MEMBER
CUMBERLAND GAP COAL BED
PINNACLE OVERLOOK MEMBER
LITTLE STONE GAP (AVIS)
STONEY GAP SANDSTONE

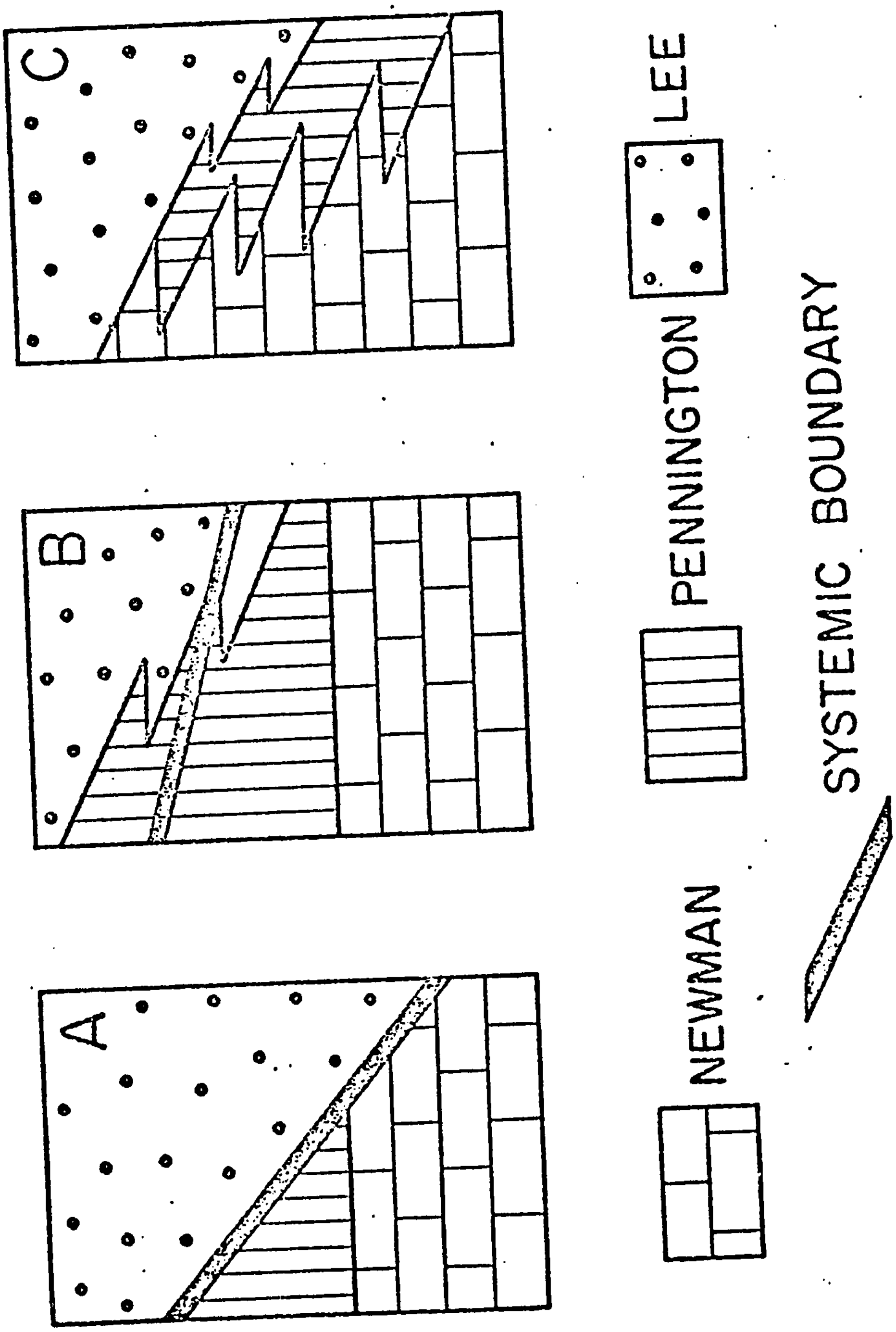
FIGURE 4. Diagrammatic sections showing possible types of systemic boundaries:

A. Lithologic boundary at erosional contact (white, 1886; Shepard, 1964),

B. Boundary crosses several lithologies (Englund, 1974; M. Miller, 1974) and

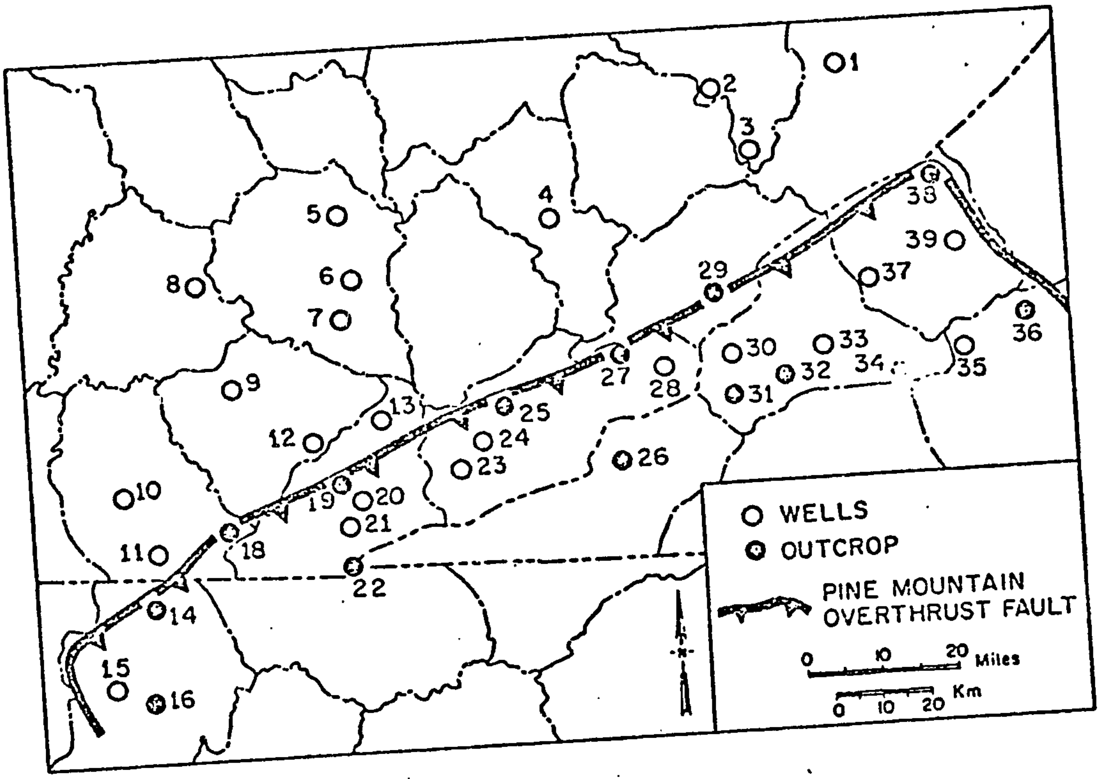
C. No systemic boundary (Ferm, 1974; Horne et al., 1974).

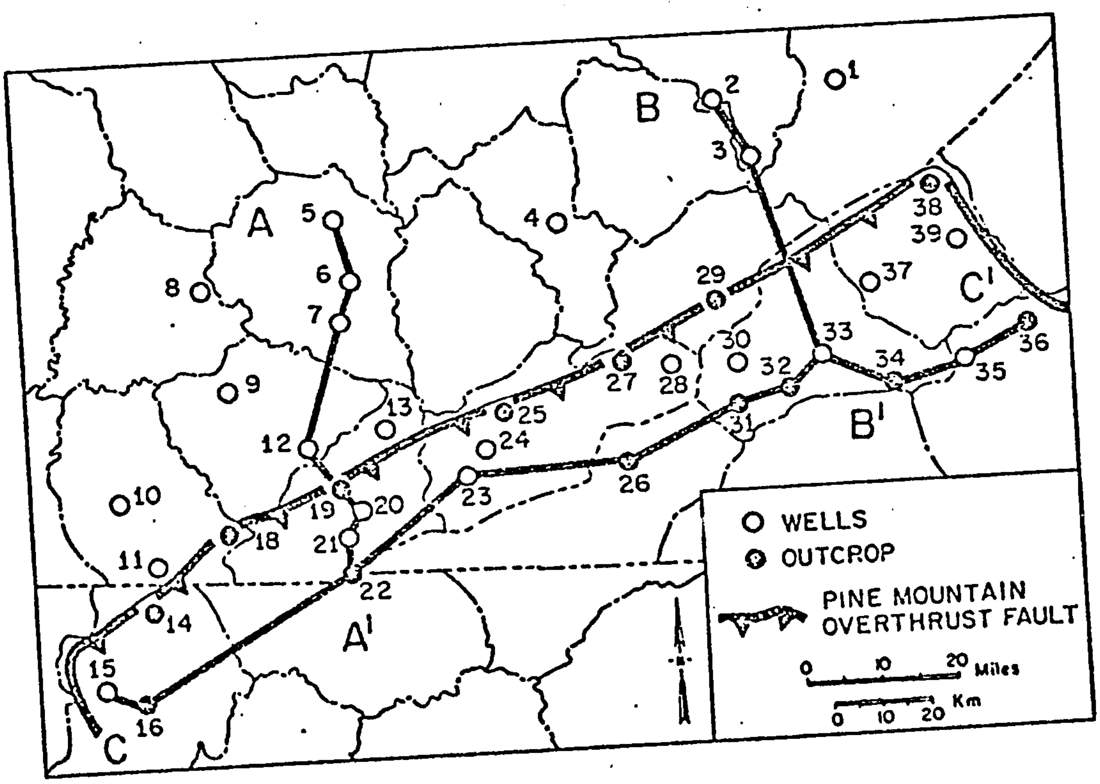
Another possible type of systemic boundry, not deemed likely here, is for it to occur entirely within one lithology.



A
B
C
NEWMAN
PENNINGTON
LEE
SYSTEMIC BOUNDARY

FIGURE 5. Location of wells and measured sections used to construct isopachs and cross sections. Numbered control points are listed in Appendix 1. Section descriptions are in Appendix 2.


WELLS
OUTCROP
PINE MOUNTAIN OVERTHRUST FAULT
0 10 20 Miles
0 10 20 Km


A
A'
B
B'
C
C'
WELLS
OUTCROP
PINE MOUNTAIN OVERTHRUST FAULT
0 10 20 Miles
0 10 20 Km

STRUCTURAL AND STRATIGRAPHIC SUMMARY

Cumberland Overthrust Sheet

One of the major structural features in southeast Kentucky is the Cumberland overthrust sheet, which is warped into two broad folds, the Middlesboro syncline and the Powell Valley anticline. The Middlesboro syncline is bounded on the southeast by Cumberland Mountain and to the northwest by Pine Mountain, along the trace of the Pine Mountain overthrust fault.

The Pine Mountain overthrust fault, at the base of the Cumberland overthrust sheet, extends from the Jacksboro fault in Tennessee northeast through three states and terminates at the Russell Fork fault in Virginia, approximately 200 km away (Fig. 2). The overthrust fault at the southwest end of the overthrust sheet is composed of several imbricate faults which dip to the southeast and converge to a single bedding plane fault in the subsurface (Englund, 1968, p. 28).

The Jacksboro and Russell Fork fault zones are strike-slip fault zones 0.8 to 1.6 km wide. Movement of the overthrust sheet was approximately 17.6 km to the northwest along the Jacksboro fault (Englund, 1968, p. 30) and 6.4 km northwest along the Russell Fork fault (M. Miller, 1974, p. 15). The Rocky Face fault, located near the Tennesse-Kentucky boarder, is a high angle normal fault with the upthrown side (northeast) being slightly displaced to the northwest.

Nomenclature

The Cumberland overthrust sheet lies in three states resulting in three different stratigraphic nomenclatures for the various members of the Pennington and Lee Formations. Early correlations were made by Wanless (1946) and more recently by Englund (1968) and M. Miller (1974). A correlation of the middle Carboniferous sediments on the Cumberland overthrust sheet, which will be used in this report, was constructed from a synthesis of these and other works (Table 3).

The name Pennington was originally applied by Campbell (1893, p. 28) to the sequence of thin limestones, varicolored shales and siltstones and quartzwackes that occur between the massive carbonates (Newman-Greenbrier) and the conglomeratic quartzarenites (Lee) at Big Stone Gap, Lee County, Virginia. In 1896, Campbell and Mendenhall applied the names Hinton Formation, Princeton Sandstone and Bluestone Group to strata occupying a similar stratigraphic position along the New River in West Virginia, without indicating their relationship to Campbell's earlier Pennington Formation. Wilpolt and Marden (1949) remeasured the section of Campbell and Mendenhall and correlated the Pennington with the Hinton, Princeton and Bluestone. Harris and Miller (1958) raised the name Pennington to group status, thereby including the Hinton Formation, Princeton Sandstone and Bluestone Formation and equating these three to the stratigraphic sequence of Campbell (1893).

The upper part of the Bluestone Formation was recognized by Englund (1968), and more recently by M. Miller (1974) in the subsurface between Big Stone Gap and Elkhorn City (Fig. 6) as the coal bearing Pocahontas Formation of Campbell (1896, p, 3).

Southwest of Pennington Gap, the Pennington is divided into two unnamed members. Based on comparison of lithology and stratigraphic position, the unnamed lower member is correlative with the Stoney Gap Member of the Hinton Formation and the upper member with the remainder of the Hinton, the Princeton and Bluestone Formations. The Pinnacle Overlook sandstone is correlative with the Princeton (Fig. 6).

The name Pocahontas was originally applied by Campbell (1896, p. 3) to a coal-bearing sequence of sandstone, siltstone, shale and underclay. It was not recognized in the Cumberland overthrust sheet by earlier workers as a mappable unit and was included in either the Pennington (Wentworth, 1922; Wilpolt and Marden, 1959) or Lee Formations (Eby, 1923; Butts, 1940). Later detailed mapping has indicated the Pocahontas Formation is present in outcrop (Englund and Delaney, 1966, Fig. 2) and can be traced into the subsurface (Englund, 1974, Fig. 1; M. Miller, 1974, Fig. 23).

The name Lee was originally applied by Campbell (1896, p. 36) to a sequence of massive conglomeratic quartzose sandstone exposed on Cumberland Mountain in Lee County, Virginia, and was subsequently applied to lithologically similar sandstones at the same stratigraphic position throughout Virginia and southeastern Kentucky (Table 3).

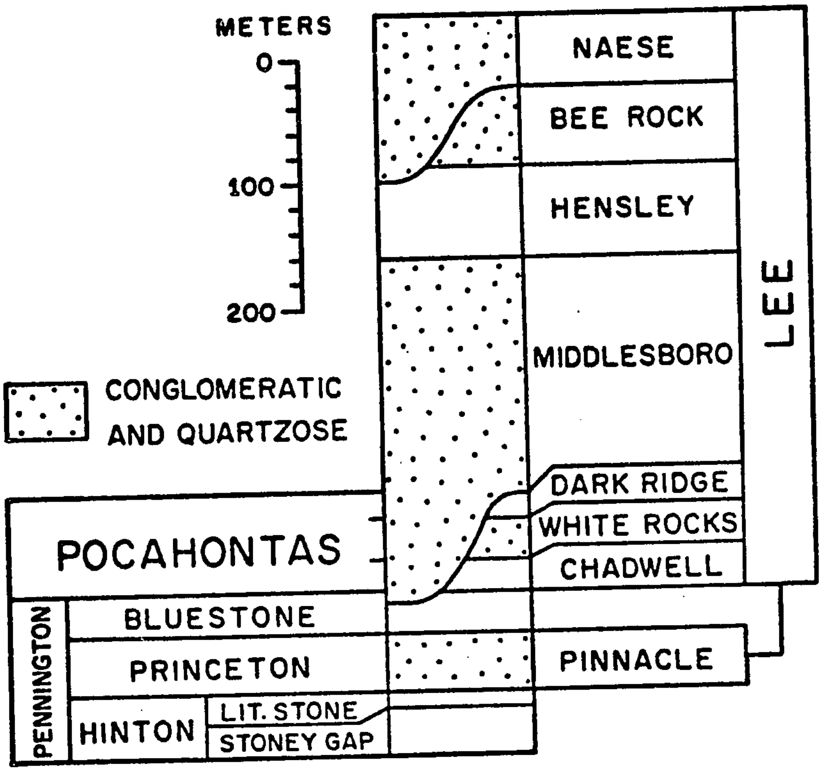
TABLE 3

STRATIGRAPHIC NOMENCLATURE OF MIDDLE CARBONIFEROUS SEDIMENTS ON THE CUMBERLAND OVERTHRUST SHEET

		Tennessee 1, 2, 3		Pine Mountain Kentucky 1, 4, 5			Cumberland Mountain Kentucky 1, 4, 5, 8			Big Stone Gap Virginia 6, 7		
Pennsylvanian	Pottsville	Crab Orchard	Wartburg	Lee		Naese	Lee		Naese			Bee Rock
						Bee Rock			Bee Rock			
			Vandever		D	Hensley		D				New River
			Newton		C	Middlesboro		C				
			Whitwell		B			B	Dark Ridge / White Rocks			Pocahontas
			Sewanee		A			A	Chadwell			
Mississippian	Chester	Gizzard	Signal Point	Pennington	Upper		Pennington	Upper		Pennington		Bluestone
			Warren Point			Pinnacle			Pinnacle			Princeton
			Racoon Mtn.						Little Stone Gap		Hinton	Little Stone Gap
												Middle Red
		Pennington			Lower	Stoney Gap		Lower				Stoney Gap
				Newman		Upper	Newman		Upper			Bluefield
		Bangor				Lower			Lower			Greenbrier
												Maccrady

1. Milici (1974); 2. Wilson et al. (1956); 3. Ferm et al. (1972); 4. Englund (1964), 1968);
5. Wanless (1946); 6. Wilpolt and Marden (1959); 7. Miller (1974); 8. Maughan and Tazelaar (1973).

FIGURE 6. Relationship between Pennington Group, Pocahontas Formation and Lee Formation. The Pocahontas has been shown to be equivalent, in part, to the three lower members of the Lee Formation (Englund and Delaney, 1966, p. 49). The unconformity at the base of the Middlesboro Member, which truncates the Pocahontas (or equivalents) southwest of Middlesboro, is recognized throughout the overthrust sheet. The unconformity at the base of the Naese Sandstone Member, southwest of Middlesboro, truncates the Bee Rock Sandstone Member, and replaces it as the uppermost member of the Lee Formation.


METERS
0
100
200
CONGLOMERATIC
AND QUARTZOSE
NAESE
BEE ROCK
HENSLEY
MIDDLESBORO
LEE
DARK RIDGE
WHITE ROCKS
CHADWELL
POCAHONTAS
BLUESTONE
PRINCETON
PINNACLE
PENNINGTON
HINTON
LIT. STONE
STONEY GAP

DESCRIPTIVE STRATIGRAPHY

The outcrop stratigraphy for the Cumberland overthrust sheet has been summarized and described by previous workers (Table 1). These descriptions are supplemented by information contained on numerous U.S. Geological Survey quadrangle maps, and sections measured by the writer at localities 14, 18, 25, 27 and 31 (Fig. 5 and Appendix 2).

Understanding the lateral variation within the Pennington, Pocahontas and Lee Formations and their intertonguing relationships, as determined from outcrop studies and subsurface cross sections, is essential in attempting to determine the relationship between lithology and the nature of the Mississippian-Pennsylvanian systemic boundary. In both outcrop and subsurface studies, the basal sandstones of the Pocahontas tongue out and interbed with grayish-red and greenish-gray shale and siltstone in the Bluestone Formation of the Pennington Group. The intertonguing of the Pennington and Lee Formations involves the northwestward pinching out of the quartzarenite sandstone tongues of the Lee into varicolored shales, siltstones and quartzwackes of the Pennington.

The location of measured sections and wells used to prepare cross sections and isopach maps are listed in Appendix 1 and shown in Figure 5.

Pennington

The Pennington Formation is recognized everywhere along the outcrop primarily by its characteristic ripple bedded fine grained sandstones, interbedded varicolored shales and argillaceous limestones. Near the upper part of the Pennington occur the Princeton-Pinnacle quartzarenite sandstone bodies, in part conglomeratic, which are lithologically similar to the sandstones of the Lee and hence referred to as tongues of the Lee (Fig. 6). These tongues, which are present throughout much of the overthrust sheet (Fig. 7, 8, and 9), appear to pinch out to the northwest and do not seem to be connected to the overlying Lee sandstones.

Isopachs of the interval between the Newman Limestone and the first widespread sheetlike conglomeratic quartzarenite of the Lee (Fig. 10) show a Pennington interval ranging between 135 and 400 meters thick. The general thickening to the northeast is caused by an increasing thickness in the Hinton or lower member and thinning of the Bluestone or upper member to the southwest. This decrease is due to thinning of individual beds and truncation by erosion which preceded deposition of the conglomeratic quartzarenite.

Southwest of Pennington Gap, the lower member, the Stoney Gap Sandstone of the Hinton Formation, is the most persistant part of the formation (Fig. 6). Basal beds consist of thick bedded, massive, light gray, fine to medium sandstone overlain by ripple marked beds of light gray to olive, very fine sandstone interbedded with greenish-gray shale. Marine fossils are locally abundant as bryozoan-crinoid wackestones.

Clay pebble conglomerates are common where the sandstones are crossbedded. The upper member is much more diverse, probably due to its interfingering with the quartzarenite tongues. The upper member may be divided locally into five units (Englund, 1968, p. 13): three shales separated by two sandstones. The shales are either olive or gray and contain gray-red siltstones. A gray argillaceous limestone as much as three meters thick occurs in the lowest of the units and is correlative with the Little Stone Gap Member of the Hinton. This is the Avis Limestone of Reger (1926). Thin, unnamed coals and underclays are present in the uppermost of these five units.

The intervening sandstones are thin- to thick-bedded, fine grained, micaceous, light gray and rippled. Where the sandstones grade into the Lee quartzarenites, they become more massive and coarses grained (Fig. 12).

Conodonts sampled from the Little Stone Gap Member of the Hinton Formation, the Bluestone Formation or correlative argillaceous limestones at localities 14, 18, 20, 31 and Pound Gap, Wise County, Virginia indicate an Upper Mississippian (Middle Chester) age (C. B. Rexroad, 1975, written comm., Table 4). Spore and pollen analysis of the stratigraphically lowest coals, which occur above the conodont samples, from the upper part of the Pennington Formation, are Pennsylvanian in age (R. A. Peppers, 1974, written comm., Table 5).

Good exposures of the Pennington Formation can be seen at localities 14, 18 and 29.

Pocahontas

The Pocahontas is present only in the northeast end of the Cumberland overthrust sheet and ranges in thickness from 0 to 150 meters (Fig. 6). The base of the Pocahontas interfingers with the Pennington and is truncated at the top by the conglomeratic quartzarenites of the Lee (M. Miller, 1974, p. 37). The formation thins to the northwest by truncation and is not recognized on Pine Mountain.

Sandstones constitute about 70 percent of the formation and have two distinct distribution patterns (Englund, 1974, p. 33). Linear quartzose sand bodies, as much as 45 meters thick and 5 to 13 km wide, composed of well sorted, fine to medium grained sand occur in the subsurface near the northwestern margin of the formation and trend approximately northeast-southwest (Englund, 1974, p. 37). Lobate quartz- and lithicwackes, orientated in a bifurcating pattern to the northwest, contain lenses of quartz pebble conglomerate, but are predominantly light gray, medium to coarse grained, poorly sorted sand (M. Miller, 1974, p. 37). The remainder of the formation is composed of light gray siltstone, gray or black shales and as many as 11 coals with associated underclays. Eight of these coals are mined commercially in both shaft and strip mine operations.

The Pocahontas Formation includes the oldest Pennsylvanian strata of a continental facies in the Appalachian Basin known to contain the fossil plant Neuropteris pocahontas (Read and Mamay, 1964, p. K2). Similar plant fossils occur in the intertonguing beds of the Bluestone Formation (Englund, 1974, p. 33). Marine fossils in the Bluestone below the basal tongue of the Pocahontas are reported to have an Upper Mississippian (Chester) age (Englund, 1974, p. 34).

Good exposures of the Pocahontas can be seen at localities 34 and 36.

Lee

The formation is present throughout the study area and thins to the northwest by the pinching out of lower beds (Figs. 7 and 8). To the northeast along Cumberland Mountain, the Lee sandstones interfinger with the coal bearing New River Formation (Fig. 9 and Table 3).

During the geologic mapping program, the formation has been divided locally into as many as 8 members; 6 composed of conglomeratic, fine to coarse grained quartzose sandstones and two composed of fine grained, thin bedded sandstones with gray-black shales, underclays and coals. The lowest three members (Pinnacle Overlook, Chadwell and White Rocks) are conglomeratic quartzose sandstones that interfinger with the Pennington and Pocahontas (Fig. 6).

The most common sedimentary structure of the conglomeratic sandstones are planar and trough crossbedding; massive bedding, even lamination and ripple bedding are present in lesser amounts. Ripple bedding and crossbedding are the characteristic feature of the sandstones in the 2 coal bearing members (Dark Ridge and Hensley) of the formation (Fig. 13).

Because the Lee is recognized as a rock stratigraphic unit with lower and upper contacts defined by conglomeratic quartzose sandstones, the bounding contacts are not always defined by the same member. The base is usually defined by the Chadwell or Middlesboro Member, with the Pinnacle being referred to as a tongue. The Naese Sandstone Member (Fig. 6) is present only in the southwest end of the overthrust, where it is recognized as the uppermost member along Pine Mountain. Along Cumberland Mountain, the Naese thins out toward the east, and northeast of Cumberland Gap, the uppermost member is the stratigraphically lower Bee Rock Sandstone. The Bee Rock is truncated southwest of Pineville and Cumberland Gap by a regional unconformity at the base of the Naese Sandstone (Englund, 1968, p. 18).

The Chadwell, White Rocks and Dark Ridge Members are present only in the central and northeast sections of the overthrust sheet and may be in part correlative with the Pocahontas Formation (Englund and Delaney, 1966, p. 49), (Fig. 6).

Fieldwork and cross sections prepared by the writer indicate that the Pocahontas Formation is correlative with the Chadwell, White Rocks and Dark Ridge Members of the Lee Formation, as proposed by Englund and Delaney (1966). These three lower members of the Lee, unconformably overlain by the Middlesboro Member of the Lee, are truncated southwest of Middlesboro and Pineville. Because the Pocahontas is correlative with the lower part of the Lee, throughout the rest of this paper the Pocahontas will be included in the Lee and future discussion will be in terms of the Pennington and Lee Formations. When necessary, special reference will be made to the Pocahontas Formation (the lower members of the Lee).

TABLE 4

CONODONTS OF THE UPPER PENNINGTON FORMATION

(Identified by Dr. C. B. Rexroad, Indiana Geological Survey. Sample locations are given in Appendix 4B. All samples dated Chesterian.)

	Henry Bowlin Gap Whitley Co., Ky.	Big Stone Gap Wise Co., Va.	I-75, Jellico Campbell Co., Tenn.	Pound Gap Wise Co., Va.
Cavusgnathus	X	X	X	
C. unicornis	X	X	X	X
C. convexa		X		
C. regularis		X		X
Gnathodus				
G. commutatus				
G. bilineatus				
Hibbardella				
H. milleri	X			X
Hindeodella	X	X		X
Kladognathus				
K. primus	X			
Lambdagnathus	X	X		X
Ligonodina				
L. levis	X			X
L. tenuis		X	X	X
Magnilaterella	X	X		X
Neoprioniodux				
N. camurus		X		X
N. peracutus				X
N. singularis	X	X		
N. tulensis	X	X		X

Ozarkodina	X	X	X
Spathognathodus			
S. campbelli		X	
S. cristula			

TABLE 5

SPORE ASSEMBLAGES OF LOWEST COALS

(Identified by Dr. R. A. Peppers, Illinois Geological Survey and Dr. R. M. Kosanke, U. S. Geological Survey, Denver. Sample locations can be found in Appendix 4A.)

Maceration 2195B

LaFollette, Campbell Co., Tennessee

APICULATISPORIS sp.
CALAMOSPORA sp.
DENSOSPORITES sp. (ring)
GRANULATISPORITES PALLIDUS Kosanke
LYCOSPORA GRANULATA Kosanke
L. PSEUDOANNULATA Kosanke
L. MICROPAPILLATA (Wilson and Coe) S. W. and B.
PUNCTATISPORITES sp.
RAISTRICKIA sp. (fragment)
SAVITRISPORITES NUX (Butterworth and Williams) Smith and Butterworth.
S. sp.
SCHULZOSPORA RARA Kosanke

Age: Pennsylvanian

Maceration 2095

Henry Bowlin Gap, Whitley Co., Kentucky

GRANULATISPORITES sp.
LYCOSPORA cf. L. PSEUDOANNULATA Kosanke
PUNCTATISPORITES sp.
SCHULZOSPORA RARA Kosanke

Age: Pennsylvanian

Maceration 2121

Pound Gap, Wise Co., Virginia

CRASSISPORA KOSANKEI (Potonie and Kremp)
GRANULATISPORITES cf. G. PALLIDUS kosanke
LYCOSPORA GRANULATA Kosanke
L. MICROPAPILLATA (Wilson and Coe) S. W. and B.
L. PSEUDOANNULATA Kosanke

Age: Pennsylvanian

FIGURE 7. Cross-section A-A', through the southwestern part of the Cumberland overthrust sheet, is approximately perpendicular to the axis of the Appalachian Basin (see Fig. 5). The numbered sections are located in Appendix 1. Open circles represent well logs, solid circles represent outcrop data.

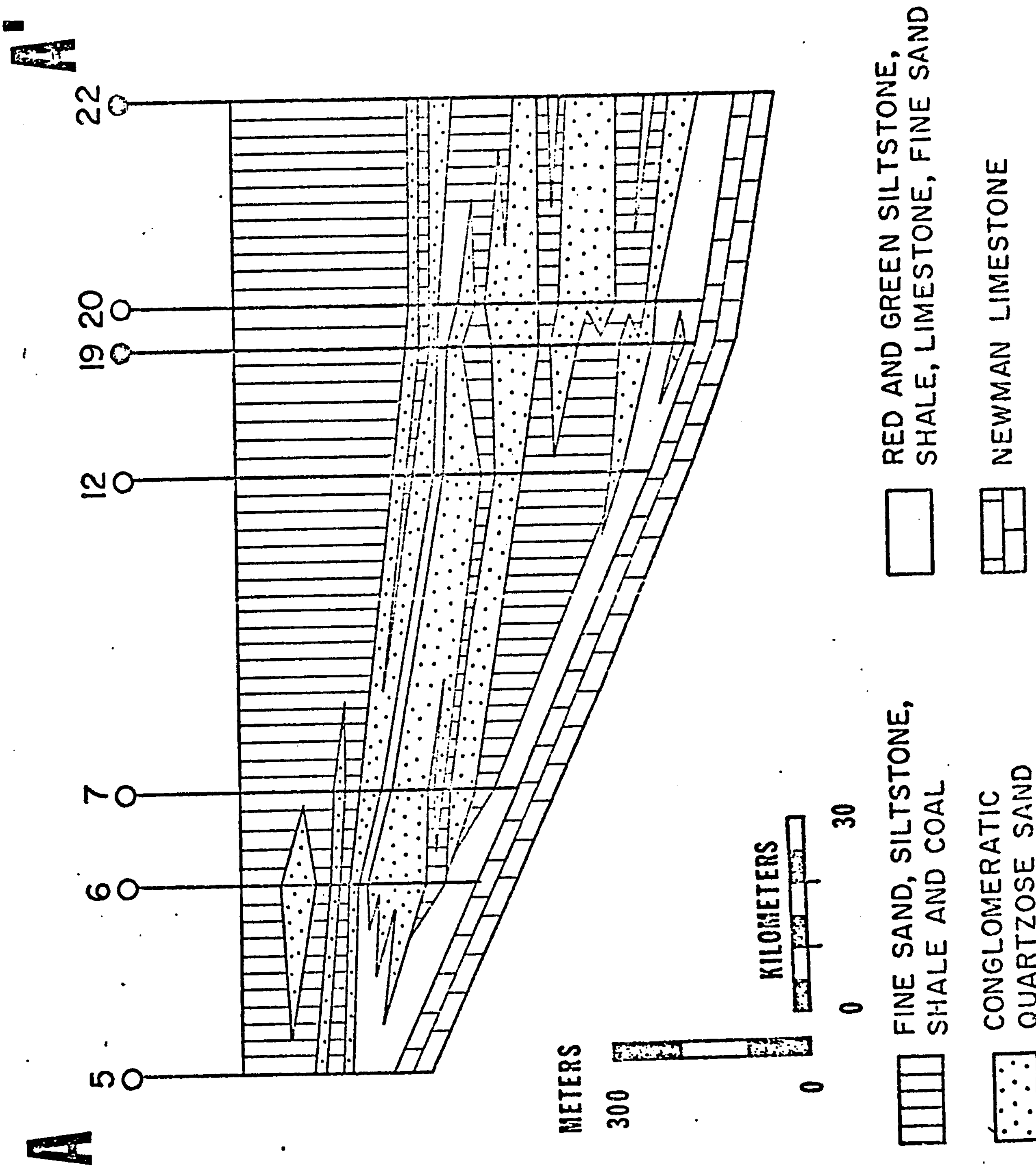

A
A'
5
6
7
12
19
20
22
METERS
300
0
KILOMETERS
0
30
FINE SAND, SILTSTONE, SHALE AND COAL
CONGLOMERATIC QUARTZOSE SAND
RED AND GREEN SILTSTONE, SHALE, LIMESTONE, FINE SAND
NEWMAN LIMESTONE

FIGURE 8. Cross-section B-B', through northeastern part of the overthrust sheet. Note the truncation of the red and green siltstone unit to the northwest by the conglomerate sandstone.

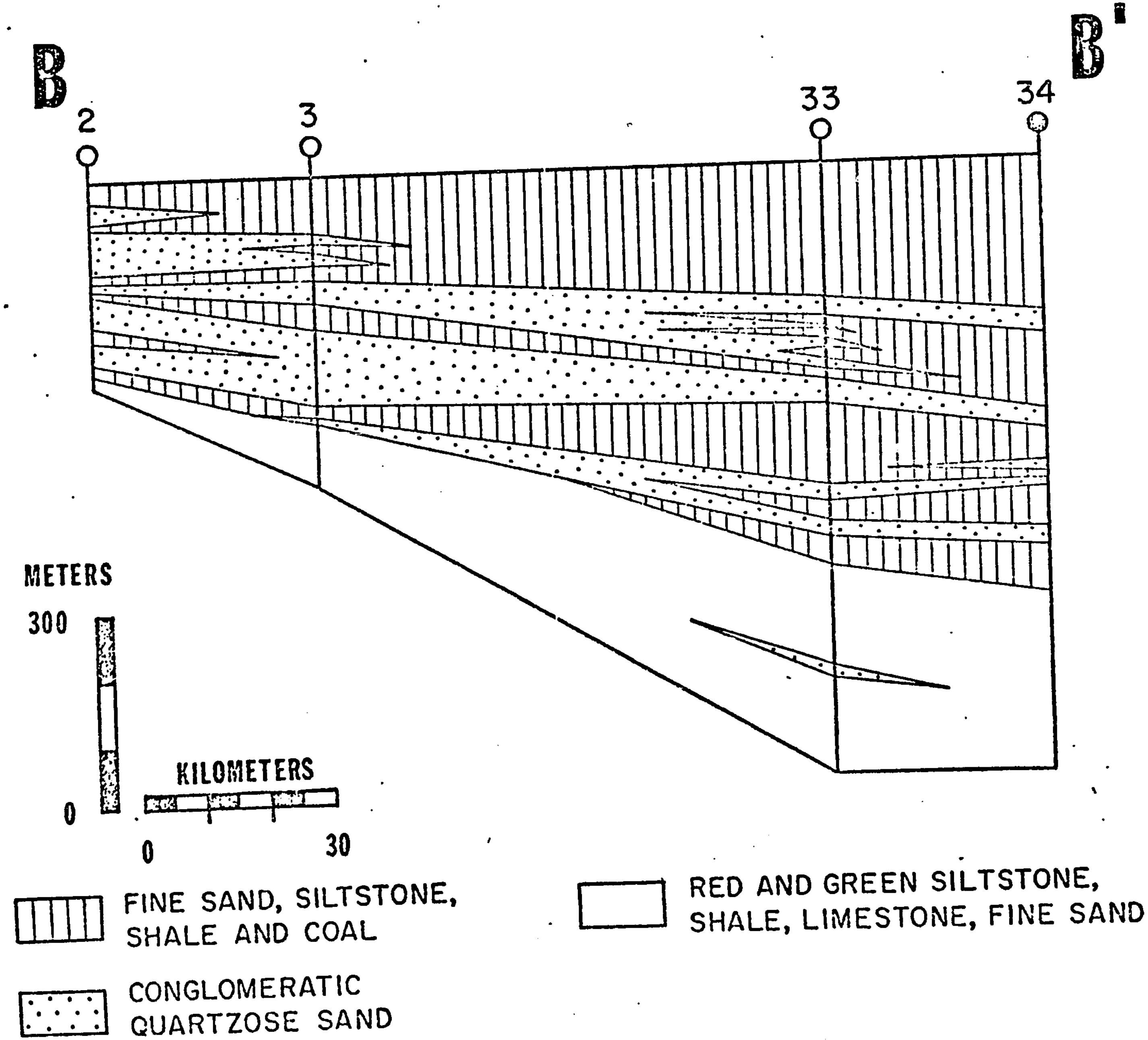

B
B'
2
3
33
34
METERS
300
0
KILOMETERS
0
30
FINE SAND, SILTSTONE, SHALE AND COAL
CONGLOMERATIC QUARTZOSE SAND
RED AND GREEN SILTSTONE, SHALE, LIMESTONE, FINE SAND

FIGURE 9. Cross-section C-C', along the strike of Cumberland Mountain (see Fig. 5). The base of the Bee Rock Sandstone Member was considered horizontal for this construction (location numbers 22-32). The apparent northeast pinching out of the conglomeratic sands is due to their position slightly northwest of the area shown in the cross-section.

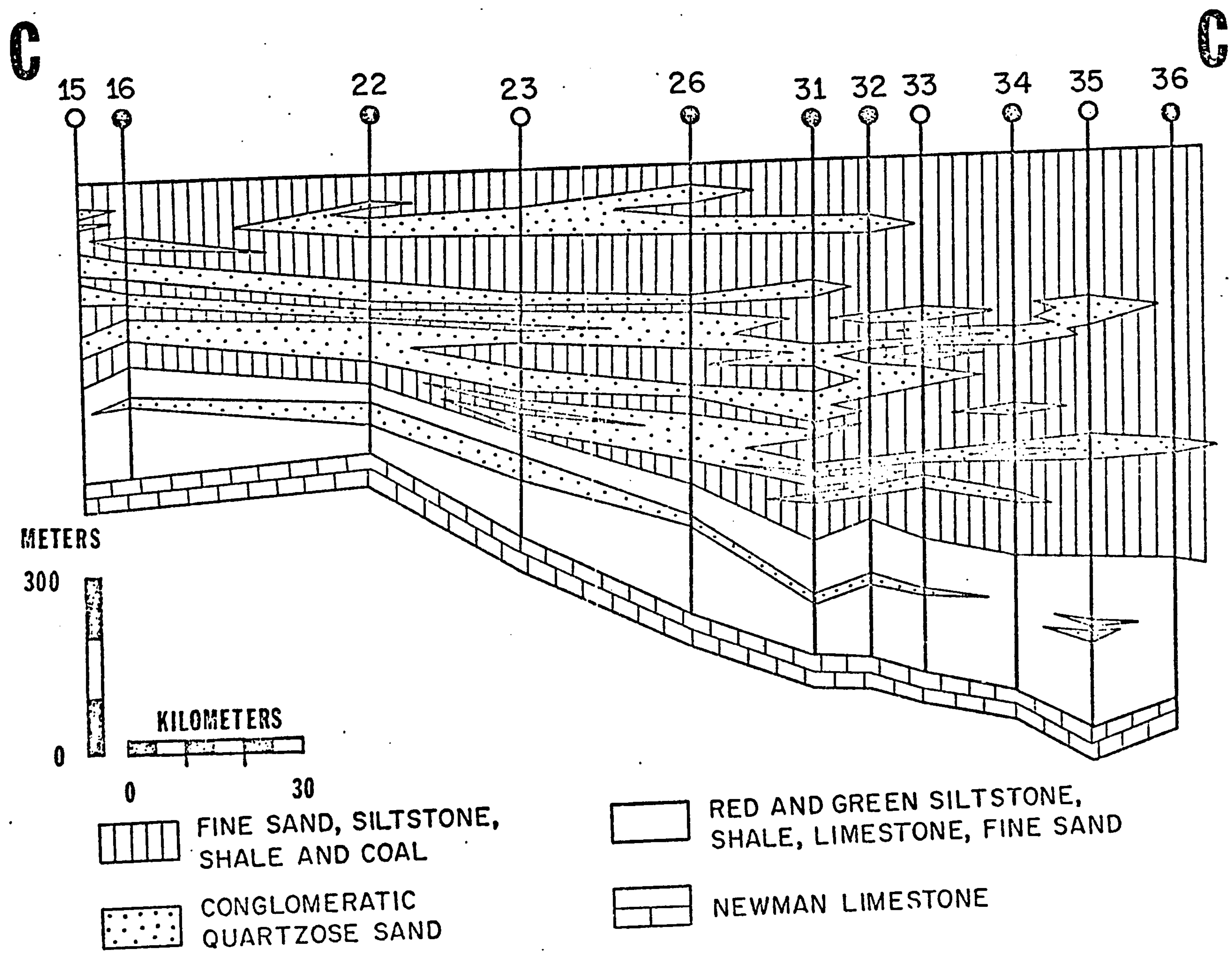
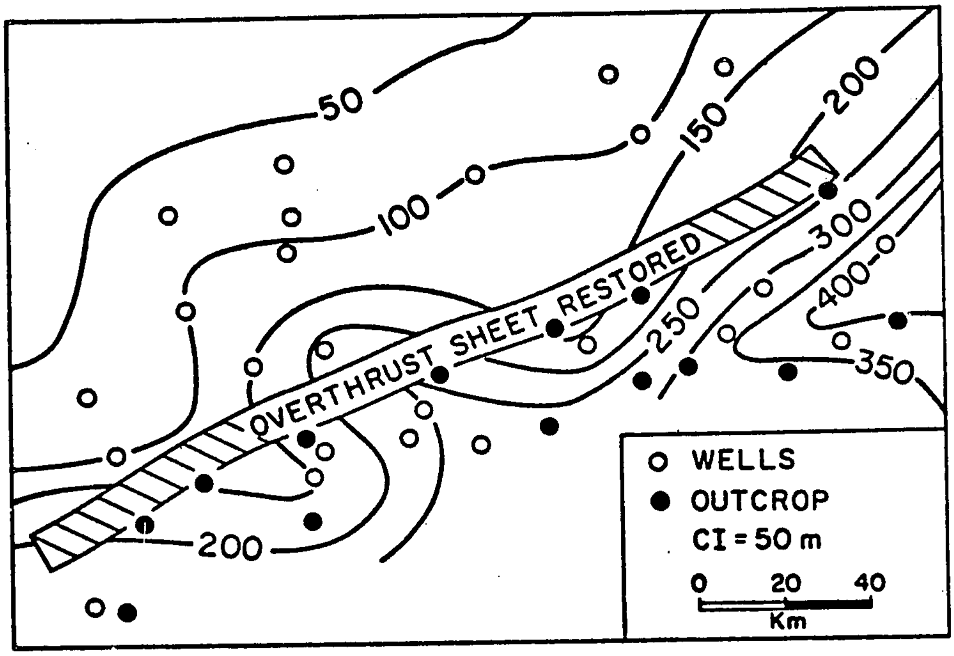

C
C'
15
16
22
23
26
31
32
33
34
35
36
METERS
300
0
KILOMETERS
0
30
FINE SAND, SILTSTONE, SHALE AND COAL
CONGLOMERATIC QUARTZOSE SAND
RED AND GREEN SILTSTONE, SHALE, LIMESTONE, FINE SAND
NEWMAN LIMESTONE

FIGURE 10. Thickness of the interval between the top of the Newman Limestone and the base of the Middlesboro Member of the Lee Formation. Mapping by the U. S. Geological Survey indicates a widespread erosional unconformity at the base of the Middlesboro. The interval shown includes the Pennington and Pocahontas Formations.

FIGURE 11. Thickness of the Lee Formation from the base of the Middlesboro Member to the Naese Sandstone Member. This interval generally thickens to the southeast, as does the interval shown in Fig. 10.


50
100
150
200
250
300
350
400
200
OVERTHRUST SHEET RESTORED
WELLS
OUTCROP
CI = 50 m
0 20 40
Km

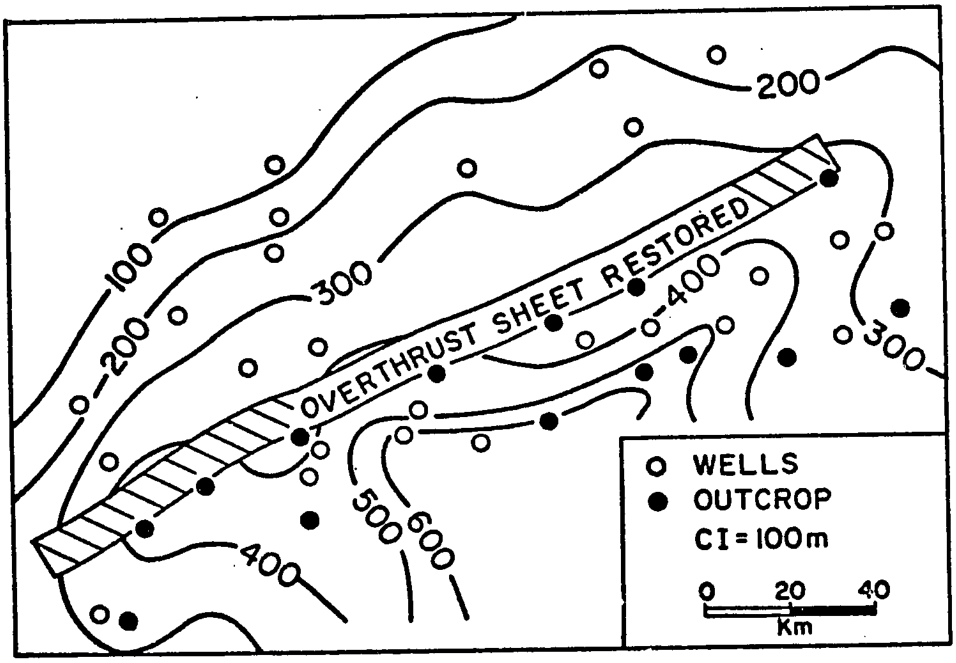
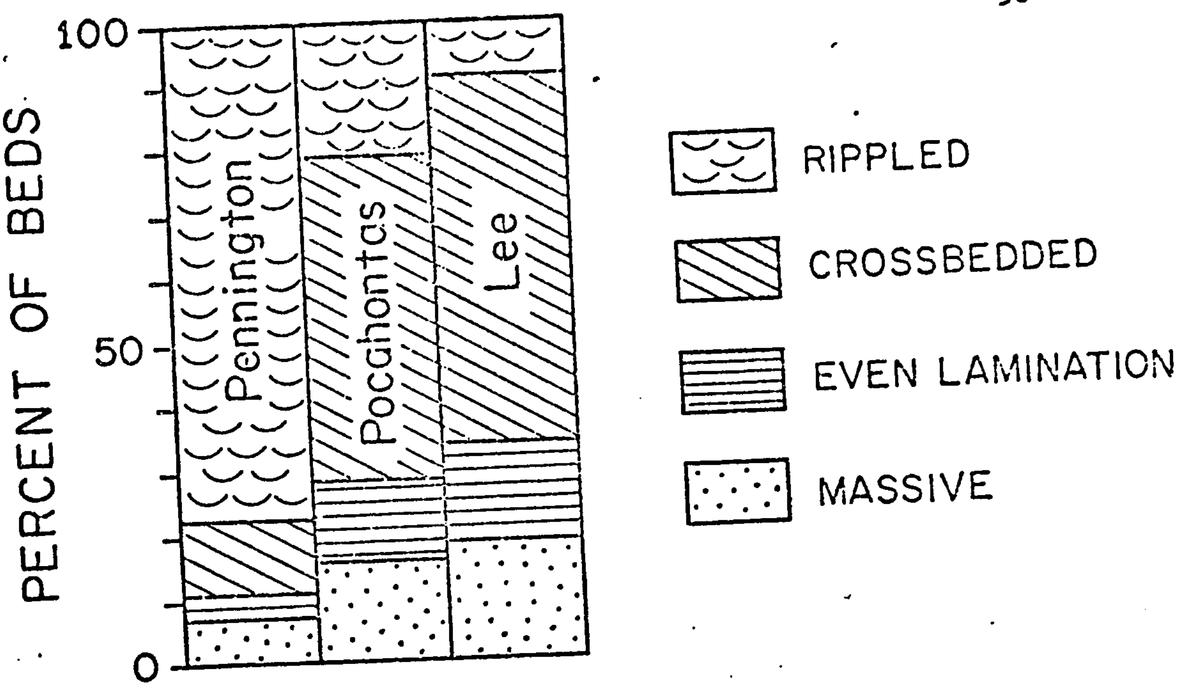
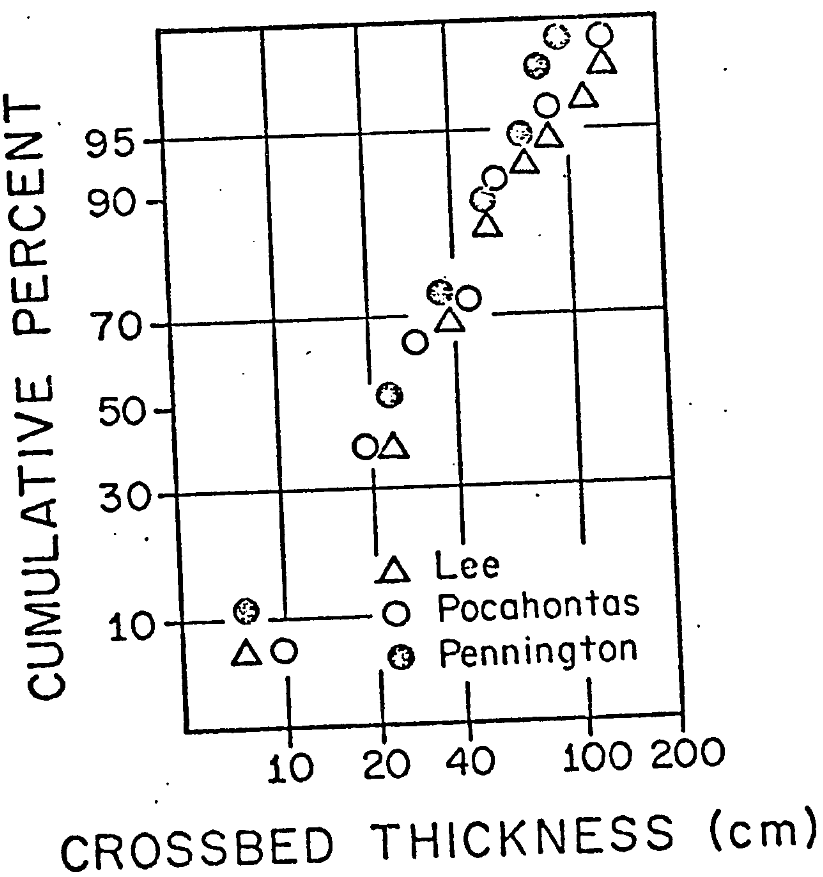

100
200
300
400
500
600
200
300
400
OVERTHRUST SHEET RESTORED
WELLS
OUTCROP
CI = 100m
0 20 40
Km

FIGURE 12. Distribution of bedding types in the sandstones of the Pennington, Pocahontas and Lee Formations. The Pennington is predominantly ripple bedded. The Pocahontas and Lee Formations are mostly crossbedded. Based on 3157 meters of section.

FIGURE 13. Crossbed thickness distributions for sandstones in the Pennington, Pocahontas and Lee Formations. Number of beds measured are 122, 61 and 1025, respectively. Note the apparent similarity of the three distributions.


100
50
0
PERCENT OF BEDS
Pennington
Pocahontas
Lee
RIPPLED
CROSSBEDDED
EVEN LAMINATION
MASSIVE


95
90
70
50
30
10
CUMULATIVE PERCENT
Lee
Pocahontas
Pennington
10
20
40
100
200
CROSSBED THICKNESS (cm)

SEDIMENTOLOGY AND DEPOSITIONAL ENVIRONMENT

In the preceding chapter the sandstones of the Pennington and Lee Formations were described and characterized by their lithology and sedimentary structures (Fig. 13). It is clear from these general descriptions that there are several types of sandstones, and such an observation prompts one to ask, "How many different types are there? How are different types related to one another? How are each of these types distributed throughout the Pennington and Lee Formations?"

Let us begin with a short review of the 'state of the art' of environmental recognition in sandstones.

Recognizing Depositional Environments

Noteworthy studies published in the last five years describing sandstones and criteria useful for determining their depositional environments include those of LeBlanc (1972), MacKenzie (1972), Pettijohn et al. (1972, Ch. 11), Shelton (1973), and Ginsburg (1975). A considerable amount of data has been obtained for terrigenous sandstones deposited in various depositional environments, related to boundary character, associated lithologies and their vertical succession, the latter including sedimentary structures, directional properties, grain-size and composition. These data are best summarized in vertical profiles, and generalized models have been developed for sand bodies with known depositional environments (Table 6).

Such data, most of which are gathered in the field, can be supplemented with grainsize probability curves and their derived textural parameters, detailed petrographic work to determine composition, and occasionally mechanical-log characteristics from nearby wells which show a vertical succession of sandbodies.

Several workers in the last 30 years have thought that sediment texture is 'process' dependent and can be used to determine depositional environments (Table 6). Shape of the grainsize log-probability curve and bivariate plots of several textural parameters have been used with variable success to distinguish depositional environments (Table 6).

Some workers employ various mathematical and statistical techniques to analyze descriptive data as an aid in the interpretation of depositional environments (Table 6). These techniques include discriminant function analysis, cluster analysis and factor analysis of both compositional and textural parameters. A more recent technique is the mathematical analysis of the bed-thickness distribution curve.

My approach to interpreting the depositional environments of the sandstones in the Pennington and Lee Formations is first to assign the sandstones to depositional environments on the basis of sedimentary structures, internal organization and bounding lithologies determined from vertical profiles measured in the field, and secondly to use probability curves, wireline logs, and various mathematical and statistical techniques to test and possibly refine these initial environmental assignments.

A summary of the field and laboratory procedures is given in Appendix 3.

Environment Of Deposition

Sand bodies which occur within the Pennington and Lee Formations can be classified in a predominantly regressive sequence of marine, shoreface, tidal and fluvial environments, on the basis of sedimentary structures, internal organization and associated lithologies (Figs. 14 to 21). The sandstones of these four environments are described below.

Marine: Marine sandstones within the Pennington Formation on the overthrust sheet have transitional bases and tops, are interbedded with abundantly burrowed gray siltstones and shales containing a marine fauna and thin bedded, carbonate wackestones. These sands show no apparent vertical variation in grainsize except where overlain by coarser shoreface sandstones. The sandstones range in thickness from 2 to 30 meters; sandbodies greater than 20 meters thick can be traced for several kilometers along Pine and Cumberland Mountains and through the subsurface because of their sheet-like geometry. Marine sandstones are predominantly rippled with crossbedding, even lamination and massive bedding being present in lesser amounts (Fig. 26). They range in color from light gray to dark green, are moderately sorted, fine to very fine grained quartzarenites and quartzwackes (Fig. 22 and Table 8). Bed thickness ranges from 5 to 125 cm. and averages about 18 cm. for both massive and crossbedded units (Fig. 23).

Clay minerals of the interbedded shales are predominantly illite with lesser amounts of kaolinite, chlorite and montmorillonite (Fig. 16).

In single outcrops, paleocurrent indicators may be random or unimodal in orientation (Fig. 21). Calculated variance for unweighted and thickness weighted crossbed measurements is 5596 and 5513 respectively (Table 9). These values are within the range of values reported by Potter and Pettijohn for marine sandstones (Potter and Pettijohn, 1963, Table 4-2).

Similar sand body characteristics of texture, composition, vertical succession of sedimentary structures and associated lithologies have been described for marine and off-shore sands by Shelton (1973), Brenner and Davies (1974) and Johnson (1975).

Shoreface: Shoreface sandstones in the Pennington and Lee Formations have transitional or unconformable basal contacts, generally coarsen upward, are burrowed at the tops of massive bedded units and gradually pass into overlying tidal sediments (Figs. 14 and 15). The sandstones may be interbedded with siltstones and shales variable in color and composition. The interbedded units may be red, green, gray or black; may be calcareous or fossiliferous and may contain thin, discontinuous wackestones. The sand bodies range in thickness from 3 to 15 meters and pass laterally into marine or tidal sandstones.

The sandstones are predominantly either massivly bedded or have low angle crossbeds (less than 5 degrees), with even lamination and ripple bedding being present in lesser amounts (Fig. 26). Bed thickness ranges from 1 to 115 cm. and averages about 20 cm. (Fig. 23). The thicker units are massively bedded.

The sandstones are white to light gray, moderately sorted, medium to coarse grained, sparsely conglomeratic quartzarenites that generally contain less than 5 percent matrix (Fig. 22; Tables 7 and 8). Accessory minerals constitute less than 1 percent of the detrital grains and are commonly present as thin laminae. Sixty percent of these minerals are opqaue, being mostly ilmenite and leucoxene (Mitchum, 1954, p. 136). Non-opaque minerals are mostly tourmaline, which may be brown, blue or colorless, contain overgrowths and be well rounded. Zircons are usually well rounded. Rutile, hornblende, apatite and garnet are present in trace amounts.

Clay mineralogy of the interbedded shales is predominantly illite or kaolinite, with lesser amounts of chlorite and montmorillonite (Fig. 16).

At single outcrops crossbedding, directions are commonly bimodal. The calculated variances for unweighted and thickness weighted measurements are 8365 and 8309, respectively (Table 9).

Similar characteristics have been described for shoreface sandstones by Reineck and Singh (1973, p. 280-349) and Johnson (1975).

Tidal: Tidal sandstones in the Pennington and Lee Formations on the Cumberland overthrust sheet generally overlie shoreface sandstones. They may grade laterally into shoreface sands or fluvial sediments and can be traced for several kilometers along Pine and Cumberland Mountain. The tidal sands are interbedded with red, gray or green siltstones and shales. Thin underclays and coals are scattered throughout the gray siltstones and shales. These sand bodies range in thickness from 2 to 15 meters and may form multistory sand bodies as much as 30 meters thick (Fig. 15). The tidal sandstones are predominantly crossbedded and ripple bedded, with even lamination and massive bedding present in lesser amounts (Fig. 26). Bed thickness in the sandstones ranges from 5 to 105 cm. and averages about 30 cm. (Fig. 23). These white to light gray, moderately sorted, coarse to fine grained quartzwackes and quartzarenites contain local concentrations of conglomerates consisting of quartz pebbles and clay chips (Fig. 15, Tables 7 and 8). Crossbedding orientations may be either unimodal, bimodal or random (Figs. 14, 15 and 26). A paleocurrent rose of all observations suggests a general southwest sediment transport direction (Fig. 24).

The sandstones may be divided into two types, tidal channel or tidal inlet and tidal flat, on the basis of geometry, sedimentary structures, directional properties and abundance of bioturbation.

Tidal channel sandstones of the Pennington and Lee Formations are characterized by erosional bases containing a basal conglomerate of quartz pebbles or clay chips, and transitional tops into overlying tidal flat sandstones, siltstones and shales (Figs. 15 and 17). Conformable basal contacts are rare. The channel sandstones may be lenticular (widths less than 100 meters) or appear continuous for several kilometers because of channel migration. Such migration has been described for tidal channels and inlets by Hoyt and Henry (1967) and Kumar and Sanders (1974). These coarse to medium grained sandstones are predominantly massive or crossbedded. Tracks, trails and burrows are not common. Several channel sandstones show a vertical sequence of bedding type, massive to crossbedded to rippled, with an associated decrease in grainsize (Figs. 14 and 15). Crossbed orientation may be either unimodal or bimodal.

Similar characteristics for tidal channel/inlet sandstones have been described by Kumar and Sanders (1974), Oomkens (1974) and Johnson (1975).

Tidal flat sandstones have transitional bases and tops, generally overlie tidal channel sandstones and are interbedded with varicolored siltstones and shales. These fine grained sandstones are predominantly rippled or flaser bedded, contain abundant tracks trails and burrows and rarely contain dessication tracks. Clay minerals in the interbedded shales are predominantly kaolinite with variable amounts of illite and lesser amounts of chlorite and montmorillonite (Fig. 16). Paleocurrent orientations obtained from thin crossbeds and assymetrical ripples may be random or bimodal in single outcrops.

Similar characteristics have been described in tidal flat sandstones by Reineck and Singh (1973, p. 355-372), Johnson (1975) and Ginsburg (1975).

Fluvial: fluvial sandstones are found only in the Lee Formation. The fluvial sandstones commonly overlie all other types of sandstones and are interbedded with green to dark gray siltstones and shales often containing underclays and coals. The fluvial sandstones can be subdivided into high- and low-sinuosity types using the abundance and sequence of bedding types, and abundance of overbank material. Models for deposition of high- and low-sinuosity rivers have been described by Moody-Stewart (1966).

Sandstones deposited by low sinuosity rivers show erosional basal contacts with a lag deposit of quartz pebbles and clay chips. Impressions of plant fragments are common (Figs. 18 and 19). The sand bodies range in thickness from 2 to 25 meters and may form multistory sand bodies greater than 80 meters thick (Fig. 20). The sandstones show a vertical fining upward in grainsize and the sedimentation units described by Smith (1970, Fig. 17) for braided streams as they grade into overlying siltstones and shales with thin discontinuous underclays and coals. Fluvial sandstones can be traced for tens of kilometers along Pine and Cumberland Mountains and through the subsurface to show a sheet-like geometry (Figs. 7 to 8). These sandstones are mostly crossbedded; massive bedding, even lamination are present in lesser amounts. Ripple bedding comprises less than 10 percent of the total bedding type. Planar crossbeds are more abundant than trough. Sandstone bed thickness ranges from 5 to 210 cm. and averages about 32 cm. (Fig. 23). These white to tan, moderately to poorly sorted, coarse to fine grained quartzarenites and quartzwackes contain abundant lenses of quartz pebble conglomerate.

Quartz pebbles have long axis measurements ranging from 15 to 60 mm. Weathering of opaque minerals at the surface often gives the outcrop a bright red or orange color. Rock fragments consist of siltstone and schist fragments with scattered clay pebbles. Feldspars are orthoclase, plagioclase, and more rarely microcline (Tables 7 and 8). The sandstones show an overall unimodal current direction to the southwest, which is parallel to the sand percent trend (Fig. 25). Calculated variances for crossbedding measurements with the unweighted and thickness weighted methods are 5893 and 5862, respectively (Table 9). This is within the range of variances suggested for fluvial-deltaic deposits (4000-6000) by Potter and Pettijohn (1963, p. 89).

Similar characteristics have been described for sandstones deposited in low-sinuosity rivers by Smith (1970), Leeder (1973) and Steel (1974).

Sandstones deposited by high-sinuosity rivers show erosional basal contacts with lag deposits consisting of clay pebbles and plant fragments. Quartz pebbles are rare. The sand bodies range in thickness from 1 to 8 meters and may form multistory sand bodies ranging from 11 to 20 meters. The sandstones show a vertical fining upward in grainsize and succession of sedimentary structures from massive to crossbeds to ripple beds as they grade into overlying siltstones and shales containing coals ranging in thickness from 5 to 340 cm. The sandstones appear lenticular in outcrop with apparent widths ranging from 15 to 120 meters. The sandstones are predominantly trough crossbedded and rippled, massive bedding and even lamination are present in lesser amounts (Fig. 26).

The sandstones range in color from tan to gray, are medium to fine grained, moderately sorted quartzwackes and sublitharenties (Fig. 22). Bed thickness ranges from 10 to 200 cm. and averages about 45 cm. (Fig. 23). Paleocurrent indicators in the sandstones are unimodal and calculated variances for unweighted and thickness weighted sets are 6816 and 7052. These are outside the range suggested by Potter and Pettijohn (1963, p. 89) for fluvial-deltaic sandstones (4000-6000) but similar to variances reported for the Copper Harbor (Keweenawan) and Hardinsburg (Mississippian) sandstones (Op. Cit., Table 4-2). For the high and low sinuosity, Lee sandstones, a t-test of the vector means and an F-test of the variances, indicates that they are not significantly different (Table 9).

Sedimentary structures, vertical profiles and characteristics of sandbodies deposited in high sinuosity (meandering) rivers are described by Allen (1965), Visher (1972), Leeder (1973) and Pettijohn et al. (1973, p. 453-464).

Distribution of marine, shoreface, tidal and fluvial sandstones, based on the vertical profiles, in the Pennington, Pocahontas and Lee Formations is shown in Figure 27.

Additional Tests

In this section, the previous environmental assignments are tested using a diverse battery of techniques. Each technique is briefly described below, followed by its application to the sandstones of the Pennington and Lee Formations. More detailed accounts of the mathematical techniques can be found in Krumbein and Graybill (1965), Harbaugh and Merriam (1968) and Davis (1973).

Log probability curves, displaying straight line segments which reflect the mechanism of sediment transport (traction, suspension and saltation), have been used to describe the depositional process during sedimentation (Visher, 1969). While an exact interpretation of depositional environment is not always possible, the size-distribution curve can be useful when compared with characteristic curves from several known depositional environments, an outstanding paper being that of Glaister and Nelson (1974). Representative curves from the depositional environments of the Pennington and Lee sandstones are shown in Figure 22B. A comparison of typical probability curves obtained from sieve data for the Pennington and Lee sandstones indicates deposition in shoreface, tidal and fluvial environments.

Identification of clastic depositional environments from wireline logs is related to the identification of sand bodies with their respective geometry, nature of bounding contacts and bounding lithologies, vertical bedding sequences and gross grainsize changes (Allen, 1975, p. 375). Comparison of typical SP and Gamma-Ray curves from Pennington and Lee sandstones, with those from known depositional environments, indicates deposition in a regeressive sequence of nearshore, deltaic and fluvial environments.

Directional properties such as crossbedding, assymetrical ripples and parting lineation show a variety of orientations for sediment dispersal systems in various depositional environments (Table 10). This limits the use of paleocurrent models in the determination of sandstone depositional environments. Potter and Pettijohn (1963, p. 89) indicate that while fluvial-deltaic and marine sandstones have crossbedding variances ranging from 4000-6000 and 6000-8000, respectively, they point out, that there is considerable overlap between the two groups. Although crossbedding variance and paleocurrent models are not diagnostic of particular depositional environments, crossbedding orientation can be used for paleohydraulic calculations and discussion of sediment dispersal related to paleogeography. Paleohydraulic calculations for the fluvial sandstones are discussed in Chapter 6; sediments dispersal and paleogeography are discussed in Chapter 7.

Standard discriminant function analysis finds a linear combination of variables which produces the maximum difference between groups. A function that produces a significant difference may then be used to assign samples of unknown origin to one of the groups (Davis, 1973, p. 443). Bivariate plots of various textural parameters, which is a graphic discriminant function for sieve and thin section data, indicated the presence of marine, shoreface and fluvial environments, but placed several samples in the wrong environment. These plots classified only slightly more than half (55 percent) of the samples correctly.

While plots of textural parameters show defininite trends from depositional environments ranging from alluvial fans to mature beaches (Glaister and Nelson, 1974, Figs. 1, 2 and 3), there is considerable overlap and scatter and environmental analysis of single samples based on these parameters are not reliable.

Discriminant function equations developed by Sahu (1964) using textural parameters obtained from sieve data classified 72 percent of the samples correctly. This apparent success may indicate that certain depositional processes are characteristic of various environments.

Discriminant function analysis using a combination of composition and textural variables achieved the highest success. A stepwise discriminant function analysis, where the relative importance of the variables is determined by the magnitude of F-values (Davies and Ethridge, 1974, p. 241), shows that .99 percent of the variance between the four sandstone types can be explained by three compositional variables: percent content of mica, feldspar and quartz (Table 11). The resulting discriminant function classified 93 percent of the samples correctly. Davies and Ethridge (1975, Figs. 26 to 28) were equally successful in distinguishing depositional environments using discriminant functions consisting of the same variables. It should be stressed, however, that in different study areas with different rock units, another combination of variables may be more effective in determining depositional environments than those indicated by my stepwise analysis. In another study, the percent matrix, percent rock fragments and percent quartz were the most important variables used in distinguishing marine and non-marine depositional environments of the Lower Cretaceous Muddy Sandstone Formation (Davies and Ethridge, 1975, p. 260-261).

Cluster analysis shows the inter-relationships in a similarity coefficient matrix of variables or samples. These relationships may be represented with dendritic networks or dendrograms, where the variables or samples are grouped according to their similarity coefficient described by Parks (1966), the latter being related to the correlation coefficient. Cluster analysis of the sieved samples, using the weight percent of quarter phi intervals as variables and the distance coefficient as a measure of similarity, divided the samples into two groups. The samples were grouped on the basis of modal class grainsize; this procedure classified 61 percent of the samples correctly. Cluster analysis of the same samples and variables that were used in the discriminant function analysis grouped 73 percent of the samples correctly. While cluster analysis is not a statistical test that can be tested for success of failure, the apparent success indicates the effectiveness of using composition and textural variables to discriminant between groups of samples. This accounts for the high success ratio represented by the discriminant function analysis.

Factor analysis interprets the structure of a similarity coefficient matrix and may be used to study the relationship between the variables (R-mode) or between the samples (Q-mode). Using the matrix of factor loadings to determine the relationship between the samples (Q-mode analysis of grainsize data) where samples with high factor loadings for the same factor are related (Klovan, 1966, p. 66), indicates that only

53 percent of the sieved samples and only 18 percent of the thinsection samples were classified correctly. The ineffectiveness of factor analysis in discriminating depositional environments using grainsize data was investigated by Glaister and Nelson (1974) in their review of statistical parameters and multivariate techniques related to environmental interpretation. They demonstrated that factor analysis tends to group samples on the basis of modal class grainsize, and is apparently insensitive to the size classes near the ends of the size distribution. My factor analysis data support their conclusion.

Analysis of bed-thickness distributions is based on the work of Kolmogorov (1951), who presented a mathematical explanation for the bed-thickness distribution curve. He proposed that the bed-thickness curve was the normal (Gaussian) curve extending from positive to negative thicknesses, negative thicknesses representing erosion (Mizutani and Hattori, 1972, p. 123). Calculation of Kolmogorov's coefficient and ratio, two parameters related to sedimentary process and depositional environment, were shown by Mizutani and Hattori (1972, p. 144) to be useful in determining depositional environments. Calculation of these two parameters for the bed-thickness distributions of the four sandstone types and comparison with those from known depositional environments indicates that these two parameters will be of limited use in distinguishing depositional environments, because there is too much overlap in the values (Table 12). However, they may be helpful in describing the sedimentation process. The use of these parameters in describing processes can be illustrated as follows: a value of 0.84 for

Kolmogorov's coefficient, found for most of the sandstones, is interpreted to mean that 100 alternations of deposition and erosion formed 84 beds. The Kolmogorov ratio of 0.93 indicates that 93 percent of the material transported into the basin at that locality was deposited (Mizutani and Hattori, 1972, p. 129). The marine sandstones had a calculated coefficient value of 0.40, which is interpreted to mean that 100 alternations of deposition and erosion produced only 40 beds. In other words, there was a considerable amount of reworking of the sand in the depositional environment. Reworking of sand in the marine environment is not uncommon, and the abundance of symmetrical ripples indicates the importance of wave action. It is noteworthy that preservation, as determined by this criteria, was so much poorer in the marine sands than for any of the other types.

Summary

The most useful procedure for determining the environments of deposition of these sandstones was the vertical profile. No other method or technique reveals as many of the gross physical properties that characterize a sand body. Thus field data, when supplemented with descriptive petrography, provide a relatively complete description of the sandstones. Discriminant function analysis, using a combination of compositional and textural variables, achieved the highest level of success (93 percent). The remaining techniques yielded somewhat poorer results (Table 13). Distribution of the four sandstone types among the Pennington, Pocahontas and Lee Formations is shown in Figure 27.

TABLE 6

DESCRIPTIVE, COMPARATIVE AND MATHEMATICAL TECHNIQUES USED TO INTERPRET ENVIRONMENTS OF DEPOSITION

Vertical Profiles	Visher (1965) Allen (1965) Klein (1970) Kumar and Sanders (1974)
Grainsize Probability Curves	Doeglas (1946) Sindowski (1957) Visher (1969) Glaister and Nelson (1974)
Wireline Logs	Weber (1971) Glaister and Nelson (1974) Allen (1975)
Paleocurrent Patterns	Tanner (1955) Potter and Pettijohn (1963) Klein (1967) Selley (1967)
Grainsize Parameter Plots	Passega (1957, 1964) Friedman (1961, 1967) Shepard and Young (1963) Moila and Weiser (1968)
Discriminant Function Analysis using composition and texture	Potter et al. (1963) Sahu (1964) Davies and Ethridge (1975)
Cluster Analysis using composition	Purdy (1963) Parks (1966) Harbaugh and Merriam (1968)
Factor Analysis using textural data	Imbrie and Purdy (1962) Klovan (1966, 1975) Klovan and Solohub (1970) Glaister and Nelson (1974)
Bed-Thickness Distribution	Mizutani and Hattori (]972)

TABLE 7

GRAINSIZE PARAMETERS FOR PENNINGTON AND LEE SANDSTONES*

	Mean	Median	Incl. Graph. Std. Dev.	Incl. Graph. Skewness
Marine				
1. **	2.04	2.05	0.55	0.05
2.	2.60	2.45	1.14	0.15
3.	2.19	2.19	0.56	0.17
4.	2.13	2.14	0.64	0.12
Shoreface				
1.	1.96	1.95	1.04	0.14
2.	1.79	1.79	0.55	0.27
3.	2.52	2.52	0.76	0.09
Tidal				
1.	1.85	1.66	0.82	0.44
2.	2.24	2.23	0.87	0.15
3.	2.41	2.33	0.92	0.23
Fluvial				
1.	2.35	2.12	1.12	0.31
2.	1.73	1.40	1.25	0.43
3.	2.45	1.91	1.35	0.46
4.	1.74	1.55	1.14	0.35
5.	1.79	1.70	1.19	0.22
6.	2.14	2.14	0.82	0.20
7.	2.28	2.28	0.63	0.19
8.	1.79	1.80	0.84	0.15

*Obtained by sieving samples into quarter phi intervals. See Appendix 3 for description of procedure.

**Sample Number - Environmental assignment based on vertical profiles.

TABLE 8A

PETROGRAPHY OF PENNINGTON AND LEE SANDSTONES

	Composition			Texture		
	Quartz	Feldspar	Rock Fragments	Mean	Sorting	Matrix %*
Marine						
BH-29	98.0	1.0	1.0	3.24	0.61	24
BH-26d	98.7	0.0	1.3	3.00	0.53	15
BH-33a	96.0	2.0	2.0	2.56	0.48	10
BH-34	94.0	1.0	5.0	2.54	0.39	16
Shoreface						
F-18b	98.9	0.0	1.1	2.33	0.40	3
F-17	96.8	1.0	2.2	2.76	0.52	5
F-12	97.8	1.1	1.1	2.44	0.46	4
BH-12	98.2	Tr	1.8	2.25	0.35	2
SG-28	95.0	0.0	5.0	2.20	0.47	7
SG-27	95.8	0.0	4.2	1.73	0.47	3
Tidal						
F-24e	99.0	0.0	1.0	1.53	0.39	10
F-16	99.3	0.0	0.7	2.64	0.62	18
F-8	93.4	0.0	6.6	2.50	0.78	24
CG-0	95.5	0.0	4.5	1.77	0.52	10
JO-1	96.4	0.0	3.6	1.77	0.94	14
JO-5	97.6	0.0	2.4	.95	0.94	14
BH-27f	96.1	Tr	3.7	1.88	0.43	6
SG-26	93.3	Tr	6.7	1.45	0.45	6
Fluvial						
F-22	99.0	0.5	0.5	2.56	0.61	36
BH-40	93.0	3.0	14.0	1.92	0.46	13
BH-39	97.0	1.0	2.0	1.90	0.30	13
BH-36c	98.0	1.0	1.0	1.83	0.46	2
BH-36	97.0	1.0	2.0	1.65	0.36	9
BH-34a	97.0	Tr	3.0	3.57	0.51	23
BH-30	92.0	Tr	8.0	2.08	0.43	11
BH-28	89.0	2.0	9.0	2.89	0.50	19
BH-27g	85.0	4.0	11.0	2.65	0.40	20
BH-27e	90.8	2.2	7.0	1.93	0.34	8
BH-27b	96.6	0.0	3.4	3.28	0.71	36
BH-27a	90.8	8.4	0.8	3.63	0.48	24
SG-22	94.5	Tr	5.5	1.79	0.45	7

**Less than 62 microns

***Sample Locations: BH - Highway 421 (Section 25, Appendix 2)
F - Henry Bowlin Gap (Section 18, Appendix 2)
SG - Hurricane Gap (Section 27, Appendix 2)
JO - Jellico (Section 14, Appendix 5)
CG - Cumberland Gap, Bell Co., Kentucky (Pinnacle Overlook Member)

TABLE 8B

AVERAGE COMPOSITION AND TEXTURE OF PENNINGTON AND LEE SANDSTONES

	Composition			Texture		
	Quartz	Feldspar	Rock Fragments	Mean	Sorting	Matrix %
Marine	96.7	1.0	2.3	2.83	0.50	16
Shoreface	97.1	0.4	2.5	2.29	0.45	4
Tidal	96.3	0.2	3.5	1.70	0.59	12
Fluvial	93.8	1.9	4.3	2.44	0.46	17

TABLE 9

CROSSBEDDING PARAMETERS FOR PENNINGTON AND LEE SANDSTONES

	Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
High Sinuosity	227*	6816**	83	220	7052	84
Low Sinuosity	212*	5893**	77	213	5862	77
Tidal	233	6241	79	227	6084	78
Shoreface	211	8365	91	217	8039	90
Marine	289	5596	75	290	5613	75

Note: Potter and Pettijohn (1963, p. 89) suggest that fluvial-deltaic and marine sandstones have variance ranging from 4000-6000 and 6000-8000 respectively.

*Not different for $t_{.99}$ (886).

**Not different for $F_{.05}$ (178, 662).

TABLE 10

PALEOCURRENT MODELS FOR ENVIRONMENTS OF DEPOSITION

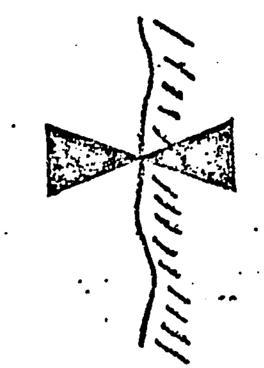
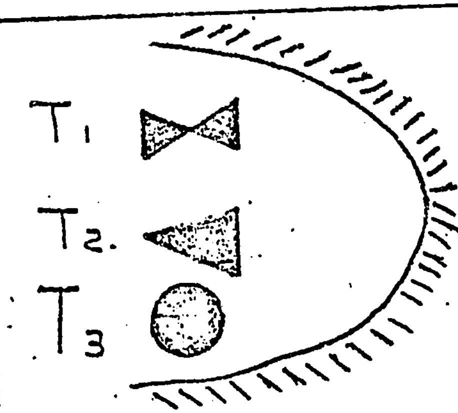
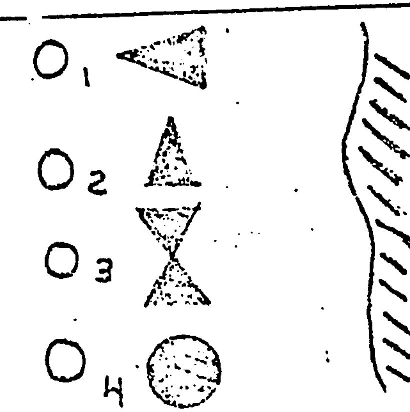
	SHOREFACE	TIDAL		MARINE	
Model		 		 	
Modern	Thompson (1937)	Hulseman (1955)	T_1	Van Straaten (1953)	O_1 O_2 O_3
	Manz (1955)	Oomkens and Terwindt (1960)	T_1 T_2	Stride (1963)	O_1 O_2
	Hoyt (1962)	Noorthoorn v.d. Kruijft and Lagaaij (1960)	T_2	Siebold (1963	O_1 O_2
	Logvinenko and Remizov (1964)	Jordan (1962)	T_1	Reinick (1963)	O_1 O_2 O_3
	Milling and Behrens (1966)	Terwindt, et. al. (1963)	T_1 T_2	Off (1963)	O_1 O_2
	Klein (1967)	Reinick (1963)	T_1	Houbolt (1968)	O_1 O_2
	Hoyt and Henry (1967)	Land and Hoyt (1966)	T_1 T_2	Boothroyd, J.C. (1969)	O_1 O_2
	Clifton (1971)	Salsman, Tolbert and Villars (1966)	T_2	Caston (1972)	O_3
	Kumar and Sanders (1974)	Klein (1970)	T_1 T_2	Davidson-Arnott and Greenwood (1974)	O_3
		Gellatly (1970)	T_1		
		Terwindt (1971)	T_1 T_2		
		Kumar and Sanders (1974)	T_1		

TABLE 10 (Continued)

	SHOREFACE	TIDAL		MARINE	
Ancient	Jordan (1964)	Tanner (1955)	T_3	Tanner (1955)	O_1 O_2
	Shelton (1965)	Hulseman (1955)	T_1	Hulsemann (1955)	O_3
	Dodge (1965)	Sealand (1961)	T_1	Baars (1961)	O_1 O_2
	Scott (1965)	Pettijohn, et. al. (1965)	T_1	Hermund (1965)	O_4
		Martini (1971)	T_1	Bigarella, et. al. (1965)	O_2
	Campbell (1971)	Swett, Klein and Smit (1971)	T_1		
		DeRaff and Boersma (1971)	T_1	McCubbin (1969)	O_2
		Jones (1972)	T_1	Pryor (1971)	O_1 O_2
		Cambell and Oaks (1973)	T_2	Campbell (1971)	O_1 O_2
		Johnson (1975)	T_1	Jones (1972)	O_2 O_3
				Hobday and Reading (1972)	O_1 O_2
				Michalson and Dott (1973)	O_1 O_2
				Banks (1973)	O_1 O_2 O_3
				Miller (1974)	O_2
				Brenner and Davies (1974)	O_4
				Johnson (1975)	O_1
				Harms, et. al. (1975)	O_2 O_3

TABLE 11

SUMMARY OF STEPWISE DISCRIMINANT FUNCTION ANALYSIS OF TEXTURAL AND COMPOSITION VARIABLES

Step	Variable	Percent Variance Explained	Cumulative Variance
1	Mica	61.7	61.7
2	Feldspar	21.8	83.5
3	Quartz	16.4	99.9
4	Sorting	0.1	100.0
5	Mean Size*	-	-
6	Rock Fragments*	-	-
7	Accessories*	-	-
8	Matrix*	-	-

* Additional variable which was not an important contributor to discriminating the four depositional environments of the Pennington and Lee sandstones.

TABLE 12

KOLMOGOROV'S COEFFICIENT AND RATIO FOR VARIOUS DEPOSITIONAL ENVIRONMENTS OF THE FOUR SANDSTONE TYPES IN THE PENNINGTON AND LEE FORMATIONS

Environment	Coefficient	Ratio
A. Reported by Mizutani and Hattori (1972):		
Alluvial-Fluvial	0.80-1.0	0.88-1.0
Nearshore	0.65-0.95	0.68-0.98
Geosynclinal	0.55-0.95	0.55-0.96
Varves	0.90-1.0	0.92-1.0
B. This study:		
Marine	0.40	0.94
Shoreface	0.84	0.93
Tidal	0.84	0.93
Fluvial	0.84	0.93

TABLE 13

SUCCESS OF CLASSIFYING SANDSTONES BY VARIOUS MATHEMATICAL AND STATISTICAL TECHNIQUES

Technique	Percent Correctly Matching Field Evidence*
1. Discriminant function	
composition and texture	93
textural parameters	72
2. Cluster Analysis	
composition and texture	73
interval weight percent	63
3. Bivariate Plots	55
4. Factor Analysis	
sieve data	53
thin section data	18

*Original classification based on vertical profiles.

Samples from all four groups were used in the discriminant function, cluster analysis and factor analysis. Bivariate plots were made using two groups at a time.

FIGURE 14. Vertical profiles through the Pinnacle Overlook Member of the Lee Formation. Arrows represent vector mean of crossbeds averaged for a 2 meter interval. Tidal sandstones are characterized by fining upward grainsize and bimodal crossbedding. Descriptions for the vertical profiles can be found in Appendix 5. Symbols for sandstone bedding types are shown in Fig. 12.

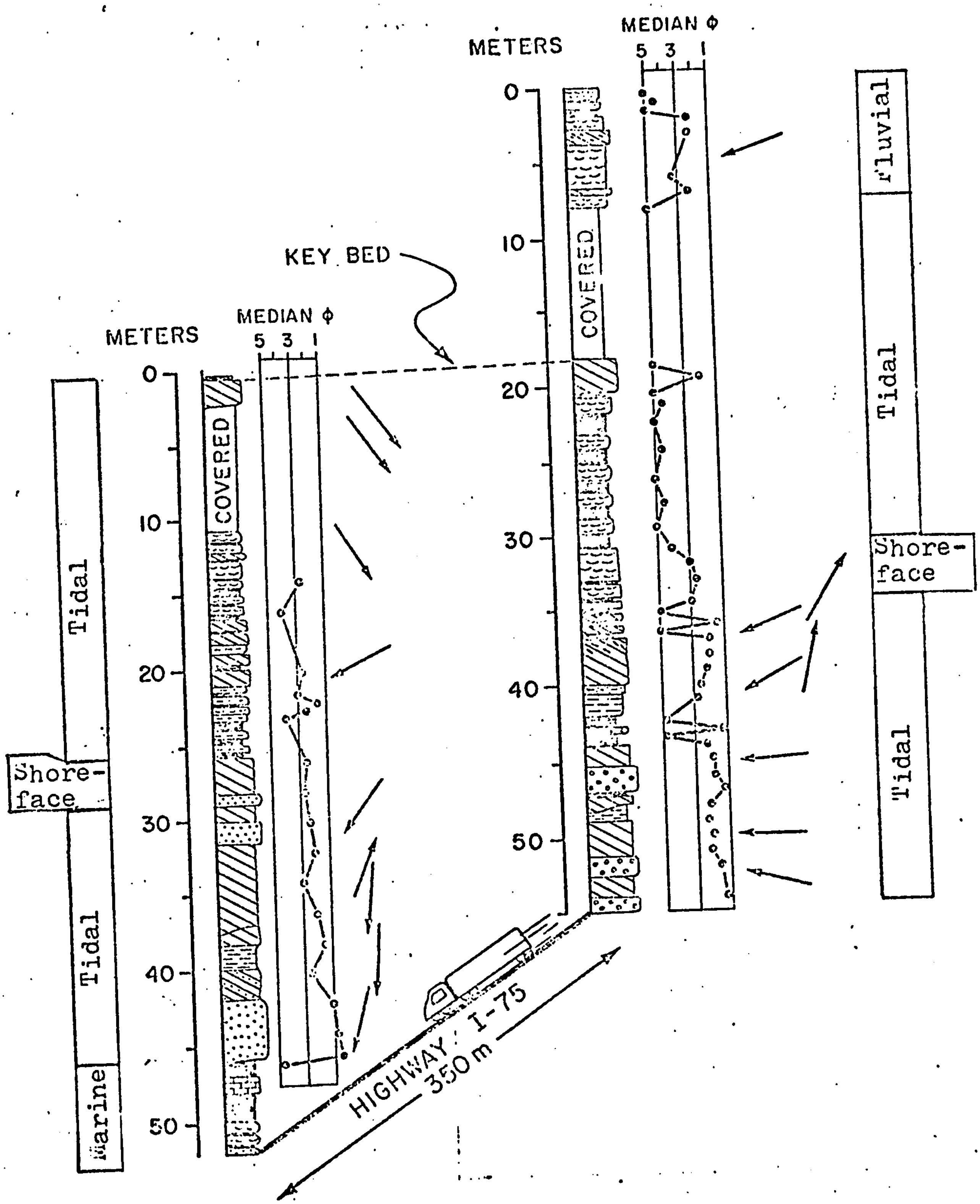

MEDIAN Φ
5 3 1
METERS
0
10
20
30
40
50
COVERED
COVERED
KEY BED
METERS
MEDIAN Φ
5 3 1
0
10
20
30
40
50
Tidal
Shore-face
Tidal
Marine
Fluvial
Tidal
Shore-face
Tidal
HIGHWAY I-75
350 m

FIGURE 15. Vertical profiles through two Pennington sandstones. At left, note general coarsening upward in grainsize from marine to shoreface environments and random crossbed orientation in tidal sandstones containing clay pebbles. At right, three fining upward tidal channels form a multistory sand body. Lower two channels have bimodal crossbedding, upper channel has unidirectional crossbedding. Description in Appendix 5.

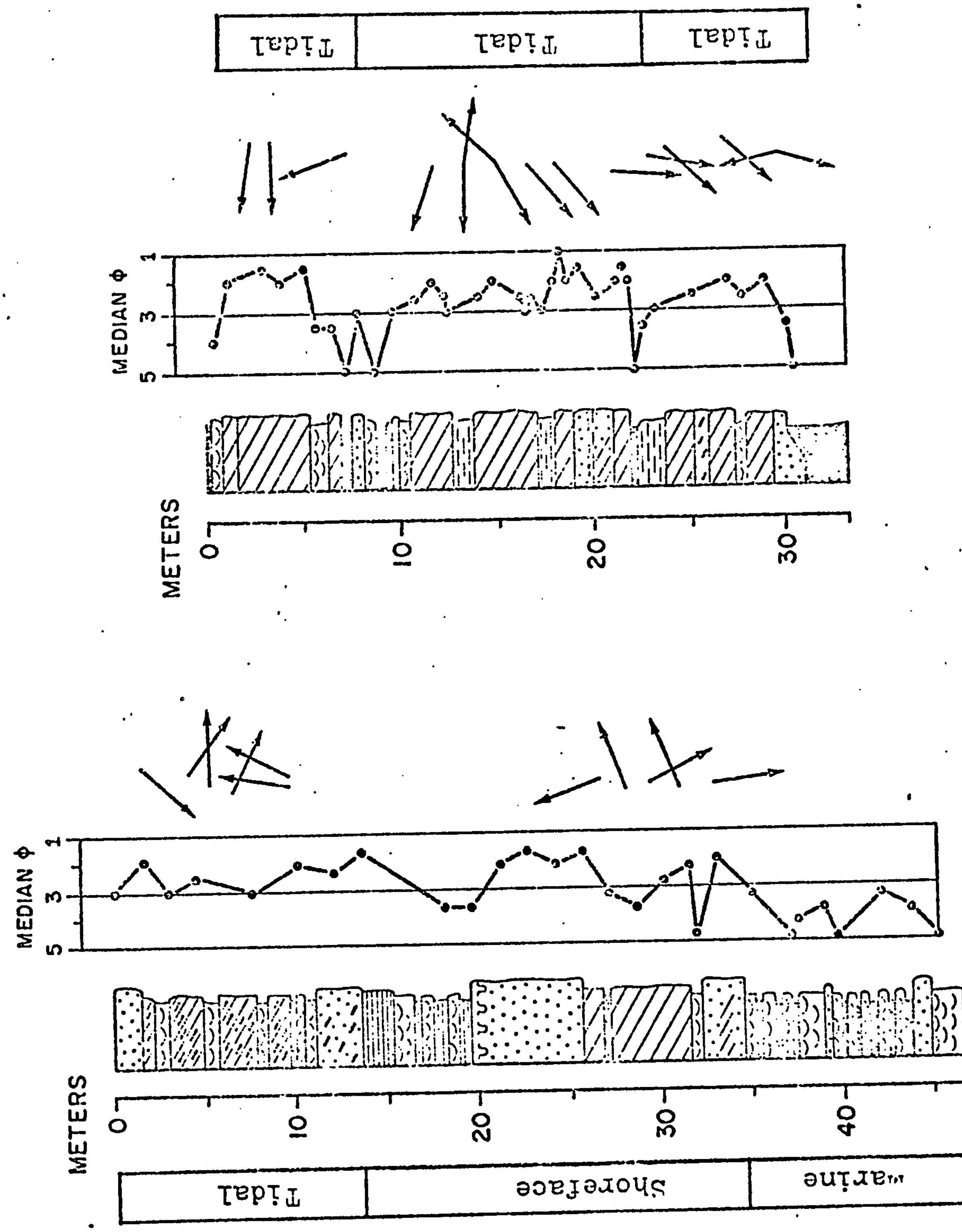

Tidal
Tidal
Tidal
MEDIAN Φ
1
3
5
METERS
0
10
20
30
MEDIAN Φ
1
3
5
METERS
0
10
20
30
40
Tidal
Shoreface
Marine

FIGURE 16. Vertical variation in clay mineralogy within the Pennington Formation. There is an apparent increase in kaolinite based on the relative peak heights. Compare with Fig. 21. Interval shown includes Units 1 to 24, Section 18, Appendix 2.

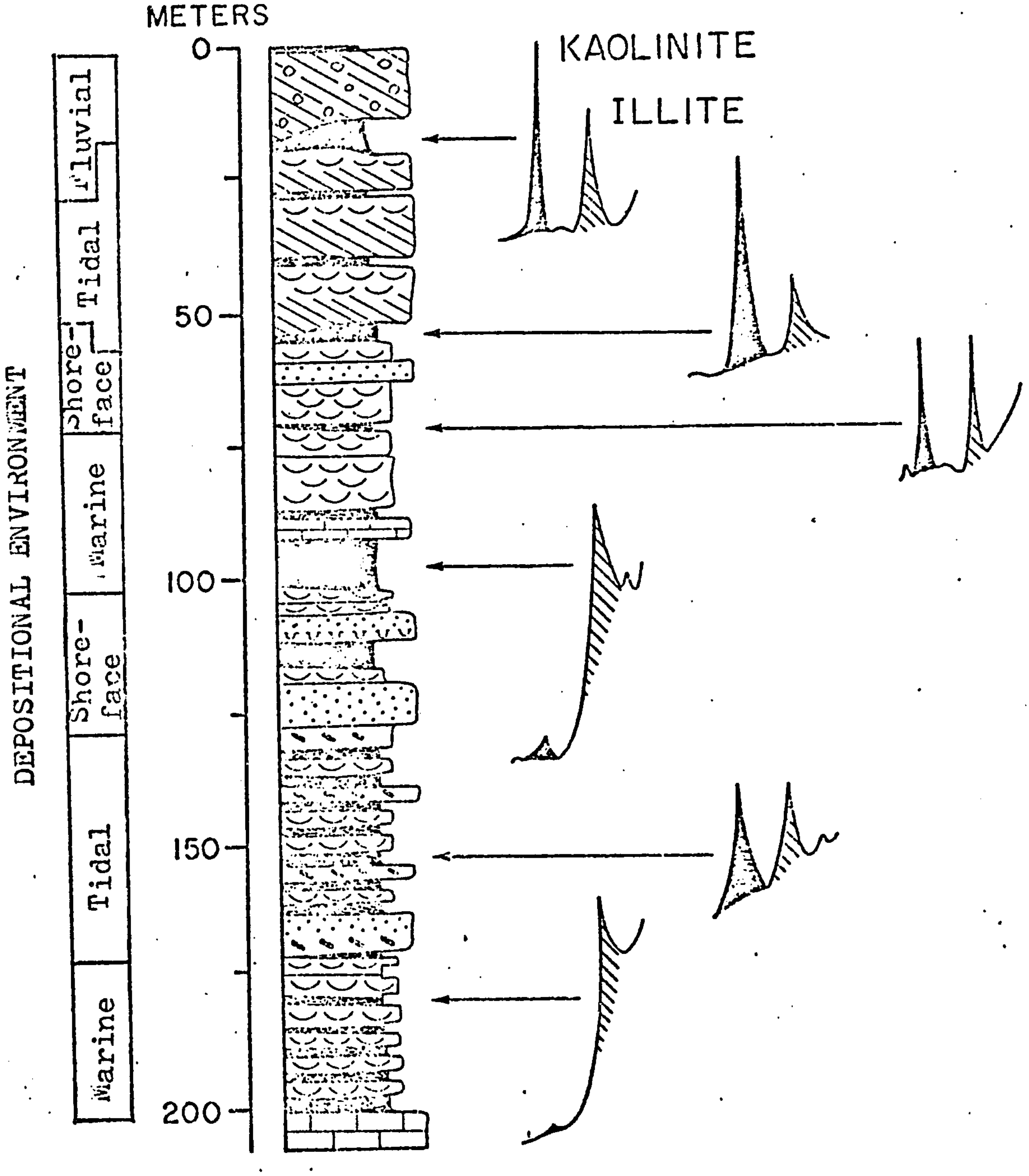
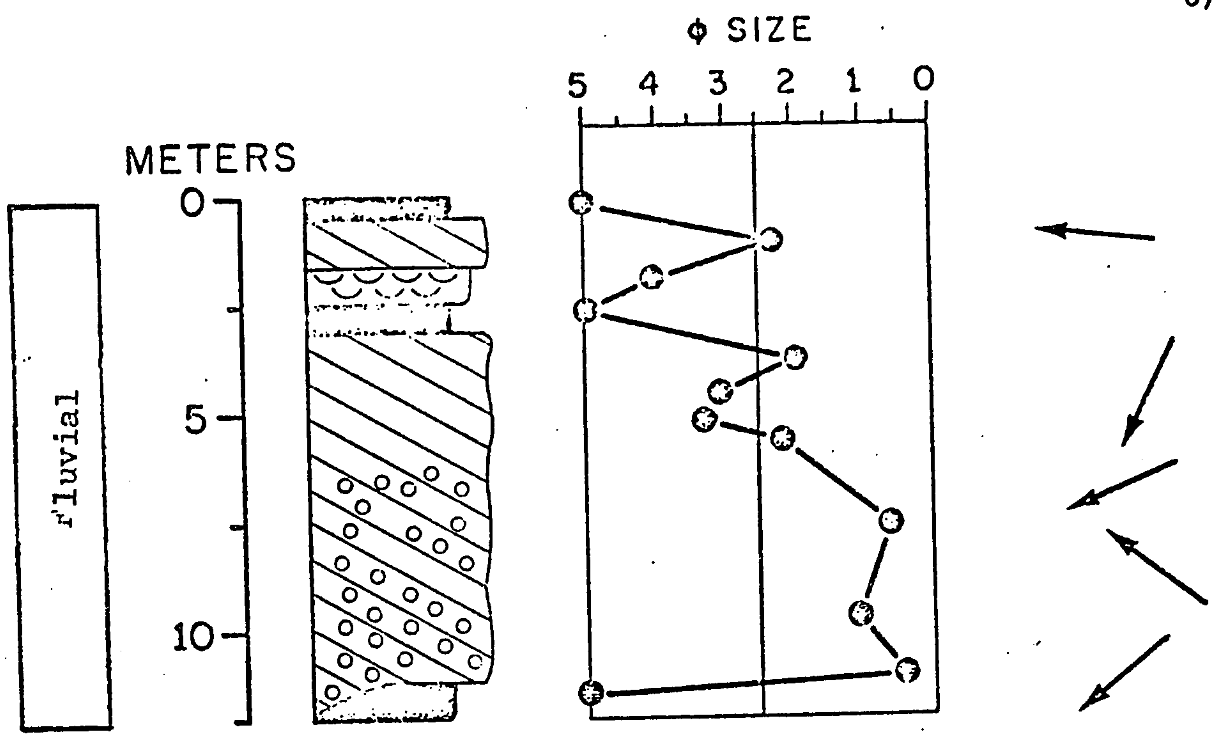

METERS
0
50
100
150
200
KAOLINITE
ILLITE
DEPOSITIONAL ENVIRONMENT
Fluvial
Tidal
Shore-face
Marine
Shore-face
Tidal
Marine

FIGURE 17. Vertical profile through fluvial sandstone. This fluvial sandstone shows a fining upward grainsize trend, variable but unimodal crossbedding direction, erosional base with lag conglomerate of quartz pebbles and is mostly cross-bedded. Description in Appendix 5.

FIGURE 18. Vertical profile through fluvial sandstone. Angular disconformity in lower third of unit is indicated by change in grainsize and shift in crossbedding orientation of approximately 90 degrees. Description in Appendix 5.


Φ SIZE
5 4 3 2 1 0
METERS
0
5
10
r'luvial

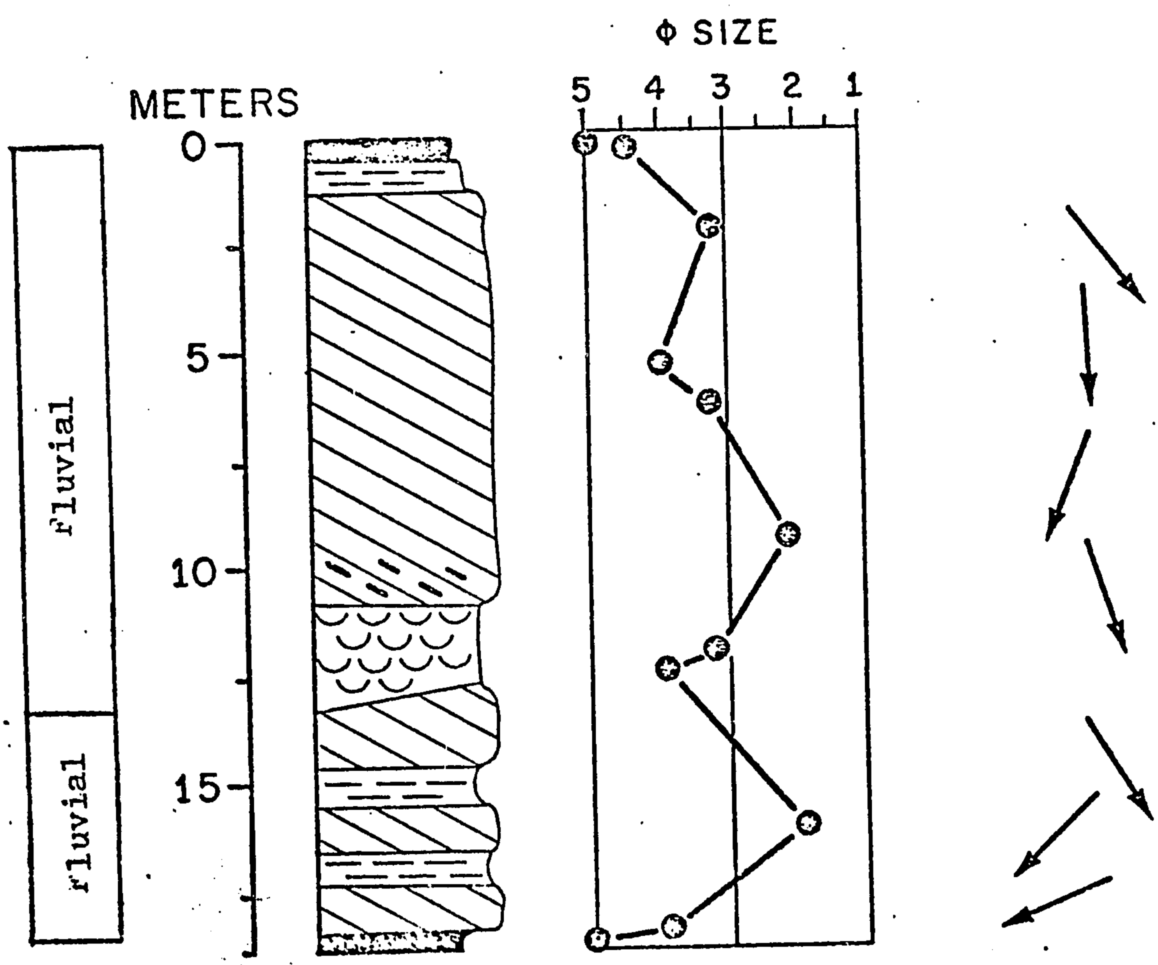

Φ SIZE
5 4 3 2 1
METERS
0
5
10
15
r'luvial
r'luvial

FIGURE 19. Vertical profiles through two low-sinuosity Lee sandstones. Rapid change in bedding type and grainsize are typical of deposits formed by braided (low-sinuosity) streams and represent rapidly changing flow conditions (Smith, 1970, p. 3004). Description in Appendix 5.

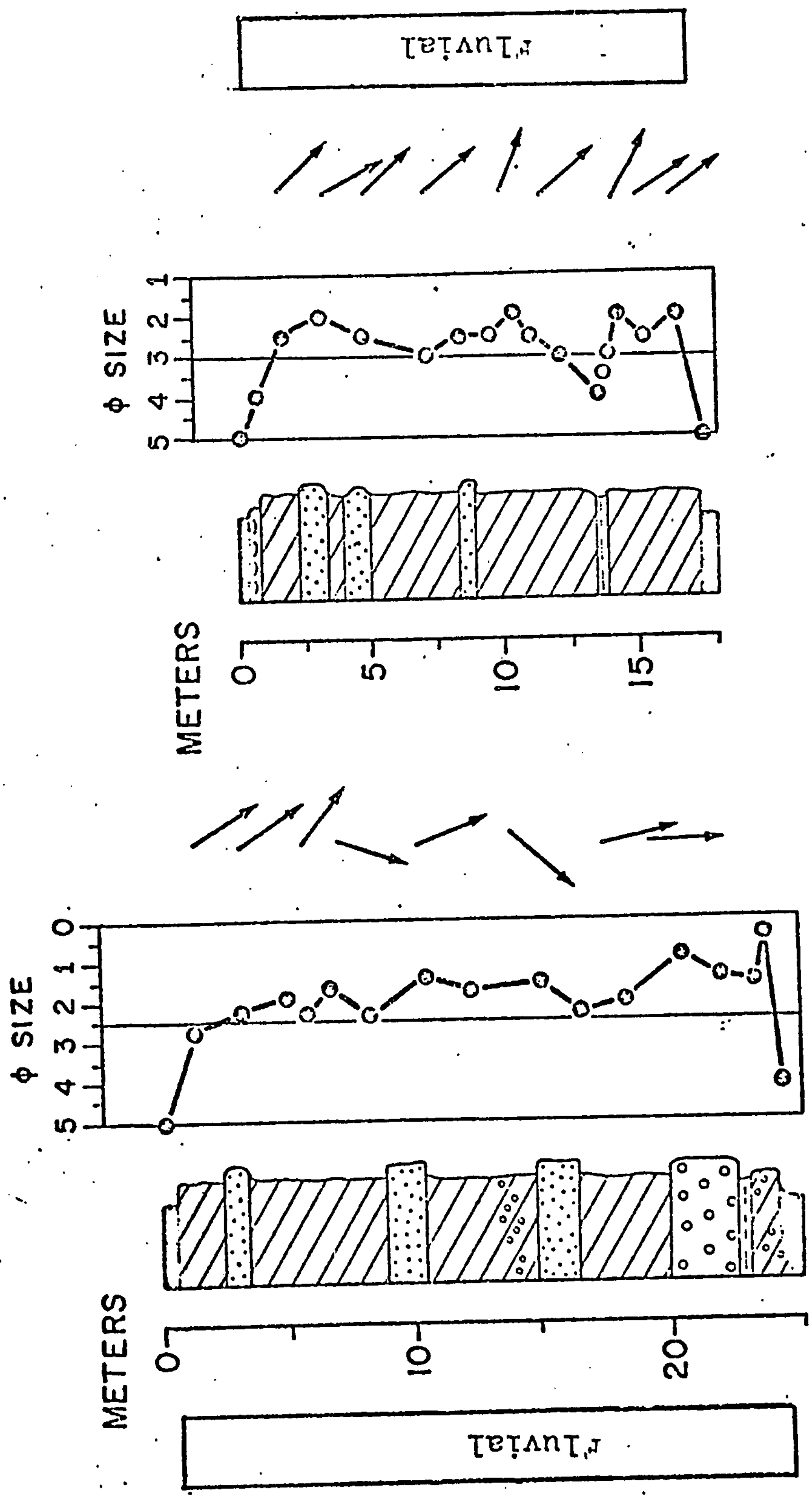
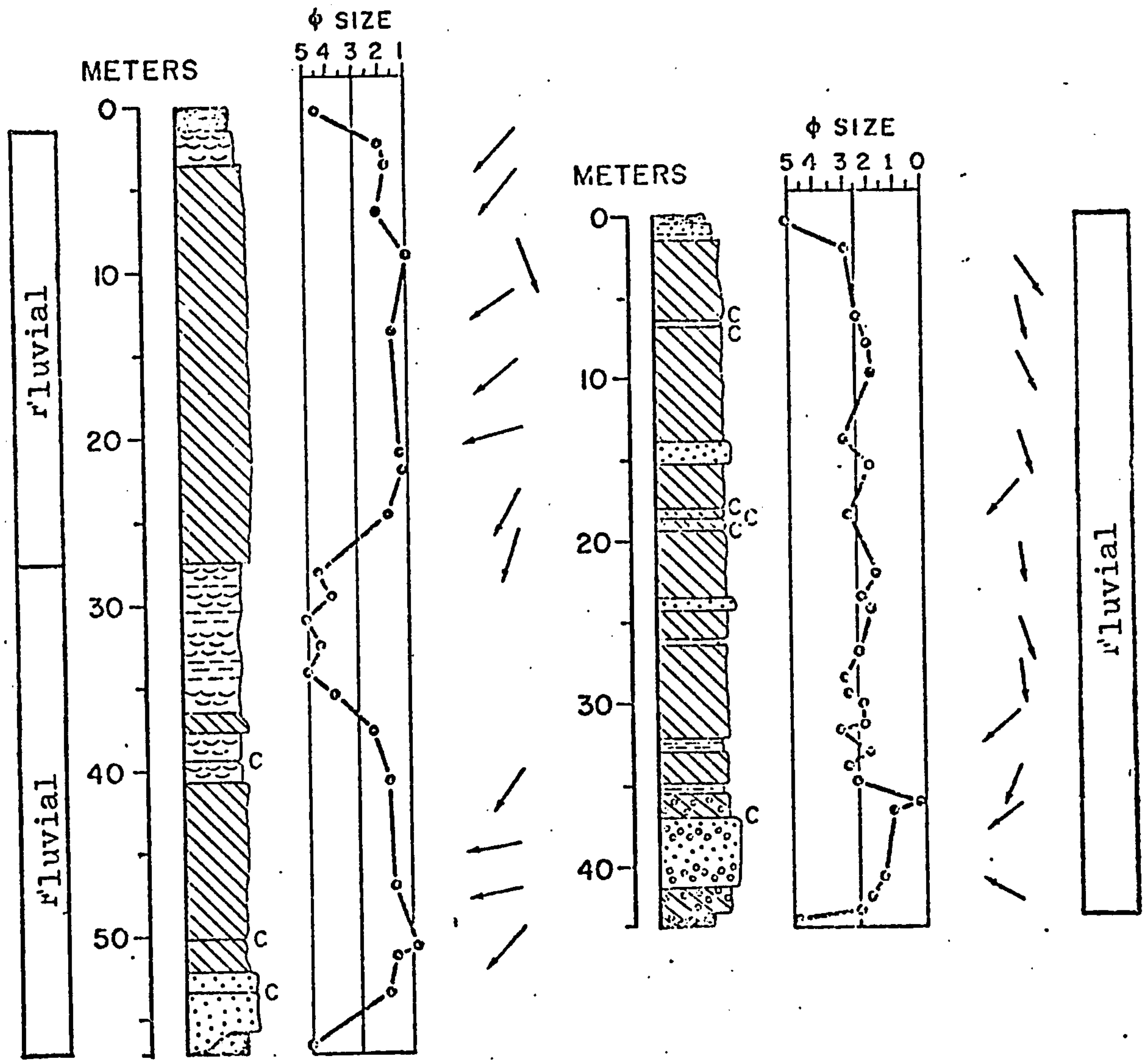

r'luvial
φ SIZE
METERS
r'luvial
φ SIZE
METERS

FIGURE 20. Vertical profiles in fluvial sandstones of the Lee Formation. At left, two channel sandstones forming multistory sand body. At right, transported coaly material is indicated by letter c. All three channel sandstones have erosional bases and fining upward grainsize trend. Paleocurrent directions are predominantly unimodal.
Description in Appendix 5.



φ SIZE
5 4 3 2 1
METERS
0
10
20
30
40
50
r'luvial
r'luvial
C
C
C
φ SIZE
5 4 3 2 1 0
METERS
0
10
20
30
40
C
C
C
C
C
C
r'luvial

FIGURE 21. Clay mineralogy through a section of the Lee Formation. Peak heights indicate kaolinite is more abundant in this section than in the Pennington Formation (Fig. 16). Interval shown represents Units 24 to 39, Section 25, Appendix 2.

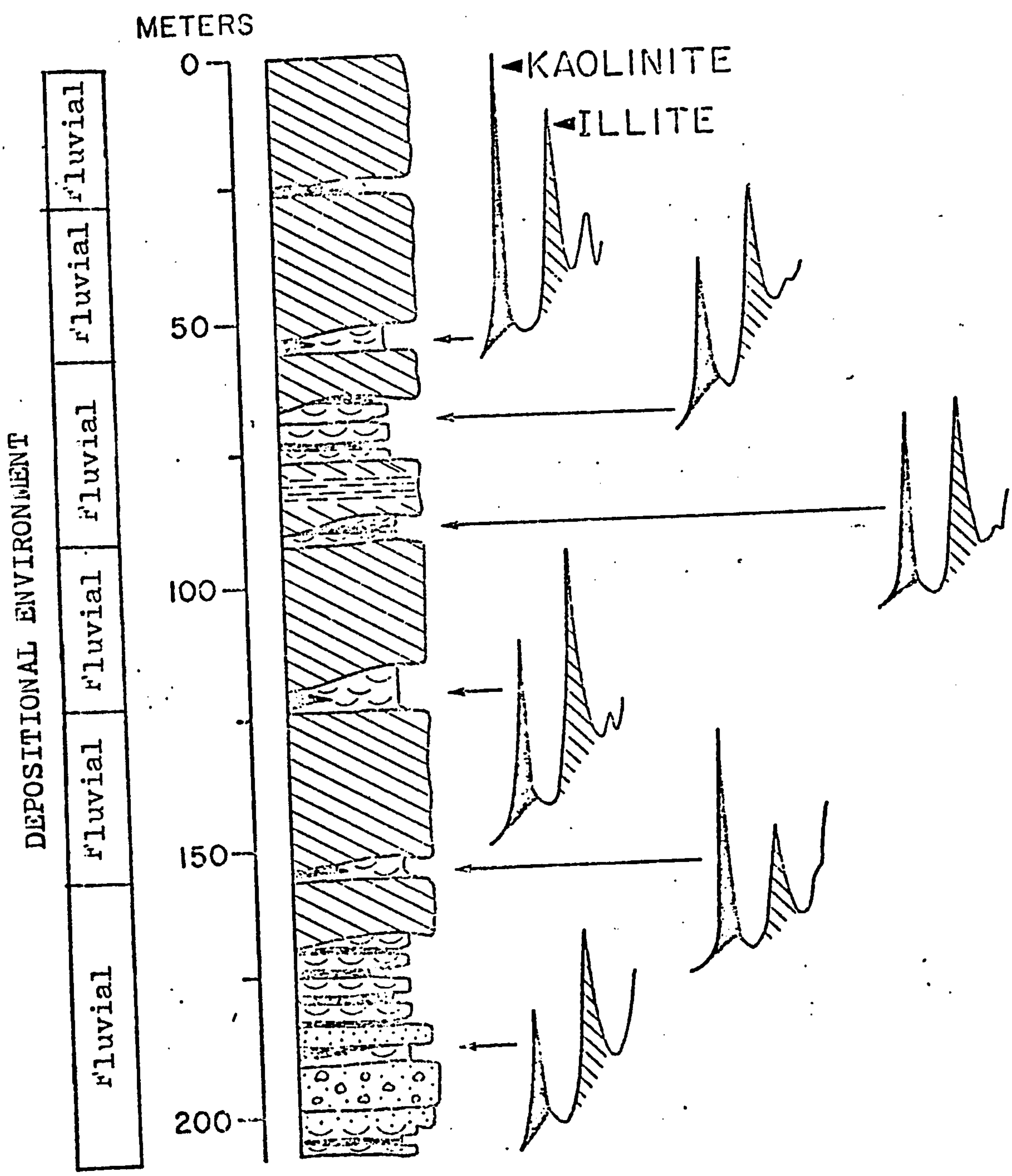

METERS
0
50
100
150
200
KAOLINITE
ILLITE
DEPOSITIONAL ENVIRONMENT
Fluvial
Fluvial
Fluvial
Fluvial
Fluvial
Fluvial
Fluvial

FIGURE 22A. Distribution of median grain sizes for sandstones of various depositional environments in the Pennington and Lee Formations. Grain size estimates were made with a binocular microscope. Number of samples is listed after sandstone type. Line for supermature quartz sand from Carr (1973, Fig. 25). The break in slope for the high-sinuosity sands at 2.0 phi is possibly related to two sub-environments, channel and overbank.

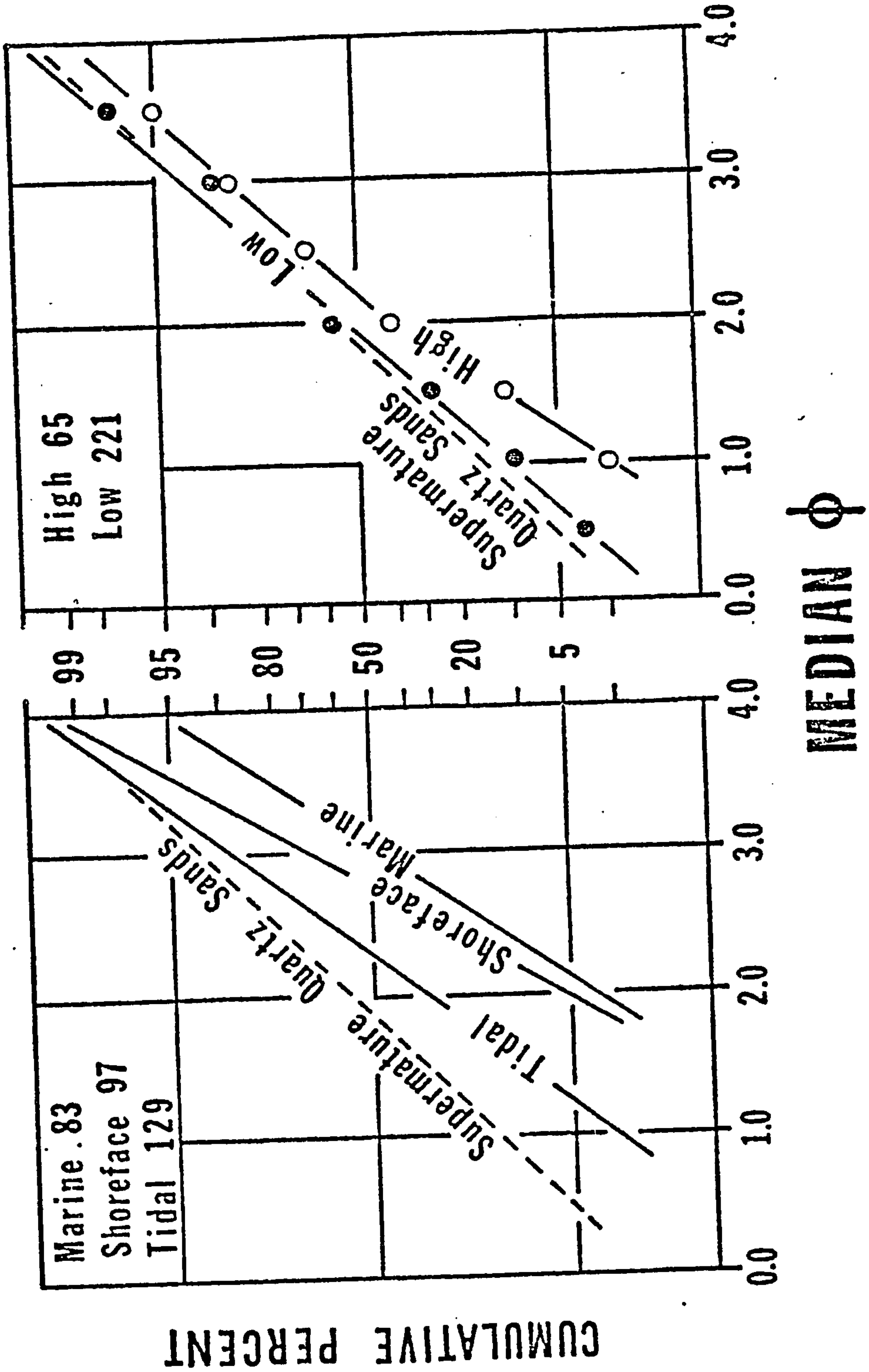

High 65
Low 221
Low
High
Supermature
Quartz
Sands
Marine 83
Shoreface 97
Tidal 129
Marine
Shoreface
Tidal
Supermature
Quartz
Sands
99
95
80
50
20
5
0.0
1.0
2.0
3.0
4.0
MEDIAN φ
CUMULATIVE PERCENT

FIGURE 22B. Typical grain-size probability curves for sandstone depositional environments in the Pennington and Lee Formations. Depositional environments were determined using field criteria. According to some investigators (Visher, 1969; Glaister and Nelson, 1974), different environments of deposition have characteristic or typical curves.

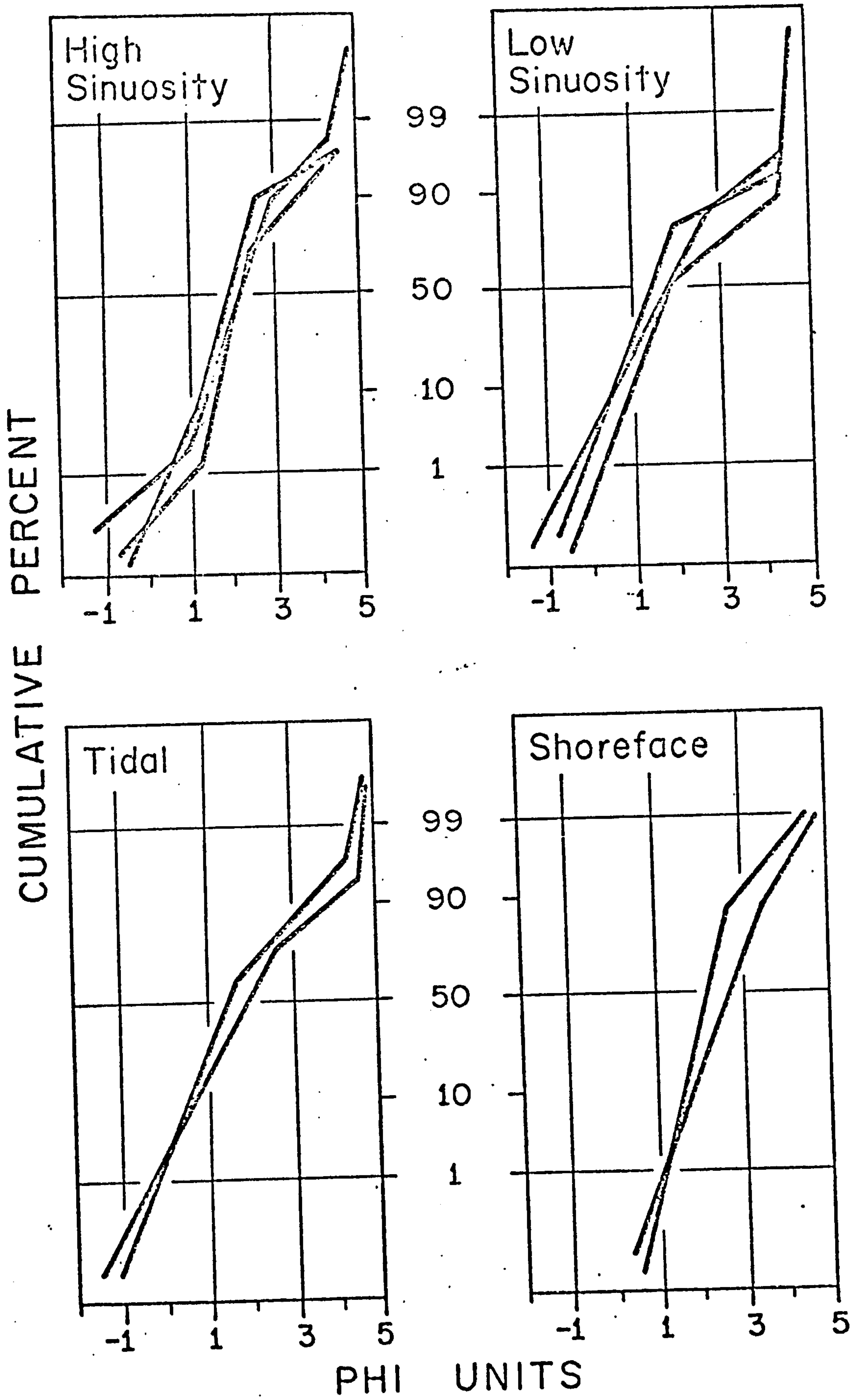

High Sinuosity
Low Sinuosity
Tidal
Shoreface
99
90
50
10
1
-1
1
3
5
CUMULATIVE PERCENT
PHI UNITS

FIGURE 23. Cumulative bed thickness curves for sandstones of various depositional environments in the Pennington and Lee Formations. The beds of the high-sinuosity fluvial sands are slightly thicker than those of low-sinuosity. A similar observation was made for the Silurian sandstones in the Appalachian Basin by Smith (1970, p. 3010). The number of observations is reported beside each sandstone type.

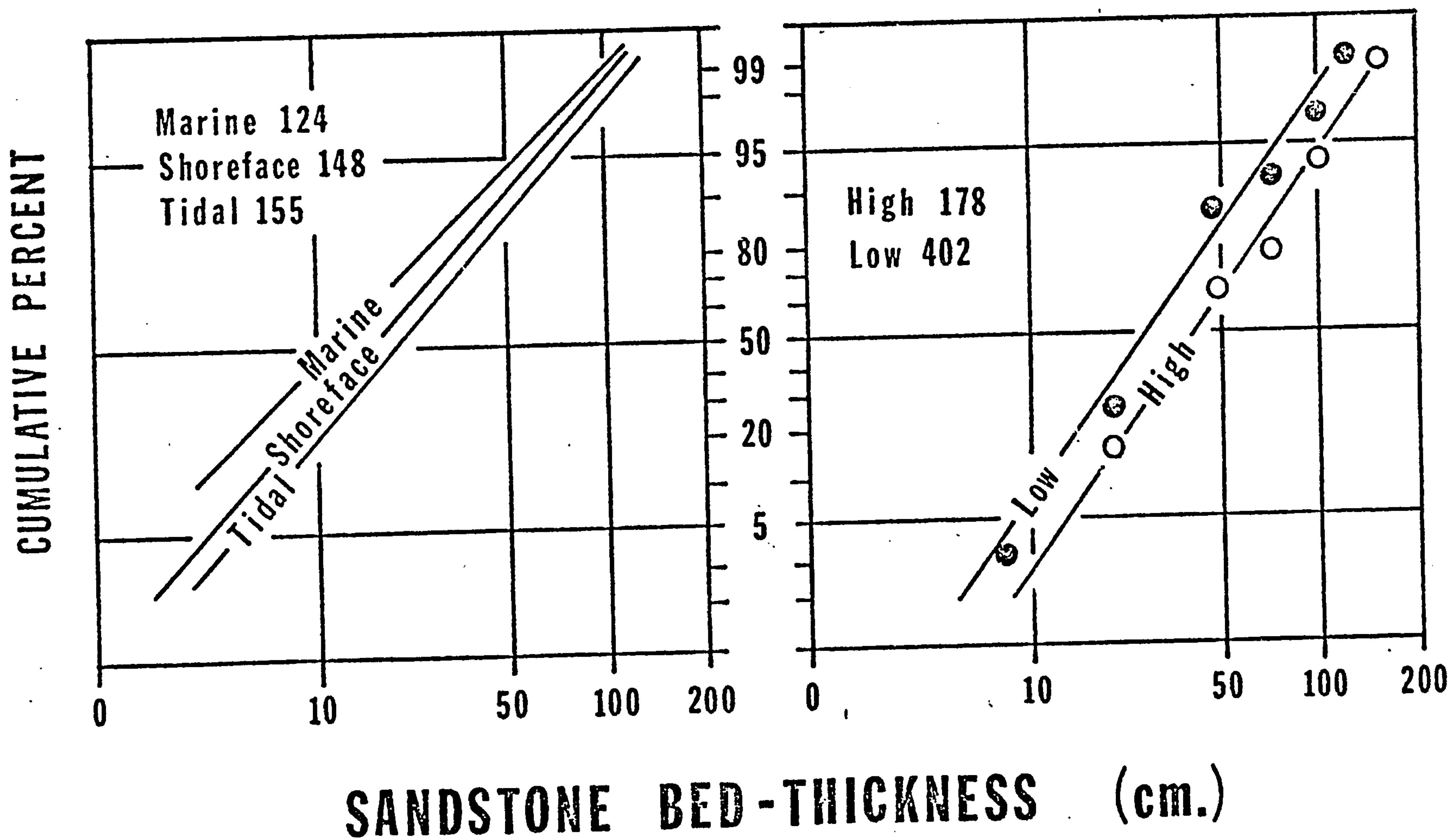
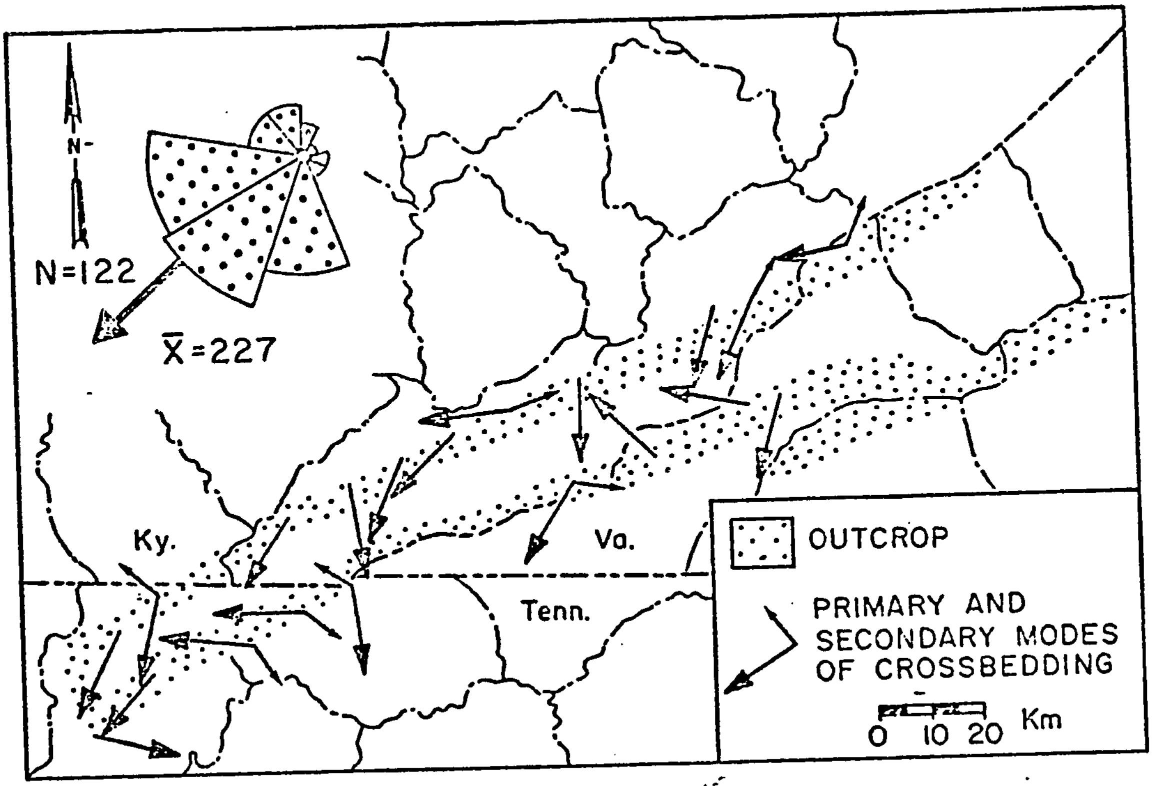

CUMULATIVE PERCENT
Marine 124
Shoreface 148
Tidal 155
Marine
Shoreface
Tidal
High 178
Low 402
High
Low
99
95
80
50
20
5
0
10
50
100
200
SANDSTONE BED-THICKNESS (cm.)

FIGURE 24. Paleocurrent map of crossbedding in tidal sandstones of the Pennington and Lee Formations. General transport direction is to the southwest, as indicated by the paleocurrent rose. Eight of the 21 localities had bimodal orientations.

FIGURE 25. Paleocurrent directions in the fluvial sandstones of the Lee Formation—averaged for 15 minute quadrangles. Compare general transport with Fig. 24. The average transport direction is south-southwest, approximately parallel with the sand percent trend. The high sand ratios continue southwest through Tennessee and swing around to the west in northcentral Alabama (Stearns and Mitchum, 1962, Fig. 12).


N
N=122
X̄=227
Ky.
Va.
Tenn.
OUTCROP
PRIMARY AND SECONDARY MODES OF CROSSBEDDING
0 10 20 Km

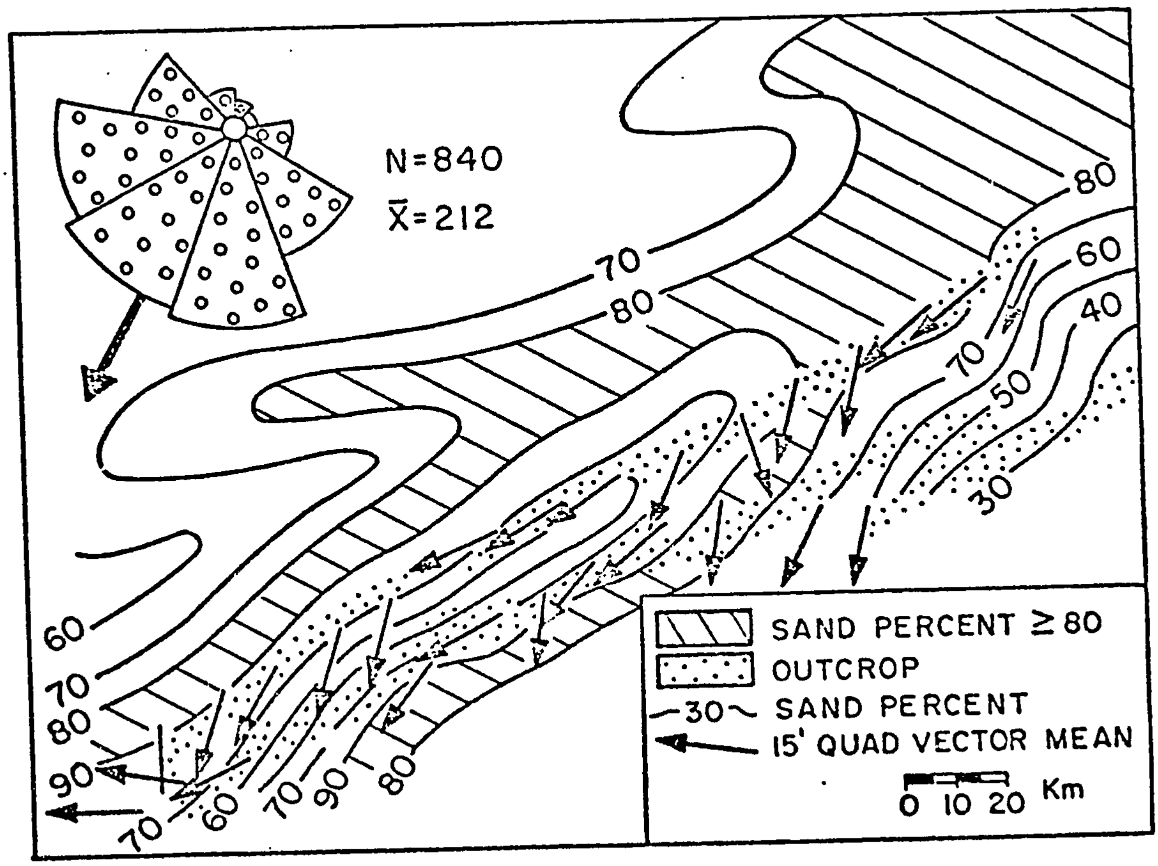

N=840
X̄=212
70
80
60
40
50
30
90
SAND PERCENT ≥ 80
OUTCROP
30 SAND PERCENT
15' QUAD VECTOR MEAN
0 10 20 Km

FIGURE 26. Distribution of bedding types and crossbedding orientation for sandstones of various depositional environments in the Pennington and Lee Formations. The marine sandstones are predominantly ripple bedded while the fluvial sandstones are mostly crossbedded. Tidal sandstones are generally rippled or crossbedded; shoreface sands are massive or crossbedded. Compare crossbed orientations with those shown in Table 10.

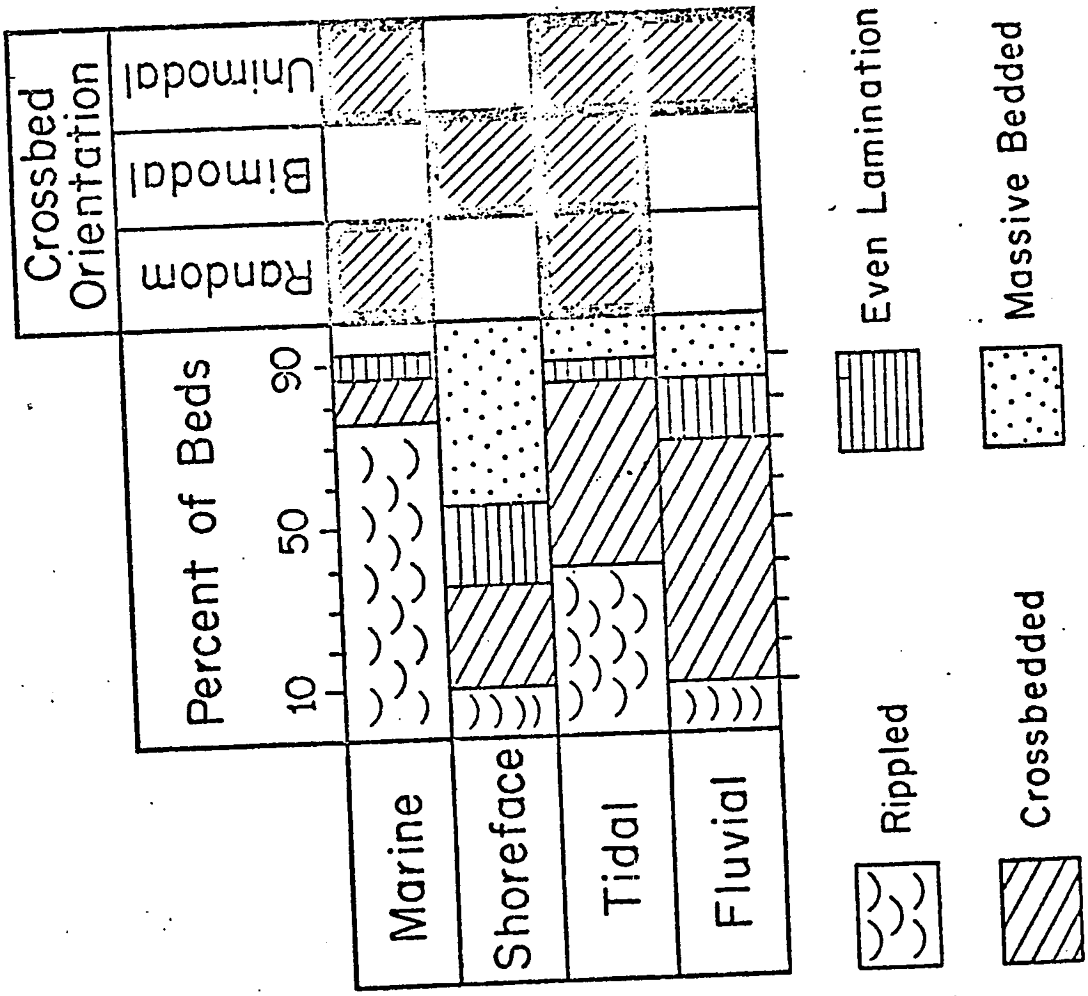
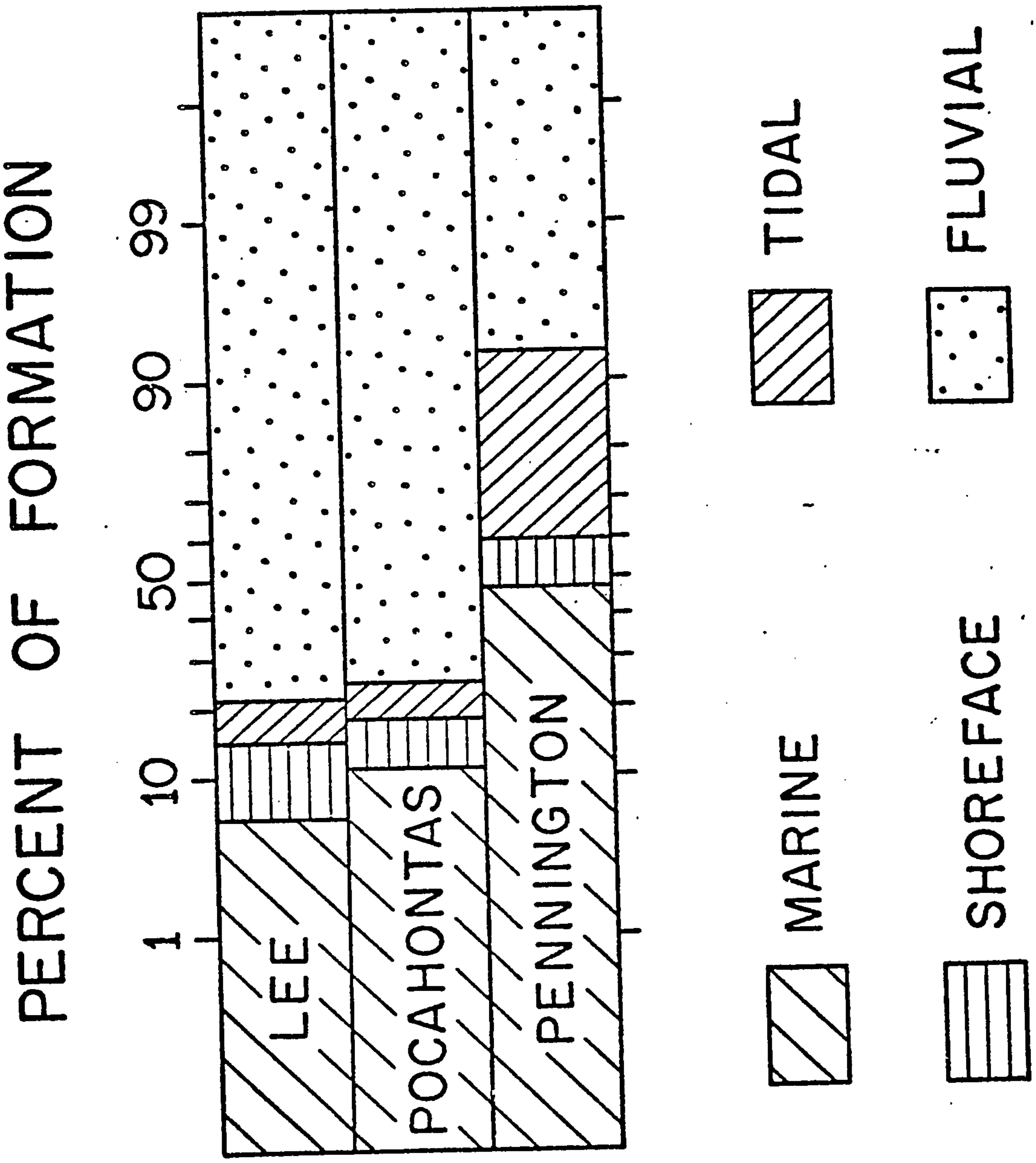

Crossbed Orientation
Random
Bimodal
Unimodal
Percent of Beds
10
50
90
Marine
Shoreface
Tidal
Fluvial
Rippled
Crossbedded
Even Lamination
Massive Bedded

FIGURE 27. Distribution of sandstone deposition environments in the Pennington, Pocahontas and Lee Formations. The overall regressive nature of the stratigraphic sequence is indicated by the increase in fluvial and decrease in marine environments from the Pennington to Lee Formation.
Based on vertical profiles through 2482 meters of sandstone.


PERCENT OF FORMATION
1
10
50
90
99
LEE
POCAHONTAS
PENNINGTON
MARINE
SHOREFACE
TIDAL
FLUVIAL

SYSTEMIC BOUNDARY

One of the principal objectives of this study was to locate the position and determine the character of the Mississippian-Pennsylvanian systemic boundary. Recognizing the position of systemic boundaries is rather easy when they are identified by angular unconformities, disconformities with several geologic units missing, or paraconformities identified by contrasting lithologies. Unfortunately, none of these situations are applicapable to the Mississippian-Pennsylvanian boundary in the Cumberland overthrust sheet.

The discussion in this chapter is designed to answer the following questions related to the Mississippian-Pennsylvanian systemic boundary in the sediments of the Cumberland overthrust sheet:

1. Why is the boundary generally so obscure?
2. How does one locate it in specific outcrop sections?
3. How useful are the sandstone lithologies and depositional environments described in Chapter 4 in locating the systemic boundary?
4. What is the relationship, if any, between the character and position of the systemic boundary in the Cumberland overthrust sheet and other portions of the Central Appalachian Basin?

Locating The Boundary

The position of the systemic boundary within the Cumberland overthrust sheet is difficult to identify, because it is not characterized by contrasting lithologies or an erosional unconformity (see discussion in Introduction - Objective 2).

The position of the boundary within the overthrust sheet is best established with paleontologic data. Conodonts, obtained from limestones and calcareous shales, and spore-pollen assemblages, obtained from coal macerations, both have definitive Mississippian and Pennsylvanian taxa. The sampling procedure was designed to obtain samples as close as possible in vertical sequence to detect the change from Mississippian to Pennsylvanian assemblages.

Locations of limestone and coal samples can be found in Appendix 4. Listing of conodont and spore taxa are given in Tables 4 and 5 and Appendix 4.

Age determinations by Dr. R. M. Kosanke and Dr. R. A. Peppers of spore assemblages, and Dr. C. B. Rexroad of conodont assemblages from sections at Campbell Co., Tenn., Whitley Co., Ky., and Wise Co., Va., indicate that the Mississippian-Pennsylvanian boundary is within the Pennington Formation as mapped by the U. S. Geological Survey (Fig. 28). A similar position for the systemic boundary was reported by Englund (1974, p. 33), using paleontological data, northeast of the Russel Fork Fault in the subsurface of Buchanan Co., Va. (Fig. 2).

In many outcrops, paleontological data are either very scarce or lacking. In the absence of paleontological data, and knowing that the systemic boundary is not identified simply as the contact between varicolored siltstones and shales and quartzose conglomeratic sandstones, how does one determine the position of the systemic boundary? Two other methods can be used.

Field Tracing of Lithologies To Paleontologically Dated Sections And Sandstone Depositional Environments

The first, and often the simplest, is to correlate the lithologic units in question, to a section containing paleontological markers. This can be illustrated with Section 14 (Appendix 5), located along Interstate Highway 75, south of Jellico, Campbell Co., Tennesse. The sandstone body (Fig. 14), interpreted as a tidal channel deposit, overlies a carbonate wackestone, the Avis Limestone (Unit 1, Section 14, Appendix 5), dated by Rexroad as Mississippian based on the conodont assemblage shown in Table 4. Without paleontological evidence above the sandbody, from either spores or conodonts, all that could be said is that its age is either Mississippian or Pennsylvanian. However, 17.6 km northeast of Jellico along Pine Mountain at Henry Bowling Gap, the same sandstone thins and is stratigraphically lower than an unnamed limestone dated Mississippian with conodonts (Table 4) and a carbonaceous shale reported to be Chesterian (Mississippian) based on plant fossils (Englund, 1971, p. 15). Therefore, the sand body is of Mississippian age.

The distribution of sandstone depositional environments and their paleontologic ages can be summarized as follows. The sandstones record a transition from shallow marine, through shoreface and various tidal environments to fluvial-deltaic sequences. Quartzose sandstones deposited in a marine environment were all dated Mississippian. Sandstones containing quartz pebbles were found to be either Mississippian or Pennsylvanian in age (Fig. 28), and were deposited in shoreface of tidal environments (Chapter 4). All the conglomeratic sandstones deposited in fluvial environments were dated Pennsylvanian.

In the absence of any paleontologic data, placing the systemic boundary at other locations within the overthrust sheet can be attempted as follows. Knowing that a sandbody represents a marine deposit implies that it is Mississippian in age. Similarly, fluvial sandbodies are all Pennsylvanian. How ver, shoreface and tidal sandstones can be either Mississippian or Pennsylvanian in age. Unless the shoreface or tidal sandbody occurs between two marine (Mississippian) or fluvial (Pennsylvanian) sandstones in a vertical section, only paleontologic data can give a conclusive age determination. An example of the latter, a shoreface and tidal sandstone between a marine and fluvial sandstone, can be seen at Henry Bowlin Gap (Appendix 1, No. 18; Location 18, Fig. 5). This section is shown in Figure 16. The marine sandstone (Unit 11, Section 18, Appendix 2) overlies an unnamed limestone and shale (Units 9 and 10 dated Mississippian by Rexroad (Table 4). The shoreface and tidal sandstones, Units 12 to 19, are overlain by a fluvial sandstone, Units 21 to 24, and shown in Figure 17. Throughout the study area, fluvial sandstones were dated Pennsylvanian. But what age are the shoreface and tidal sandstones at this locality? A thin coal and underclay (maceration 2095, Table 5), which occurs at the base of Unit 12, was dated Pennsylvanian. Therefore, the overlying shoreface and tidal sandstones are Pennsylvanian.

Sedimentologic Model And The Systemic Boundary

As stated previously, there is no widespread erosional surface separating Mississippian and Pennsylvanian Age sediments on the Cumberland overthrust sheet. However, field mapping by the U. S. Geological Survey (Englund, 1969, p. 21), cross sections by Miller (1974, Pl. 4) and my fieldwork and cross sections indicate the presence of a widespread erosional surface at the base of the Middlesboro Member of the Lee Formation. In outcrop, the erosional surface is identified as the unconformable basal contace of the conglomeratic sandstones deposited in a low sinuosity fluvial environment. On a regional scale in the Cumberland overthrust sheet, the unconformity is most strikingly represented by the erosion of the Pocahontas Formation (equivalent to the lower three members of the Lee) as it thins from 150 meters along Cumberland Mountain to less than 20 meters on Pine Mountain, where it is often thin or missing so that it is rarely recognized in outcrop and is not mappable as a separate unit.

A synthesis of sedimentologic, stratigraphic, and paleontologic data has resulted in my proposing a regressive model for sedimentation in this portion of the Central Appalachian Basin (Fig. 29). A regressive model was proposed by Mitchum (1954, p. 238), but he assigned all of the Lee sandstones to a marine depositional environment with some scattered fluvial sediments containing thin coals. Miller (1974, p. 126), in another regressive model, assigned the quartzose and conglomeratic sands of the Lee Formation, in particular the equivalents of the Middlesboro and Bee Rock Members, to a barrier island depositional environment and interpreted the erosional surfaces at the base of the sandstones to have been caused by barrier island migration.

My model, while also regressive, has a different interpretation for the depositional environment of the quartzose conglomeratic sandstones of the Middlesboro, Bee Rock and Naese Members. I believe that the sedimentologic data, presented in vertical profiles in Chapter 4, strongly indicates deposition by low sinuosity rivers, with the erosion at the base of the sandstones related to uplift and scour preceding deposition. Based on this model, the Pocahontas and Pennington Formations were truncated during uplift prior to the deposition of the Middlesboro Member of the Lee Formation (or equivalents) and the erosional surface between two Pennsylvanian Formations.

North and west of the overthrust sheet, the erosional surface truncates older formations so that the sustemic boundary is represented by an erosional surface and commonly a sharp lithologic contrast. In northeastern Ohio, the Sharon Conglomerate, equivalent to the upper members of the Lee, was deposited on an erosional surface of Mississippian sediments (Meckel, 1967, p. 242) in depositional environments described as low sinuosity, braided streams (Mrakovich and Coogan, 1974).

Along the western margin of the Appalachian Basin in central Kentucky, the conglomeratic sandstones of the Lee Formation fill erosional valleys that were incised into Middle Mississippian sediments (Newman and Borden Formations) before deposition (Sheppard, 1964). However, just east of this area toward the center of the basin, quartzose sand bodies within the Pennington Formation have been paleontologically dated Mississippian and interpreted as nearshore-tidal sandstones (Martin, 1975, p. 66). It is proposed that erosion, preceding deposition of the Middlesboro Member, was less extensive in the area studied by Martin than that which occured farther west, where there are paleovalleys and where the Cincinnati Arch may have acted as a weak positive high. Uplift along the arch and its possible influence as a positive area has been discussed by Seiver and Potter (1956, p. 331) and Arkle (1974, p. 9). Although the arch was not a barrier to sedimentation, minor uplift along the arch could be responsible for the formation of the paleovalleys that were cut into Mississippian sediments preceding deposition of the Lee sandstones. Also, minor uplifts along the Waverly Arch, which is approximately 96 kilometers east of the Cincinnati Arch (Woodward, 1961, p. 134) were invoked by Dever (1973; in Martin, 1975, p. 13) and Martin (1975, p. 15) as controlling deposition of Late Mississippian sediments and causing erosional surfaces. It is possible that the Waverly Arch was also active during the Pennsylvanian, causing uplift resulting in erosion.

It should be pointed out that this interpretation is in sharp contrast with one presented by Ferm _et al_. (1974), in which the Lee sandstones have been interpreted as barrier islands. While some of the sandstones have been deposited in shoreface environments, certainly not all of the sandstones have the same depositional environment. Vertical sequences of sandstones must be studied carefully to interpret their depositional environments accurately, and my analysis of the Lee sandstones indicates that they were deposited predominantly in a low sinuosity fluvial environment (Fig. 27; Chapter 4).

The Ferm et al. model is also in contradiction with the paleontological interpretations used in this paper and by Englund (1974). Ferm et al. (1974, Fig. 4) interpret the Newman (Upper Mississippian), Pennington, Lee and Breathitt (Middle Pennsylvanian) as time equivalents, representing sedimentation in environments ranging from off-shore carbonate tidal bars to upper delta plain coal swamps. In their opinion, marine fauna cannot be compared with continental flora to establish age determinations, because the fauna are environmentally controlled. Although the biostratigraphic control used in this paper cannot conclusively disprove the Ferm et al. interpretation, because the conodont and spore assemblages were not found in the same sample, it is felt that the sedimentological model proposed in this paper for identifying the systemic boundary adequately explains the paleontological data, without having to equate Upper Mississippian and Upper Pennsylvanian sediments.

Summary

The position of the systemic boundary within the Cumberland overthrust sheet is obscure because it crosses several diachronous lithofacies, and is best established by means of paleontologic data, in combination with the field tracing of mappable units to paleontologically dated sections. While marine sand bodies all appear to be Mississippian, and fluvial sand bodies Pennsylvanian, shoreface and tidal sandstones can be of either age and therefore only correctly dated with paleontological data.

The systemic boundary occurs within the Pennington Formation and crosses several lithologies. Northwest of the overthrust sheet, the regional unconformity at the base of the Middlesboro Member of the Lee Formation, or equivalents, may truncate all of the lower members of the Lee, so that there the systemic boundary is characterized by an erosional surface and sharp lithologic contact.

FIGURE 28. Sample locations for conodont and spore-pollen assemblages used to position the systemic boundary at three locations within the overthrust sheet. See Tables 4 and 5 for listing of taxa. Coals are identified by maceration number. Samples for conodont analysis are identified by slide name and listing in letter from Dr. C. B. Rexroad, July 17, 1975. Detailed sample locations for the coal macerations can be found in Appendix 4A. Detailed sample locations for the conodont samples can be found in Appendix 4B. All coal macerations in this figure were dated Pennsylvanian, all conodont assemblages dated Mississippian.

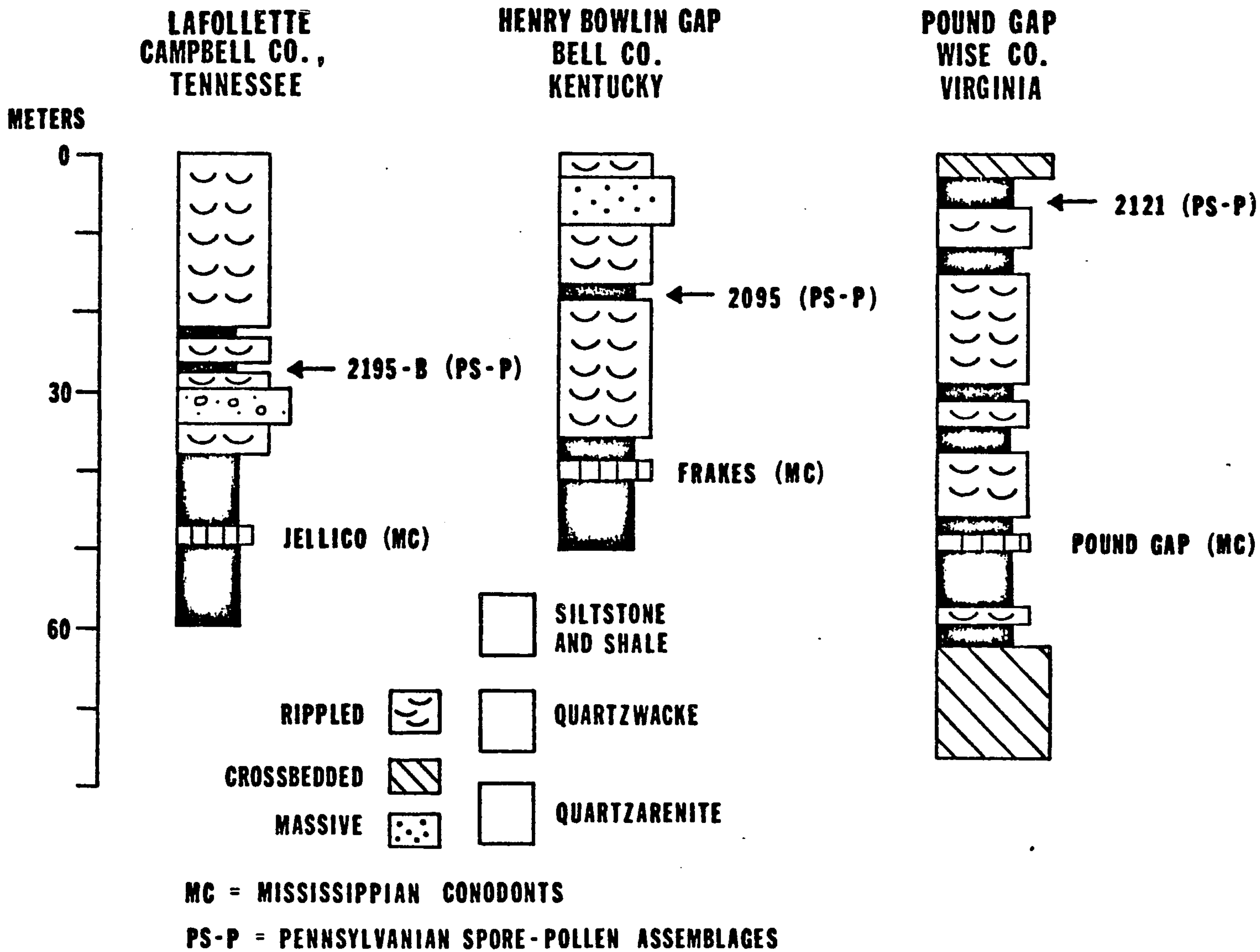

LAFOLLETTE
CAMPBELL CO.,
TENNESSEE
HENRY BOWLIN GAP
BELL CO.
KENTUCKY
POUND GAP
WISE CO.
VIRGINIA
METERS
0
30
60
2195-B (PS-P)
JELLICO (MC)
2095 (PS-P)
FRAKES (MC)
2121 (PS-P)
POUND GAP (MC)
SILTSTONE AND SHALE
QUARTZWACKE
QUARTZARENITE
RIPPLED
CROSSBEDDED
MASSIVE
MC = MISSISSIPPIAN CONODONTS
PS-P = PENNSYLVANIAN SPORE-POLLEN ASSEMBLAGES

FIGURE 29. Generalized models for deposition of the Pennington, Pocahontas and Lee Formations. The Pocahontas is equivalent to the Chadwell, White Rocks and Dark Ridge Members of the Lee Formation (see Fig. 6).

A. Initial deposition of Pennington Formation consisting of marine, shoreface and tidal sediments. Paleontological data indicate that the Mississippian-Pennsylvanian systemic boundary is within the Pennington Formation, as mapped by the U. S. Geological Survey. The systemic boundary, visualized as a time plane, is indicated by the heavy solid line and labelled in upper left corner of figure (M = Mississippian, P = Pennsylvanian).

B. Continued regression results in the deposition of the Pocahontas Formation with marine shoreface, tidal and fluvial environments. The Pocahontas contains several economically important coals. Formation assignments of the sandstones can be confusing because the formations are identified by characteristic lithologies and the transitional character of the depositional environments results in the interfingering of the lithologies.

C. Later, uplift terminates deposition of the Pocahontas during early Pennsylvanian. Erosion of Pocahontas and Pennington Formations precedes deposition of Middlesboro and Upper Members of the Lee Formation, characterized by deposition in low-sinuosity rivers flowing southwest.

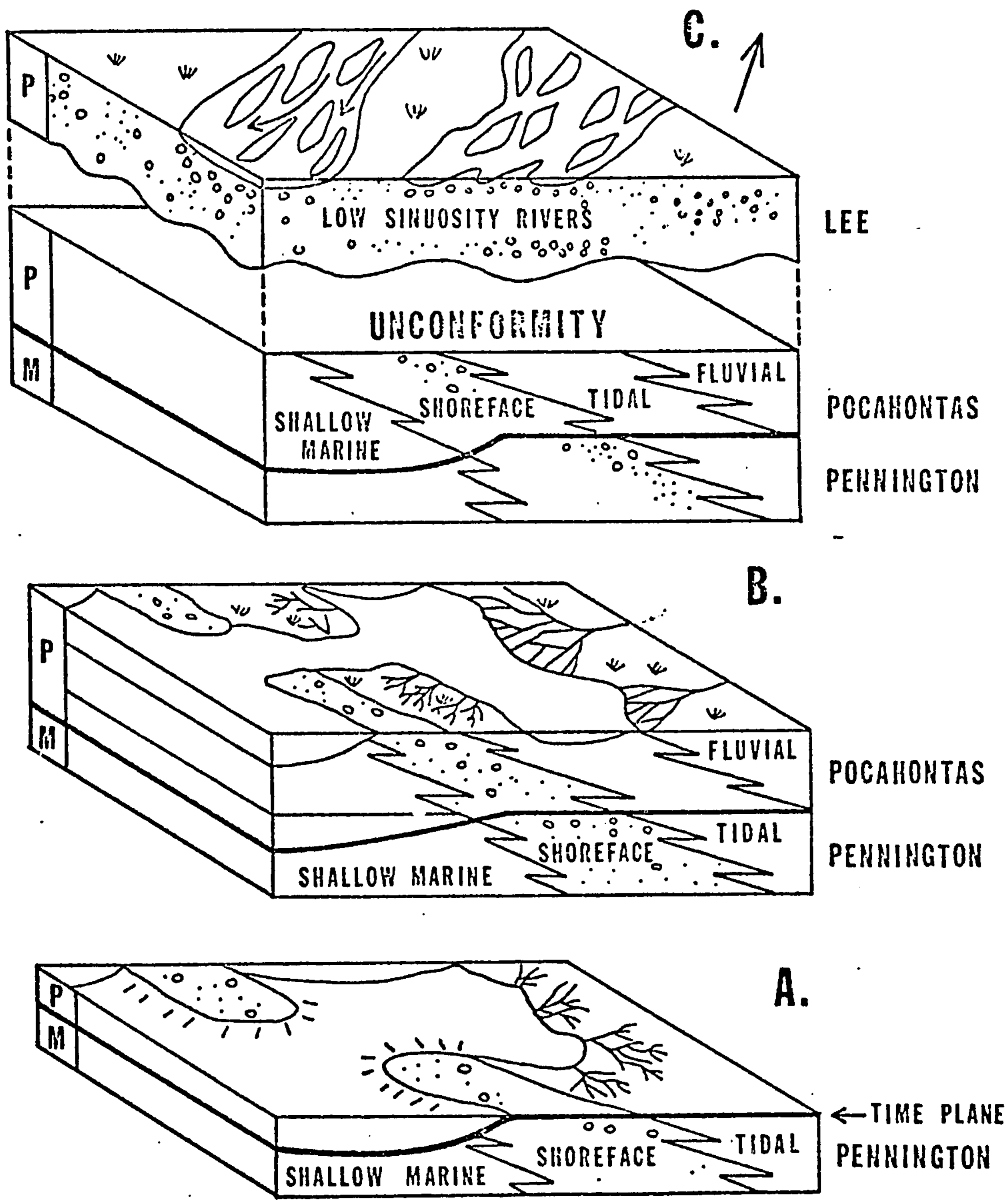
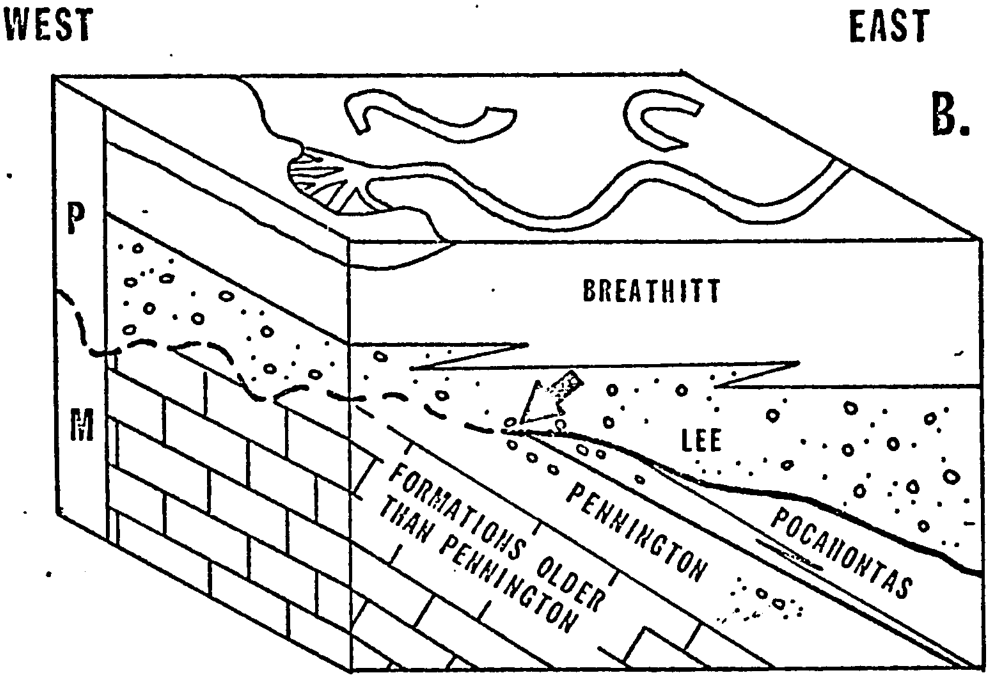

C.
P
P
M
LOW SINUOSITY RIVERS
LEE
UNCONFORMITY
FLUVIAL
TIDAL
SHOREFACE
SHALLOW MARINE
POCAHONTAS
PENNINGTON
B.
P
M
FLUVIAL
POCAHONTAS
TIDAL
SHOREFACE
SHALLOW MARINE
PENNINGTON
A.
P
M
←TIME PLANE
TIDAL
SHOREFACE
SHALLOW MARINE
PENNINGTON

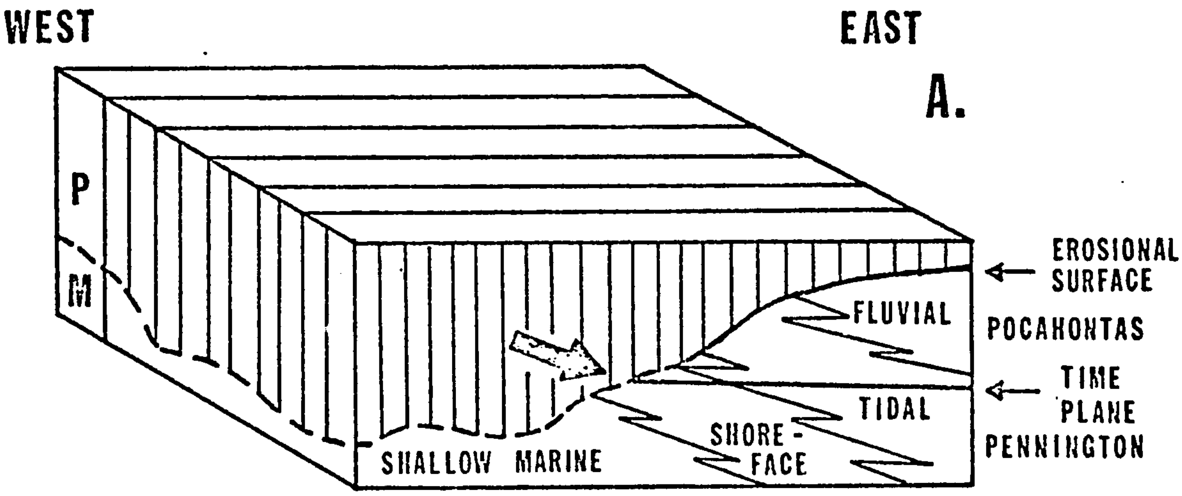
FIGURE 30. Generalized models indicating the position and character of the Mississippian-Pennsylvanian Systemic boundary (heavy solid and dashed line) to the Pennington, Pocahontas and Lee Formations. The Pocahontas is equivalent to the Chadwell, White Rocks and Dark Ridge Members of the Lee Formation.

A. Uplift and erosion (indicated by lined pattern) of Pocahontas and Pennington sediments prior to deposition of the Middlesboro Member of the Lee Formation (redrawn from Fig. 29C). Where erosional surface intersects systemic boundary (arrow), the systemic boundary may appear erosional or lithologic in character (indicated by heavy dashed line).

B. North and west of the Cumberland overthrust sheet in the subsurface, and into outcrops in central Kentucky and Ohio, the systemic boundary appears lithologic and erosional (indicated by heavy dashed line) where Pennsylvanian conglomeratic sandstones (Lee Formation or equivalents) rest unconformably on eroded Mississippian sediments. Where the erosional surface intersects the systemic boundary and conglomeratic sandstones overlie conglomeratic sandstones (indicated by arrow), the boundary is a paraconformity whose position may be indeterminant without paleontologic data to establish age, and a detailed sedimentological analysis of the sandstones to interpret their depositional environment. Conglomeratic sandstones in the Pennington may be either Mississippian or Pennsylvanian and represent deposition in shoreface and tidal environments (see Fig. 29B). Fluvial sandstones are always Pennsylvanian. Ages of shoreface and tidal sands can be established only with paleontologic data.

The Breathitt Group, consisting of deltaic and high sinuosity fluvial deposits, conformably overlies and is interbedded with the Lee Formation throughout the Cumberland overthrust sheet and eastern Kentucky.


WEST
EAST
B.
P
M
BREATHITT
LEE
FORMATIONS OLDER THAN PENNINGTON
PENNINGTON
POCAHONTAS


WEST
EAST
A.
P
M
EROSIONAL SURFACE
FLUVIAL
POCAHONTAS
TIME PLANE
TIDAL
SHORE-FACE
PENNINGTON
SHALLOW MARINE

PALEOHYDROLOGY

The discussion in this section centers around Objective 3: to investigate the paleohydraulics of sand deposition in the Pennington and Lee Formations. The goal of this exercise is to speculate on the hydraulic conditions which existed during sedimentation, in an attempt to quantify and further describe the various depositional environments.

Physical processes of sedimentation have been studied by numerous workers, with two comprehensive reviews being those of Allen (1970) and Pettijohn et al. (1972, Ch. 9). A collection of experimental papers (Middleton, 1965) describes the relationships between grain size, water depth and velocity, slope and sedimentary structures. Although these are complex relationships, they have been represented in a simplified scheme by Simons et al. (1965, Table 1 and Figure 14) in which the type of sedimentary structure is related to flow regime. Estimates for values of stream power and flow regime for the various depositional environments, obtained from the graphs of Allen (1970, Fig. 2.6) and Simons et al. (1965, Fig. 21), are summarized in Table 14.

On a larger scale: can estimates be obtained for tidal range and tidal and fluvial discharge based on sedimentary structures, channel-water depth and width, using velocity estimates obtained from graphs derived from experimental flume data? Estimates for discharge through tidal channels seems risky at this time, because discharge is related to tidal range and length or duration of tidal flow. However, estimates of paleotidal range for middle Carboniferous sediments in the overthrust sheet vary from 2.5 to 8.0 meters, using the method based on the vertical distribution of sedimentary structures described by Klein (1970b, Fig. 2).

One may be more successful, however, in attempting to quantify the fluvial environments by turning to the field of paleohydraulics, where hydraulic parameters are estimated from empirical relationships developed from work on modern rivers. The relationships between channel depth, width, sinuosity, discharge, channel length and drainage basin area (Table 15) are summarized by Leopold, Wolman and Miller (1964), Schumm (1968, 1972) and Allen (1970). Ranges for the various exponents used in these equations were investigated by Joering (1972). Before beginning these calculations one can ask the following questions: "How accurate will my estimates be for these sandstones using only outcrop data? Which of the estimated parameters will be useful in further describing the depositional environments of the sandstones? How useful, if at all, will the parameter estimates be in a discussion of tectonic setting (slope) and paleogeography (drainage basin area and channel length which approximates distance from the source area)?"

Sandstones of the Lee Formation record deposition in two differet fluvial environments; the lower members (equivalent to the Pocahontas) and the Hensley Member in high sinuosity rivers and the Middlesboro, Bee Rock and Naese Members in low sinuosity rivers (Figs. 6 and 29). I will begin by estimating the channel parameters of width and depth from outcrop data. These estimates, when combined with grainsize data and assemblages of sedimentary structures, can be used to estimate flow velocity and discharge. Subsequent estimates for slope, drainage basin area and channel length can then be obtained from the empirical relationships relating discharge to these three parameters.

Channel Parameters

Measuring channel width and depth in ancient fluvial deposits has been attempted for high sinuosity rivers by several methods. Schumm (1968) based his estimates for some Quaternary sediments from the dimensions of oxbow lakes. Cotter (1971) estimated water depth and channel width as the thickness and one and a half times the width of crossbedded units interpreted as point bar deposits in some Cretaceous deposits. Leeder (1973) estimated channel depth as the thickness of the sandstone member in a fining-upward sequence and calculated channel width from an empirical relationship between channel width and depth for modern rivers with sinuosities greater than 1.7.

A reasonable estimate for water depth is necessary, because depth is directly related to discharge, a quantity used to determine flood discharge and drainage basin area (Table 15, Eqs. 7, 9, and 10). Figure 31 shows the error introduced into the estimates of the other parameters because of an incorrect depth estimate. Because the high sinuosity rivers had sinuosities greater than 1.7, channel depth and width were calculated by the method described by Leeder (1973). See Table 15, Equations 1 and 3.

Estimation of depth in low sinuosity rivers is somewhat more difficult. Some workers believe that water depth and crossbed thickness are empirically related based on data obtained during flume experiments (Allen, 1970, p. 78). Other flume experiments show that crossbed thickness may range from 34 to 90 percent of the water depth, suggesting that water depth cannot be accurately estimated from crossbed thickness

(Jopling, 1965, p. 58). Miall (in press) estimated channel depth from the mean thickness of crossbeds using an empirical relationship between mean crossbed thickness and water depth (Table 15, Eq. 2). While the original water depth must have at least equalled the crossbed thickness, it is difficult, if not impossible, to determine how much of the original crossbed thickness is preserved by burial in the fluvial environment. To obtain a range of values for the various hydraulic parameters in the low sinuosity environment, calculations were made using the empirical depth-thickness method (Table 15, Eq. 2) and the hypothesis that the crossbed thickness was approximately 50 percent of the original water depth.

Sinuosity in high-sinuosity rivers is calculated from the width/depth ratio (Table 15, Eq. 5). In low-sinuosity rivers, variation in the moving average of crossbedding within a vertical profile is interpreted as a measure of the change in orientation of the entire river tract is related to sinuosity (Miall, in press), (Table 15, Eq. 6). The subsequent calculation for width in low sinuosity rivers is made from the relationship between sinuosity and the width/depth ratio (Table 15, Eq. 4).

Sinuosity calculated for the high-sinuosity rivers range from 1.7 to 1.8 (Table 16B), and have width/depth ratios ranging from 13 to 18. These calculations suggest that Pennsylvanian rivers were characterized by mixed load transport. Modern mixed load transport rivers have sinuosities ranging from 1.3 to 2.0 and width/depth ratios ranging from

10 to 40 (Schumm, 1968, p. 40). Sinuosity for the low-sinuosity Pennsylvanian rivers ranges from 1.1 to 1.3 and have width/depth ratios ranging from 39 to 73. The predominance of sand and crossbedding in the vertical profiles (Fig. 33) along with the concentrations of gravel suggest bed load transport. Schumm (op cit.) described modern rivers characterized by bed load transport as having a braided channel morphology, sinuosities ranging 1.0 to 1.3 and width depth ratios usually greater than 40.

Flow Velocity and Discharge

Most rivers flow at discharges less than or equal to their mean annual discharge about 75 percent of the time (Leopold et al., 1964, p. 243). In the vertical profiles used for the paleohydraulic calculations about 73 percent of the total thickness comprised crossbedded sand. The remaining 27 percent of the sands represent flow conditions of higher (massive beds and even lamination) or lower (ripples) energy. If the percentage of crossbedding is acceptable as an estimate of the proportion of total time under which conditions were suitable for crossbed formation, then such conditions must have been close to those defined by the term 'mean annual discharge'.

The grain size of a deposit formed by bed load transport is related to flow velocity and provenance. The mean grainsize of the sand in the crossbedded units ranges from coarse to fine, sizes which will be eroded at velocities of approximately 40 cm/sec. (Sundborg, 1967, Fig. 1). Medium to coarse sand deposits will be characterised by a crossbedding forms for flow velocities ranging from 50 to 100 cm/sec (Friend and Moody-Stewart, 1972, Fig. 27). The following calculations for the low-sinuosity sandstones were made using a flow velocity of 50 cm/sec. Although the sands deposited by the high sinuosity rivers are somewhat finer grained, the same velocity of 50 cm/sec was used to simplify the calculations. It was felt that no more error was introduced into the calculations that than by having an incorrect estimate for water depth.

Pebbles in the Lee sandstones are interpreted as representing greater flow velocities. The largest quartz pebbles found in the Cumberland overthrust sheet commonly have diameters less than 6.5 cm. The calculated flow velocity required to move this pebble is 230 cm/sec (Malde, 1968, p. 46).

Using estimates of the channel cross-section area (width times depth) and mean and maximum flow velocity, it is possible to calculate discharge for both average and flood conditions. The mean annual discharge is the product of the cross-section area and mean flow velocity, with the mean flow velocity estimated at 50 cm/sec. The results are shown in Tables 16A and 16B. Flood discharge has been shown to be empirically related to the mean annual discharge (Table 15, Eq. 8 and 9), but the equation requires an estimate of the percent silt plus clay in the channel perimeter, represented by M in Equations 8 and 9 (Table 15). For bed load streams this ranges from 1 to 5 percent and for mixed load streams from 5 to 20 percent (Schumm, 1968, p. 40). Using M=5 and M=15 for the low- and high-sinuosity streams, respectively, estimates were made for bankful depth and annual flood discharge (Table 15, Eq. 8 and 9), (Tables 16A and 16B). Flood discharges in the low-sinuosity rivers average 4 to 6 times the normal discharge; while in the high-sinuosity rivers, estimates for flood discharge range from 5 to 8 times the estimated average discharge.

Slope, Drainage Area and Channel Length

Calculation of channel slope (Table 15, Eq. 11), gives a range of values from 0.0017 to 0.005 and 0.0003 to 0.0006 for low and high sinuosity rivers respectively (Tables 16A and 16B). Leopold et al. (1964, Fig. 7-39) show that channel morphology (braided or meandering) is dependent on slope and discharge. For discharges calculated for the low-sinuosity rivers, the channels would be braided, if the slopes exceeded .001. Thus, it appears that the channels were probably braided or only slightly sinuous (less than 1.3). Similarly, the high-sinuosity channels would be meandering if their slopes were less than .002. The calculated values were less than .0004, indicating that the channels were probably meandering with sinuosities ranging from 1.6 to 1.9).

Drainage area and discharge have been shown to be empirically related (Table 15, Eq. 10). The values of a and b depend on numerous factors including climate and relief. Data from different climatic zones and topography are provided by Leopold et al. (1964, p. 320) and a range of probable drainage areas can be obtained by varying these coefficients. For the Pennsylvanian rivers, values of a=4.0 and b=0.74 were used in Equation 10 (Table 15).

The relationship between drainage area and channel length (Table 15, Eq. 12) was used to estimate channel length. These results are summarized in Tables 16A and 16B.

Paleogeographic Implications

While paleohydraulic parameter estimates of drainage basin area and channel length are speculative, it is though that they are probably within an order of magnitude of being reasonably correct. As shown in Figure 31, an error by a factor of three in estimating water depth would result in estimates of drainage basin area and channel length being in error by factors of 10 and 4, respectively. The parameter estimates shown in Tables 16A and 16B can be used to further describe the depositional environments of the fluvial sandstones.

Fluvial environments which deposited the high-sinuosity sandstones (Pocahontas Formation) were characterized by rivers with discharges ranging from 61 to 335 meters^3/sec. Deposition took place approximately 500 to 1000 kilometers from the source area in a drainage basin ranging in area from 60,000 to 180,000 sq. kilometers.

Subsequent uplift in the northeast (Fig. 29) caused the development of a low-sinuosity river system which transported sand and gravel southwest along the axis of the basin. Paleohydraulic calculations suggest that discharge ranged from 220 to 650 meters^3/sec, and that southeastern Kentucky was approximately 1600 kilometers from the source area in a drainage basin covering approximately 250,000 sq. kilometers. The transition from low to high sinuosity (Middlesboro to Hensley Members) is interpreted to indicate both a decrease in slope and discharge, caused possibly by erosion of the source area after uplift ceased and less likely by climatic changes influencing rainfall. The return to low-sinuosity rivers (Bee Rock and Naese Formations) would reflect an increase in slope caused by renewed uplift.

One of several possible drainage basin configurations for Pennsylvanian rivers is shown in Figure 40. In this reconstruction, southeastern Kentucky is approximately 1300 kilometers from the head of the source area, to correspond with a channel length calculated to range between 1300 and 2000 kilometers (Table 16A). This figure will be discussed in the section dealing with the relationship between the Appalachian Basin and other Carboniferous Basins in eastern North America.

TABLE 14

ESTIMATES FOR STREAM POWER AND RANGE OF FLOW REGIME FOR VARIOUS DEPOSITIONAL ENVIRONMENTS OF MIDDLE CARBONIFEROUS SANDS

Environment	Stream Power[1.]	Flow Regime[2.]
Marine	100-2000*	Lower
Shoreface	100-20,000	Lower to Upper
Tidal	100-20,000	Lower to Transition
Fluvial	1000-40,000	Lower to Upper

1. Estimated from Allen (1970, Fig. 2.6). Units are $ergs/cm^2/sec$. Based on grainsize and sedimentary structures.

2. Estimated from Simons et al. (1965, Fig. 21). Based on grainsize and sedimentary structures.

* Maximum velocity for wave induced water movement to form assymetrical ripples ranges from 10 to 70 cm/sec (Allen, 1970, Fig. 5.8).

TABLE 15

EQUATIONS USED FOR PALEOHYDRAULLIC CALCULATIONS

Depth	(1) d =	thickness of sandstone member in fining upward cycle	Leeder (1973, p. 266)
	(2) $d^{1.19} = H/.086$	d = water depth H = mean thickness of crossbeds	Allen (1970, Eq. 2.2)
Width	(3) $w = 6.8d^{1.54}$	w = width d = depth	Leeder (1973, Eq. 1)
	(4) $w^{.27} = 3.5d^{.27}/P$	P = sinuosity	Schumm (1972, Eq. 10)
Sinuosity	(5) $P = 3.5F^{-.27}$	P = sinuosity F = width/depth	Schumm (1972, Eq. 10)
	(6) $P = \sec 1/2$	= variation in moving average of crossbeds within profile	Miall (in press, Fig. 11)
Discharge	(7) $Q_m = AV$	A = area = wd V = average velocity for mean grainsize of crossbeds	Allen (1970, Eq. 1.2)
Bankfull Depth	(8) $d_b = .6M^{.34}Q_m^{.29}$	M = percent silt plus clay Q_m = mean annual discharge	Schumm (1968, p. 50)
Flood Discharge	(9) $Q_{ma}^{.42} = d/(.09M^{.35})$		Schumm (1968, p. 50)

TABLE 15 (Continued)

Drainage	(10) $Q_{ma} = aA^b$	a,b functions of several variables including climate and relief	Leopold et al. (1964, p. 251)
Slope	(11) $s = 30(F^{.95}/w^{.98})$	s = slope F = width/depth w = width	Shumm (1972, Eq. 6)
Channel Length	(12) $L = 1.4A^{.6}$	L = channel length A = drainage basin area	Leopold et al. (1964, p. 145)

Note: Equations 8, 9, 11 and 12 in English units, all others metric.

TABLE 16A

PALEOHYDRAULIC CALCULATIONS FOR
LOW SINUOSITY RIVERS

Number	Depth	Width	Width/Depth Ratio	Sinuosity	Bankfull Depth	Average Discharge	Flood Discharge
19-A[1]	4.0	156	39	1.3	4.7	312	1538
2-75-B	3.9	209	53	1.2	5.1	416	1876
18	3.4	173	53	1.2	4.6	285	1446
20-A1	4.2	307	73	1.1	5.8	651	2558
20-A2	4.3	225	53	1.2	5.3	482	2075
20-B	3.4	131	39	1.3	4.3	220	1210

Drainage Area: Minimum = 162,000 sq. kilometers

Maximum = 328,000 sq. kilometers

Channel Length: Minimum = 1300 kilometers

Maximum = 2000 kilometers

Slope: Ranges from .0017 to .005

Depth, width and bankfull depth are in meters.

Discharge is in meters^3/second.

1. Sample numbers, except for 2-75-B refer to figures in text. See Appendix 6 for location of 2-75-B.

TABLE 16B

PALEOHYDRAULIC CALCULATIONS FOR
HIGH SINUOSITY RIVERS

Number	Depth	Width	Width/Depth Ratio	Sinuosity	Bankfull Depth	Average Discharge	Flood Discharge
3-93-1[1.]	3.7	51	13	1.8	5.7	95	680
3-71-1	6.1	110	18	1.7	6.9	335	1580
3-74-1	4.6	71	15	1.7	6.6	163	1420
3-52-1	3.1	39	13	1.8	5.0	61	733

Drainage Area: Minimum = 60,000 sq. kilometers

Maximum = 180,000 sq. kilometers

Channel Length: Minimum = 500 kilometers

Maximum = 1000 kilometers

Slope: Ranges from .0003 to .0006

Depth, width and bankfull depth are in meters.

Discharge is in meters^3/second.

1. Sample location listed in Appendix 6.

FIGURE 31. Relationship between error in water depth estimate and error in subsequent paleohydraulic calculations. Overestimating depth by a factor of three results in discharge and drainage basin area estimates being wrong by a factor of approimately 8 and 12, respectively. Values were calculated with a computer program using the outline and equations listed in Fig. 33.

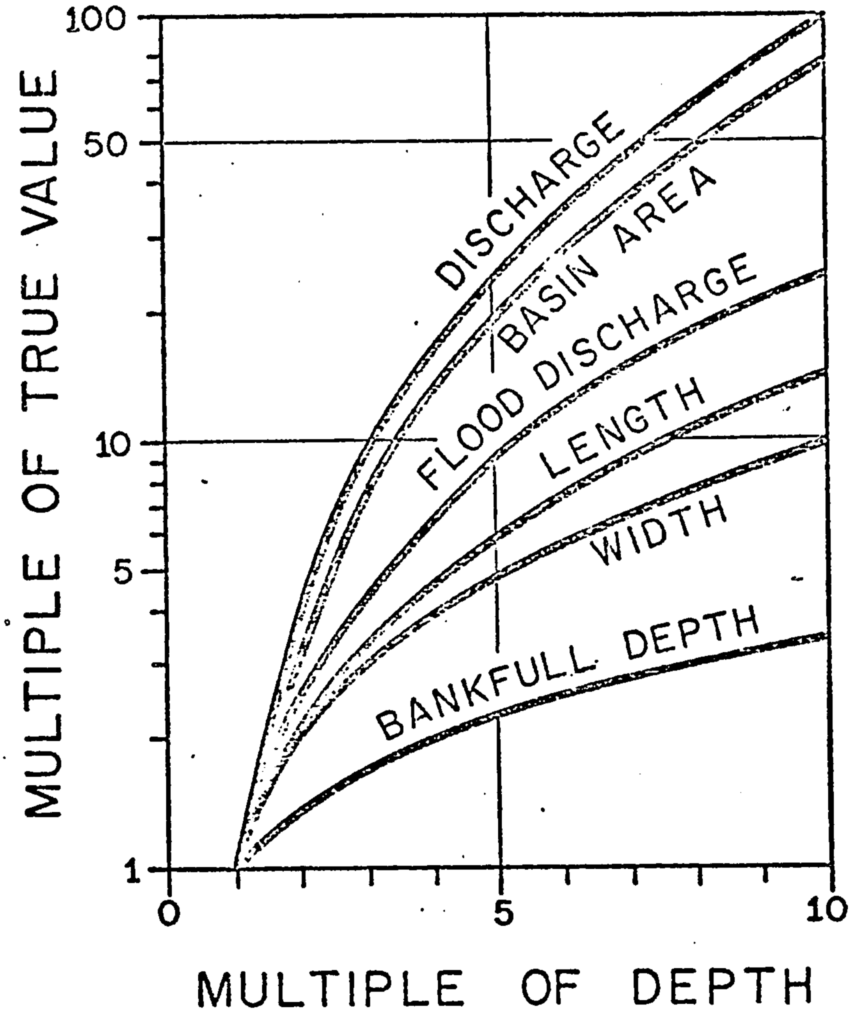

DISCHARGE
BASIN AREA
FLOOD DISCHARGE
LENGTH
WIDTH
BANKFULL DEPTH
MULTIPLE OF TRUE VALUE
MULTIPLE OF DEPTH
100
50
10
5
1
0
5
10

FIGURE 32. Distribution of bedding types for various grainsizes for Lee sandstones deposited by low-sinuosity rivers. The decrease in abundance of ripple bedding and increase in massive- and cross-bedding with increasing grain size is characteristic of virtually every sand body, regardless of environment.

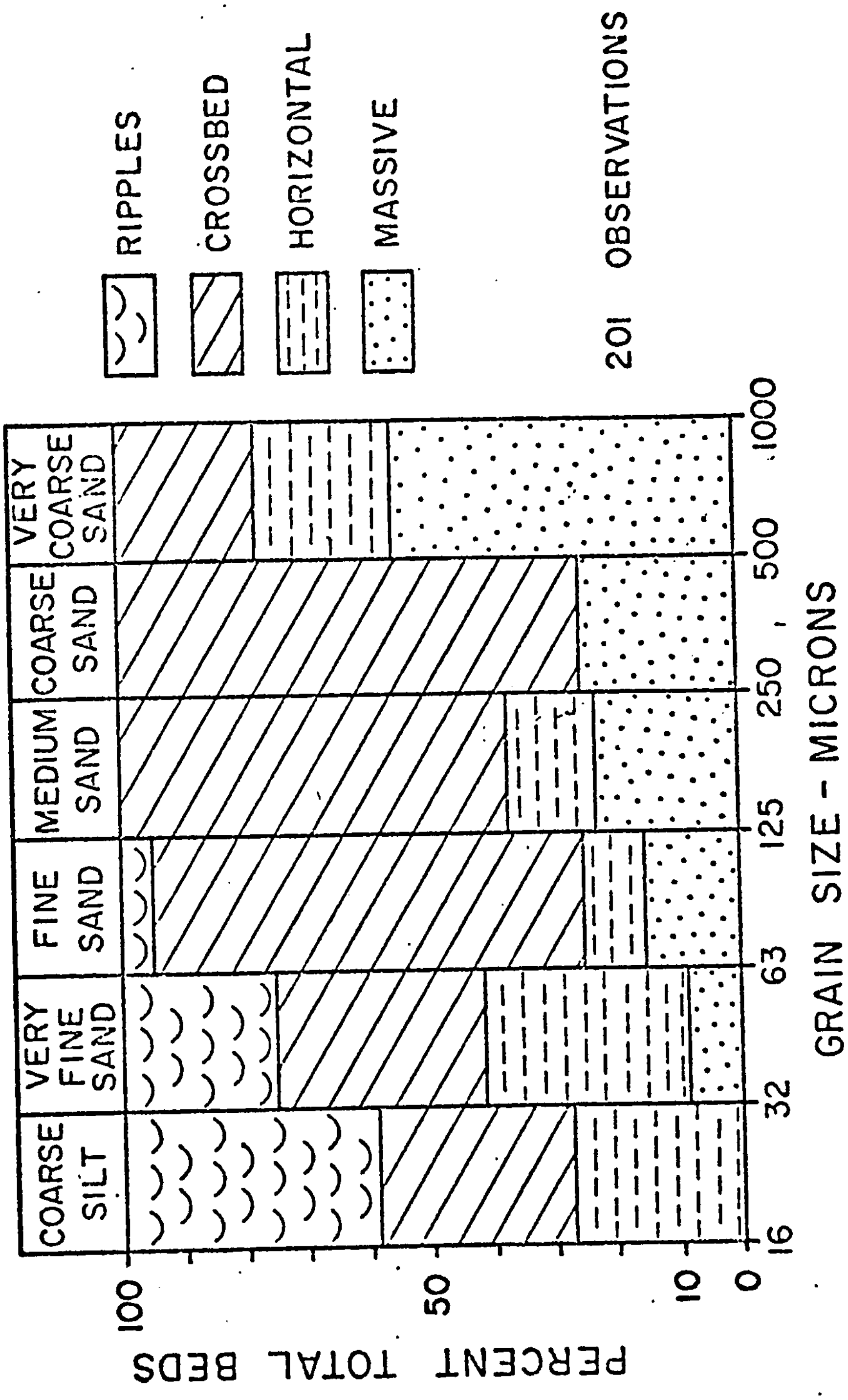
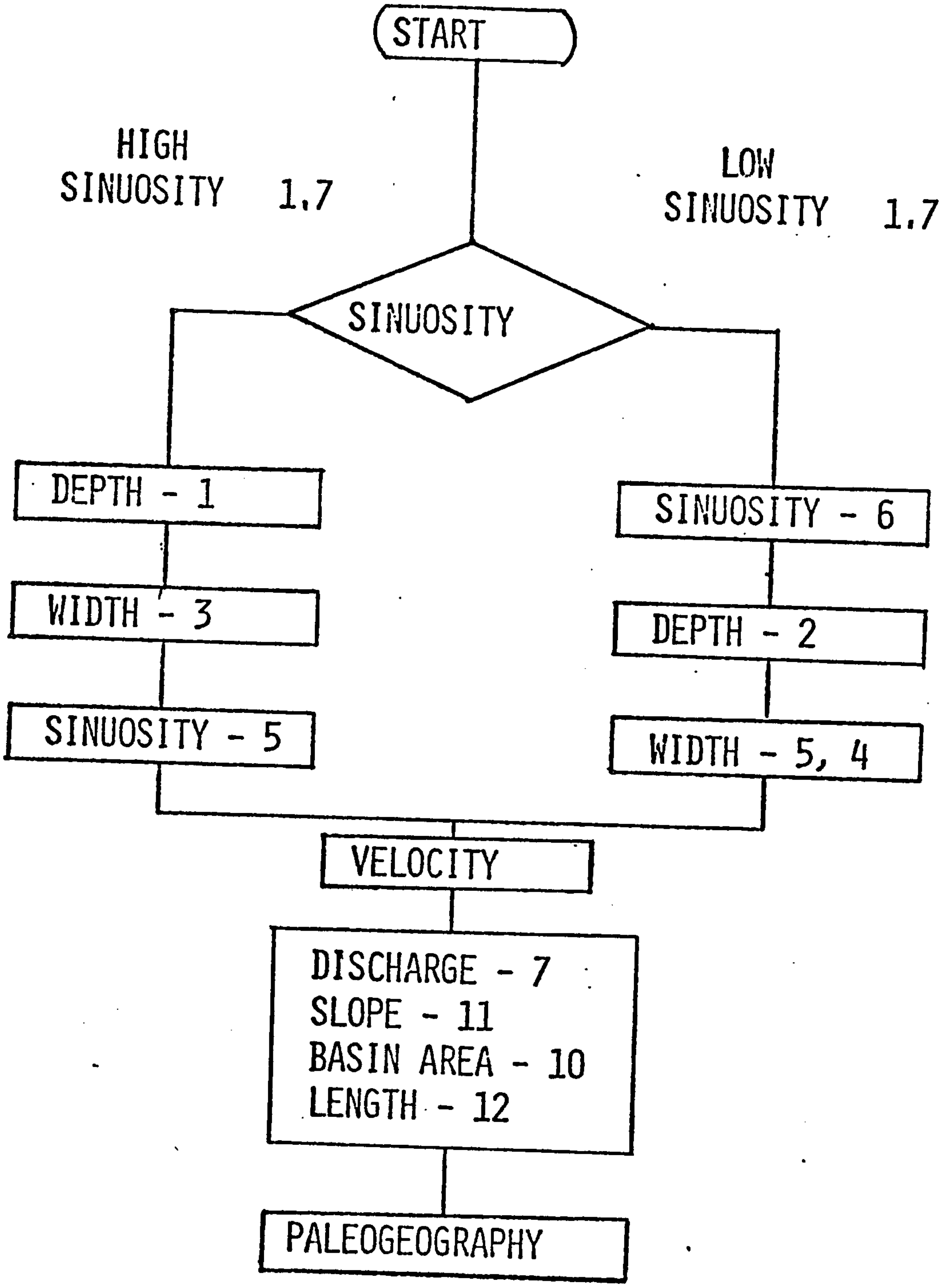

RIPPLES
CROSSBED
HORIZONTAL
MASSIVE
201 OBSERVATIONS
COARSE SILT
VERY FINE SAND
FINE SAND
MEDIUM SAND
COARSE SAND
VERY COARSE SAND
100
50
10
0
PERCENT TOTAL BEDS
16
32
63
125
250
500
1000
GRAIN SIZE - MICRONS

FIGURE 33. Outline of procedure for paleohydraulic calculations. Because procedure is different for high- and low-sinuosity rivers, the sandstones must first be classified as to type using geologic criteria. Listings of these criteria may be found in Moody-Stewart (1966, Table 1) and Smith (1970, p. 3010). Numbers in boxes next to parameter being calculated refer to equations listed in Table 15.


START
HIGH SINUOSITY 1.7
LOW SINUOSITY 1.7
SINUOSITY
DEPTH - 1
WIDTH - 3
SINUOSITY - 5
SINUOSITY - 6
DEPTH - 2
WIDTH - 5, 4
VELOCITY
DISCHARGE - 7
SLOPE - 11
BASIN AREA - 10
LENGTH - 12
PALEOGEOGRAPHY

SEDIMENT DISPERSAL AND TECTONICS

The discussion in this concluding chapter centers on two objectives:

Objective 5 - Characterize the middle Carboniferous molasse of the Appalachian Basin on the basis of provenance and sediment dispersal; and find, if possible, some modern examples similar in size and sediment dispersal pattern.

Objective 6 - Explain, if possible, the relationship of the middle Carboniferous sediments in the Appalachian Basin to equivalent sediments in other Carboniferous basins in eastern North America in terms of plate tectonic models.

Sedimentological and structural characteristics of the Appalachian Basin have been described by numerous workers. Studies of note on the fill include Pelletier (1958), Yeakel (1962), Meckel (1970) in addition to those listed in Tables 1 and 2. Structural models for the development of the Appalachian Basin include those of Kay (1951), Poole (1967), Bird and Dewey (1970), Rodgers (1970), Hatcher (1972) and Graham et al (1975).

It is not my purpose to endorse any particular viewpoint related to the structural development of the Appalachian Basin; but rather, to explore what bearing, if any, the provenance and dispersal pattern of Carboniferous sediments have on the theories of Basin origin.

Provenance And Sediment Dispersal

One of the most striking characteristics of middle Carboniferous sediments is the abundance of quartz pebbles in the Lower Pennsylvanian sandstones of the Appalachian, Michigan and Illinois Basins. Pebble composition data from four localities in the Appalachian Basin, when combined with similar data from the Illinois Basin, indicate a decrease in the percent of monocrystalline quartz pebbles from northern West Virginia into Tennessee and Illinois (Table 17). Polycrystalline pebbles account for 30 to 58 percent of the total. During a study of source areas for sediments in the Illinois Basin, Siever and Potter (1956, Fig. 3) showed that quartz pebbles were confined to the eastern margin of that basin. A review of the literature shows that many stratigraphic units in the Lower Paleozoic contain quartz pebbles in the gravel size fraction of conglomeratic sandstones (Fig. 35). Although these pebbles have not been systematically studied, it seems possible that reworking of these sediments due to uplift may have contributed to the volume of pebbles seen in the younger Pennsylvanian sandstones.

A detailed petrographic analysis of Lower Pennsylvanian sandstones in Alabama and West Virginia led Davis and Erlich (1974, p. 171) to conclude that the source area composition consisted of a granodioritic batholithic complex overlain by sedimentary, volcanic and low grade metamorphic rocks, and underlain by migmatites. Although I did not observe any volcanic rock fragments during my petrographic analysis, the presence of polycrystalline quartz, metamorphic rock fragments and feldspar types would support a low grade metamorphic and sedimentary rock source area. A similar conclusion was reached by Siever and Potter (1956, p. 330). In addition, crystallinity calculations for illite in 20 shale samples from the Lee Formation had values less than 2.1, suggesting a low or very weak grade metamorphic source area (Weaver, 1960, p. 1514).

Paleocurrent maps published in the last 20 years for Carboniferous sediments in the Appalachian Basin have been compiled and supplemented with additional data obtained by the author in West Virginia and Virginia (Fig. 37). The sediment transport is predominantly southwest, parallel with the present axis of the basin throughout most of the area. The only exception is in eastern Pennsylvania, where the direction is northwest. The predominant southwest transport direction indicates a longitudinal filling of the basin, assuming, of course, that the northeast-southwest trend of the preserved portion of the basin is approximately parallel to the orientation of the basin axis during deposition. This southwest direction of transport is consistent with a decrease in both maximum quartz pebble size and percent of monocrystalline quartz pebbles from 61 to 41 percent (Fig. 38). Because polycrystalline quartz is relatively less stable to mechanical abrasion than monocrystalline quartz (Blatt, 1967, p. 401), the apparent decrease in monocrystalline quartz from West Virginia (61 percent) to Tennessee (48 percent) can be explained three ways. First, and most likely, the decrease is due to dilution from a presently eroded metamorphic source area which lay to the southeast. Second, perhaps the recycled pebbles from Paleozoic units in Virginia and Tennessee contain a larger percent of polycrystalline pebbles than units in Pennsylvania and West Virginia. Least likely is the possibility that polycrystalline pebbles (2-4 mm) are more resistant to physical abrasion than are monocrystalline pebbles.

A longitudinal filling of the Appalachian Basin was proposed by Schlee (1963) after a study of Lower Pennsylvanian rocks in Tennesse and

Alabama (Southern Appalachian Basin). Subsequent paleocurrent and paleocurrent and petrographic work throughout the remainder of the basin support this early hypothesis, a hypothesis made when longitudinal filling of molasse basins was thought to be the exception.

Within the Pennington and Pocahontas Formations, the southwest paleocurrent direction in tidal sands is interpreted to represent the regional paleoslope. The lobate quartzwackes, oriented in a bifuracting pattern to the west and northwest and deposited in a fluvial environment, suggest a source area to the east and southeast. The southwest transport indicated by the Upper Members of the Lee (Middlesboro, Bee Rock and Naese) reflect the longitudinal filling of the basin by sediment derived from the northeast (Fig. 29). Rivers that may have drained uplifted areas to the east would have turned to the southwest and flowed parallel to the axis of the basin and down the paleoslope.

Paleocurrent directions in the overlying Breathitt Group in southeastern Kentucky indicate a northwest transport direction. Similar directions have been reported for equivalent units in West Virginia and Pennsylvania (Donaldson, 1974, Fig. 1). These later sediments were deposited by rivers flowing transverse to the basin axis and may possibly represent a lowering of the relief in the source area, suggested by the change from low to high sinuosity rivers and an overall decrease in grainsize in the sandstones. These later sediments are also less mineralogically mature, which may be due to either less abrasion during transport or indicate a shorter distance of transport from the source. Note that these sediments were transported transversly to the basin axis, and that paleohydraulic calculations suggest that the source area was approximately 500 kilometers away.

Sediment dispersal patterns for five molasse basins, which serve as possible 'modern' analogues for middle Carboniferous sediments in the Appalachian Basin are shown in Figure 39. These were selected on the following criteria: 1) the uplifted area is drained by predominantly longitudinal rivers, 2) the basin is characterised by a sediment dispersal system parallel to the basin axis, 3) the basin is approximately the same size as the preserved portion of the Applachian Basin. These basins are characterized by predominantly nonmarine sedimentation in alluvial and fluvial environments. Three of the molasse basins (Ganges, Indus, Lena) drain into ocean basins, and two (Ganges and Indus) are accumulating extensive flysch deposits on submarine fans.

Did the middle Carboniferous Appalachian Basin, which was characterized by molassic sedimentation, eventually drain into an ocean basin where extensive flysch sediments were accumulating? What is the relationship of the Carboniferous flysch in the Ouachita Trough to the Carboniferous molasse of the Appalachian Basin? What is the relationship of the Appalachian Basin to the other Carboniferous basins in eastern North America?

Relationship Between The Appalachian And Other Carboniferous Basins In Eastern North America

Carboniferous basins of central and eastern North America can be characterized on the basis of their fill, sediment dispersal pattern, depositional environment and tectonic setting (Table 18). A paleogeographic map made using these basin descriptions, and estimates for the drainage area of the Appalachian Basin obtained from paleohydraulic calculations (Table 16), is shown in Figure 40.

The Minas, Cumberland, Moncton and Sydney basins in New Brunswick and Nova Scotia have been interpreted as being part of a larger Fundy Basin, a complex rift valley, or series of intermontane basins, divided by several uplifted blocks (Belt, 1965, p. 799). The conglomerates of these basins have only a few quartz pebbles and consist primarily of igneous, metamorphic and sedimentary rock fragments (Gussow, 1953). Paleocurrents indicate both lateral transport toward the basin center and parallel to the basin axis to the northeast (Belt, 1965, Fig. 8).

The Boston and Narragansett Basins, while also lacking significant quartz pebbles, show paleocurrent patterns to the southwest (Towe, 1959). The contrast in pebble lithology, between these two basins and the Appalachian Basin, was investigated by Mutch (1968). He concluded that the observed differences were probably related to different source areas rather than variation in climate and transport mechanism. The paleogeographic setting of these basins and the Appalachian Basin is similar to that described for the intermontane basins of the Canadian Cordillera and the Himalayas and their associated molasse basins

(Eisbacher et al., 1974, p. 143). In these examples, clastic sediment is transported in longitudinal, intermontane valleys and discharged into elongate molasse basins parallel to the mountain chain.

The relationship between the Illinois and Appalachian Basins is partly explained by spore-pollen paleontologic data. Age dates on coals (Table 5, Appendix 4, Kosanke, written comm., 1975) indicate that the conglomeratic sandstones in the Appalachian Basin are older than the first conglomeratic sandstones seen in the Illinois Basin. This is interpreted to mean that while the fluvial system migrated back and forth across the Appalachian Basin depositing conglomeratic sandstones characterized by sheet-like geometry (Figs. 6 and 7), the Illinois Basin was still being subject to uplift and erosion, resulting in the formation of paleovalleys along its eastern and southern margins. The relationship between the Michigan and Applachian Basins was summarized by Potter and Siever (1956) and Siever and Potter (1956). They concluded, on the basis of paleocurrent studies and sedimentary petrology, that the two basins were filled from compositionally similar source areas which may have been geographically separate, by rivers flowing southwest, parallel to the regional paleoslope.

In summary, the main depositional basin (Appalachian) was filled with sediment coming from an uplifted source area to the northeast. Sedimentation within the source area occurred in intermontane basins, such as the Boston and Narragansett Basins. The intermontane Fundy Basin, comprised of several smaller basins such as the Cumberland and Moncton, sloped to the northeast, away from the Appalachian Basin.

The Michigan and Illinois Basins received sediments from the north, with the Illinois Basin also receiving sediment as spillover from the Appalachian Basin.

Geosynclines, Plate Tectonics and Middle Carboniferous Sedimentation

According to geosynclinal theory, the middle Carboniferous sediments reflect molassic sedimentation caused by uplift during the second geosynclinal cycle of the Applachian Geosyncline (Pettijohn, 1959, p. 641). The Pennington, Pocahontas and Lee Formations were deposited in the miogeosynclinal portion of the geosyncline, with part of the Lee Formation subsequently spreading onto the craton and being deposited in the Illinois Basin as the Caseyville and Mansfield Formations.

With regards to plate tectonics, the middle Carboniferous sediments were deposited in intermontane valleys (Narragansett, Boston and others, see Table 18), peripheral (Appalachian) and intracratonic (Illinois and Michigan) basins, and are believed to represent the uplift related to the north-to-south welding of Africa to North America (Dickinson, 1974, p. 23; Graham et al., 1975, p. 273). In this case, the peripheral basin (Appalachian) was characterized by a longitudinal sediment dispersal pattern with an associated flysch sequence (Jackfork and Atoka Flysch of the Ouachita Trough) fed longitudinally into a remnant ocean basin.

This viewpoint is quite attractive, because it:

1. Accounts for the various basin characteristics shown in Table 18,
2. Describes the relationships between the basins,
3. Relates the Middle Carboniferous molasse and flysch, and,
4. Provides a mechanism for recycling sediments to possibly concentrate quartz pebbles.

Future Considerations

In the course of this study, some questions have been raised and it seems appropriate to summarize them in this final section as items to which we may possibly turn our attention in the years to come. The following are related to sedimentation and depositional environments:

1. What properties of a sandstone are most diagnostic of its environment of deposition?
2. Can we improve the accuracy of our paleohydraulic calculations, particularly the procedure for estimating the water depth in low sinuosity rivers from outcrop data?

Due to the growing popularity of plate tectonics and the re-evaluation of sedimentary basins, some of the following questions may be answered in the coming years as additional work is completed on the geology of remote areas and we understand better the closing of the Proto-Atlantic in the Late Paleozoic and its re-opening in the Mesozoic:

1. What are the fill, sediment dispersal patterns, depositional environments and tectonic setting of Carboniferous basins in Africa?
2. Do they form a mirror image with the Appalachian Basin along the suture belt?
3. If not, how were they different; and what did the paleogeography look lik after the suturing was complete?

TABLE 17

PETROGRAPHIC COMPOSITION OF QUARTZ PEBBLES

Sample	Location	Number	Composition By Percent		
			Monocrystalline	Polycrystalline	Other**
1.	West Virginia	73	61	30	9
2.	Southern Ohio	127	58	39	3
3.	Southern Indiana	171	42	44	12
4.	Eastern Illinois	110	48	32	20
5.	Western Kentucky	165	31	58	11
6.	Eastern Kentucky	125	46	42	12
7.	Virginia	137	41	54	5
8.	Tennessee	151	48	46	6

** Types of pebbles grouped as 'Other' include: sandstone, siltstone, shale, limestone and chert.

Samples 2, 3 and 4 taken from Siever and Potter (1956, Table 5)

TABLE 18

SUMMARY OF CHARACTERISTICS FOR MIDDLE CARBONIFEROUS SEDIMENTS IN MOLASSE BASINS OF CENTRAL AND EASTERN NORTH AMERICA

Basin	Geometry	Sediment Dispersal	Lithic Fill	Setting
Sydney	oval; length = 1 1/2 x width	lateral	coarse sand, conglomerate, some coal and shale	intermontane
Moncton	elongate; length = 2xwidth	lateral and longitudinal to basin axis; northeast	conglomerate, sand and shale, coals	intermontane
Minas	elongate; length = 4xwidth	lateral and longitudinal, northeast	quartzose sand; calcareous siltstone, conglomerate, minor evaporites	intermontane
Cumberland	elongate;	lateral and longitudinal	sandstone, shale, conglomerate; granite pebbles	intermontane
Boston	oval; length 1 1/2 x width	lateral and longitudinal	sandstone, shale, conglomerate; granite pebbles	intermontane
Narraganset	elongate length = 3 x width	longitudinal to basin axis; southwest	conglomerate, sandstone, shale and coal	intermontane

TABLE 18 (Continued)

Michigan	bowl shaped	Lateral	sandstone, some conglomerate, siltstone and shale	intra-cratonic
Illinois	oval; length = 1 1/2x width	lateral and longitudinal to basin axis; southwest	conglomerate, sandstone and siltstone; coals	intra-cratonic
Appalachian	elongate; length= 3 1/2xwidth	longitudinal with basin axis; southwest	conglomerate, sandstone and shale, coals	miogeosynclinal, or peripheral

FIGURE 34. Models of sediment dispersal into molasse basins from uplifted areas. Open-headed arrows indicated minor contributions from other areas. In upper figure, radial and longitudinal sediment dispersal characterize source area and adjacent molasse basins. In lower figure, source areas are characterized by transverse sediment dispersal from both or one side. Molasse basins are being filled laterally from both sides or predominantly one side.

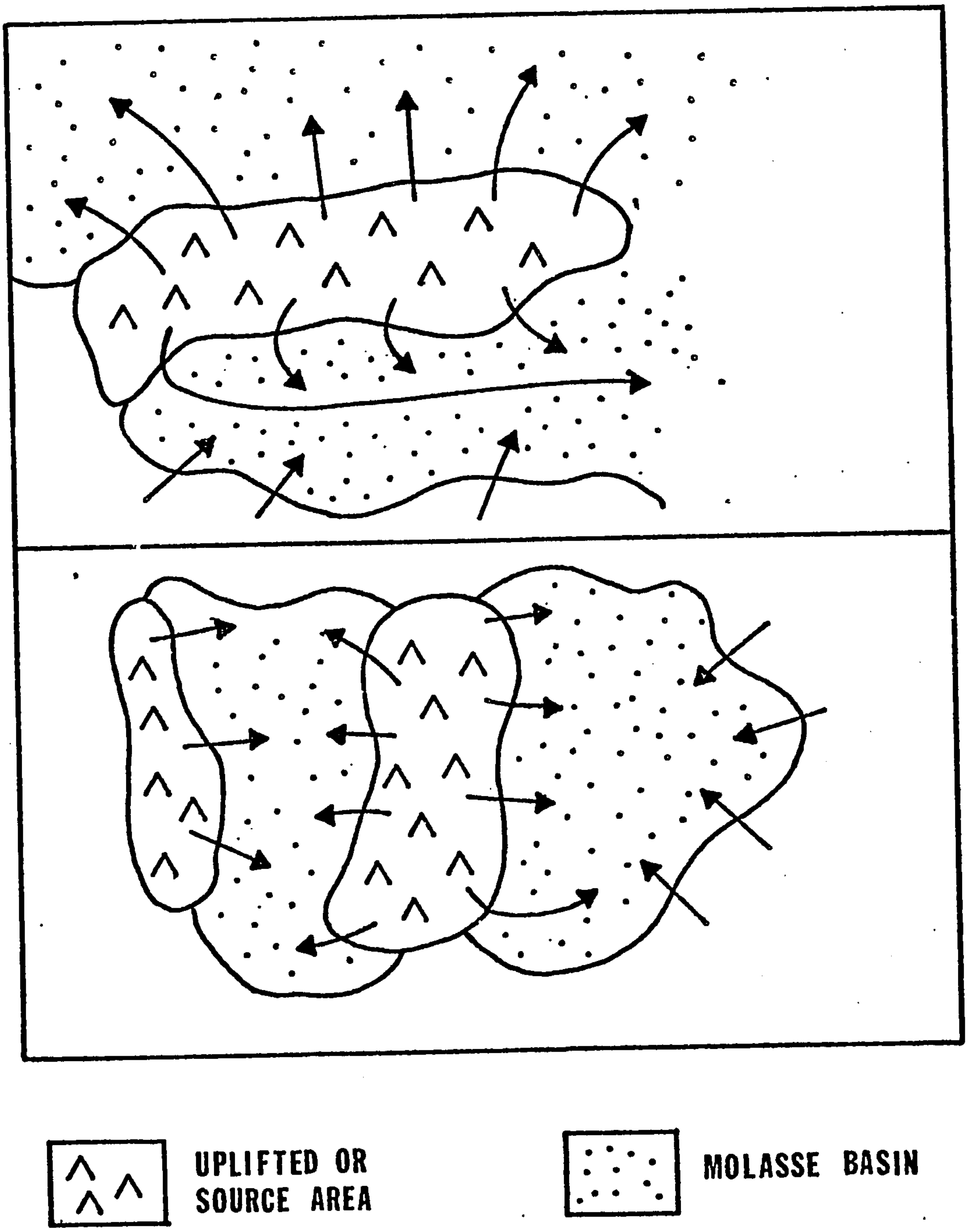

UPLIFTED OR
SOURCE AREA
MOLASSE BASIN

FIGURE 35. Distribution of stratigraphic units from Nova Scotia to Alabama which contain quartz pebbles that could have been recycled into the Pennsylvanian conglomerates. The largest number of units and maximum thicknesses occur in New York and Pennsylvania.

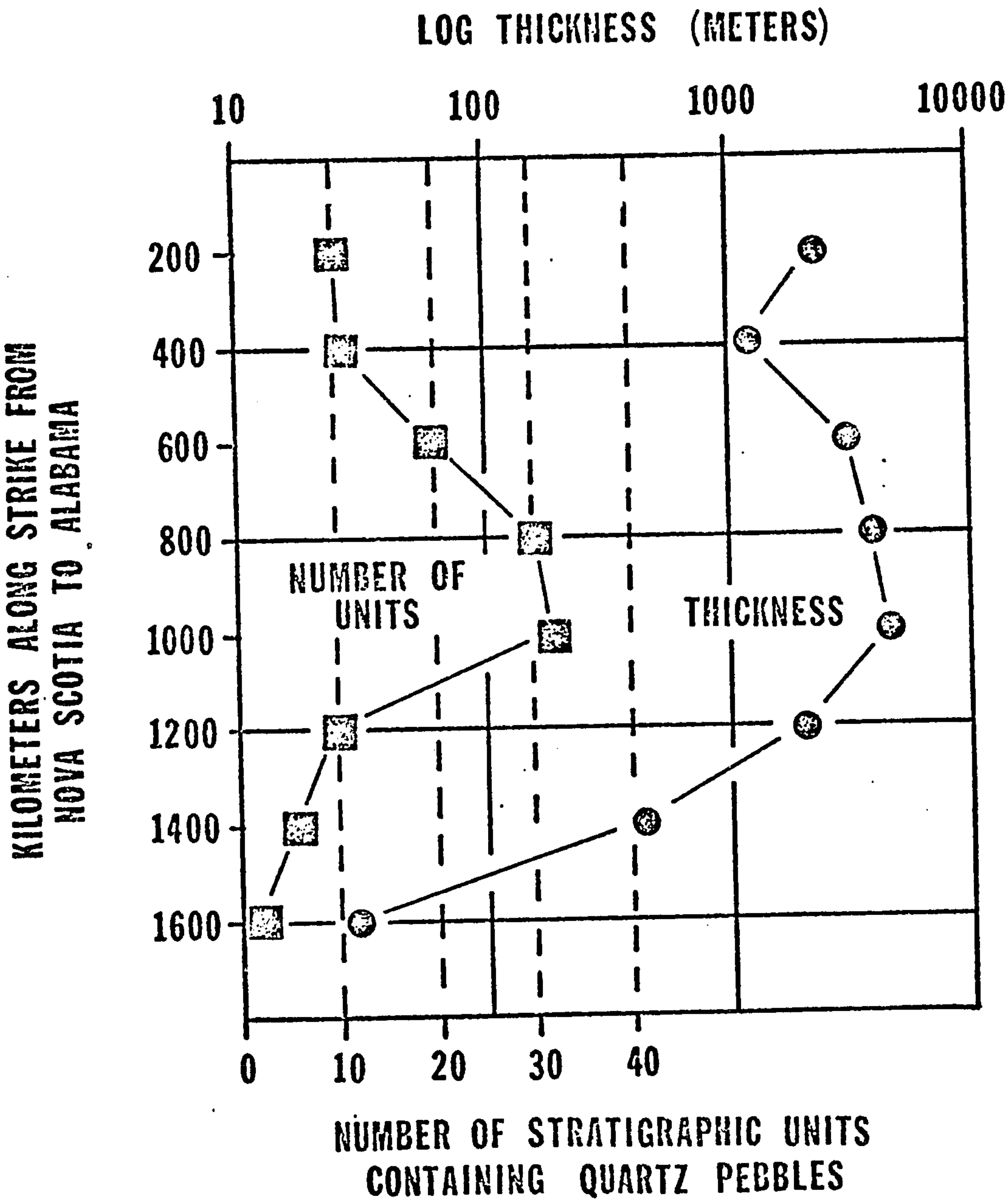

LOG THICKNESS (METERS)
10
100
1000
10000
KILOMETERS ALONG STRIKE FROM NOVA SCOTIA TO ALABAMA
200
400
600
800
1000
1200
1400
1600
NUMBER OF UNITS
THICKNESS
0
10
20
30
40
NUMBER OF STRATIGRAPHIC UNITS CONTAINING QUARTZ PEBBLES

FIGURE 36. Possible plan for recycling Lower and Middle Paleozoic quartz pebbles into Pennsylvanian conglomeratic sandstones. See Fig. 35 for distribution of units containing quartz pebbles and Table 17 for classification of pebble types.

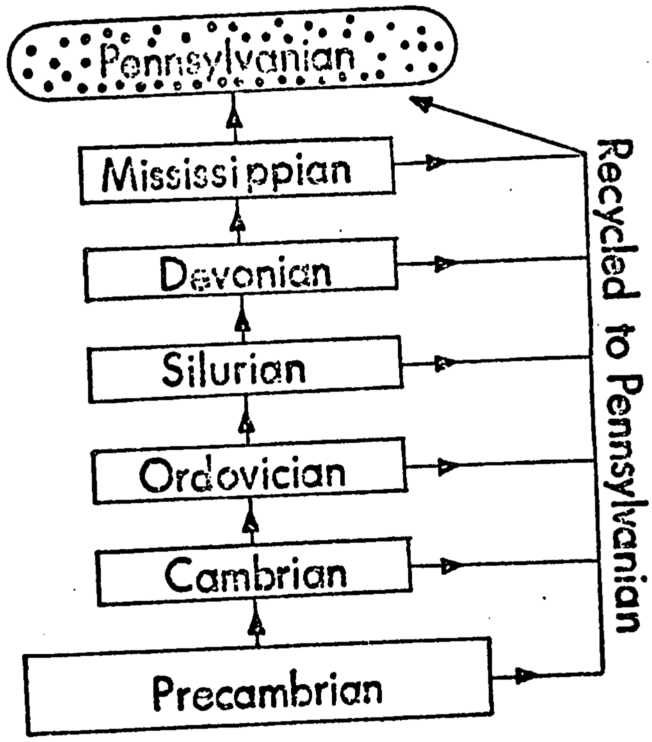

Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Precambrian
Recycled to Pennsylvanian

FIGURE 37. Sedimental dispersal indicated by paleocurrent orientations in middle Carboniferous fluvial sandstones. Solid arrows represent published paleocurrent studies listed in Table 1. Sediment flow indicates longitudinal filling of the basin. Compare with Fig. 1.

FIGURE 38. Evidence indicating a major northeast source area for middle Carboniferous sediments. Compare with Fig. 37. The relative decrease in monocrystalline quartz with respect to polycrystalline quartz, with increasing distance and subsequent abrasion, is contrary to the relative stabilities of these two quartz types proposed by Blatt (1967, p. 401) and Folk (1968, p. 89). Pebble compositions are listed in Table 17.

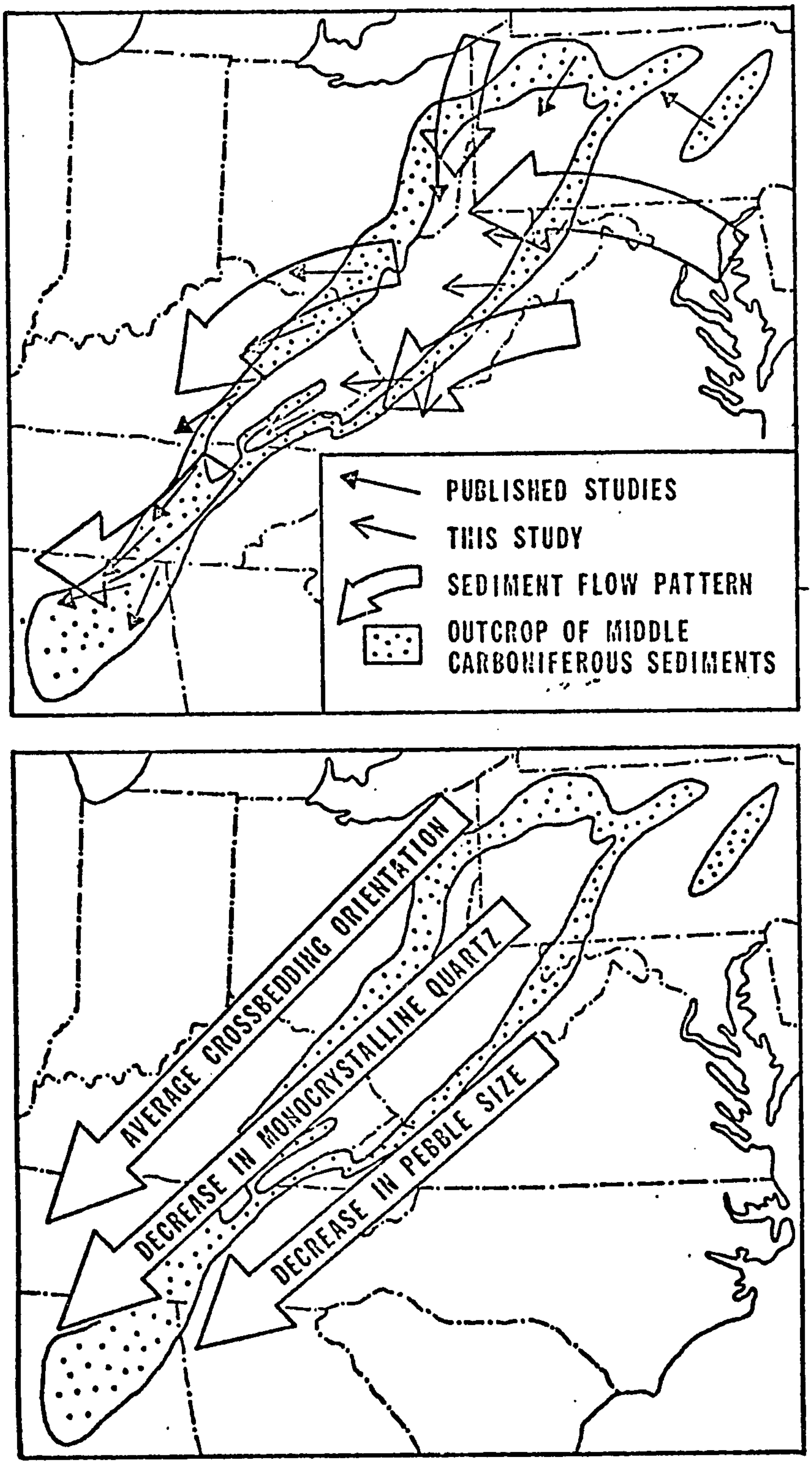
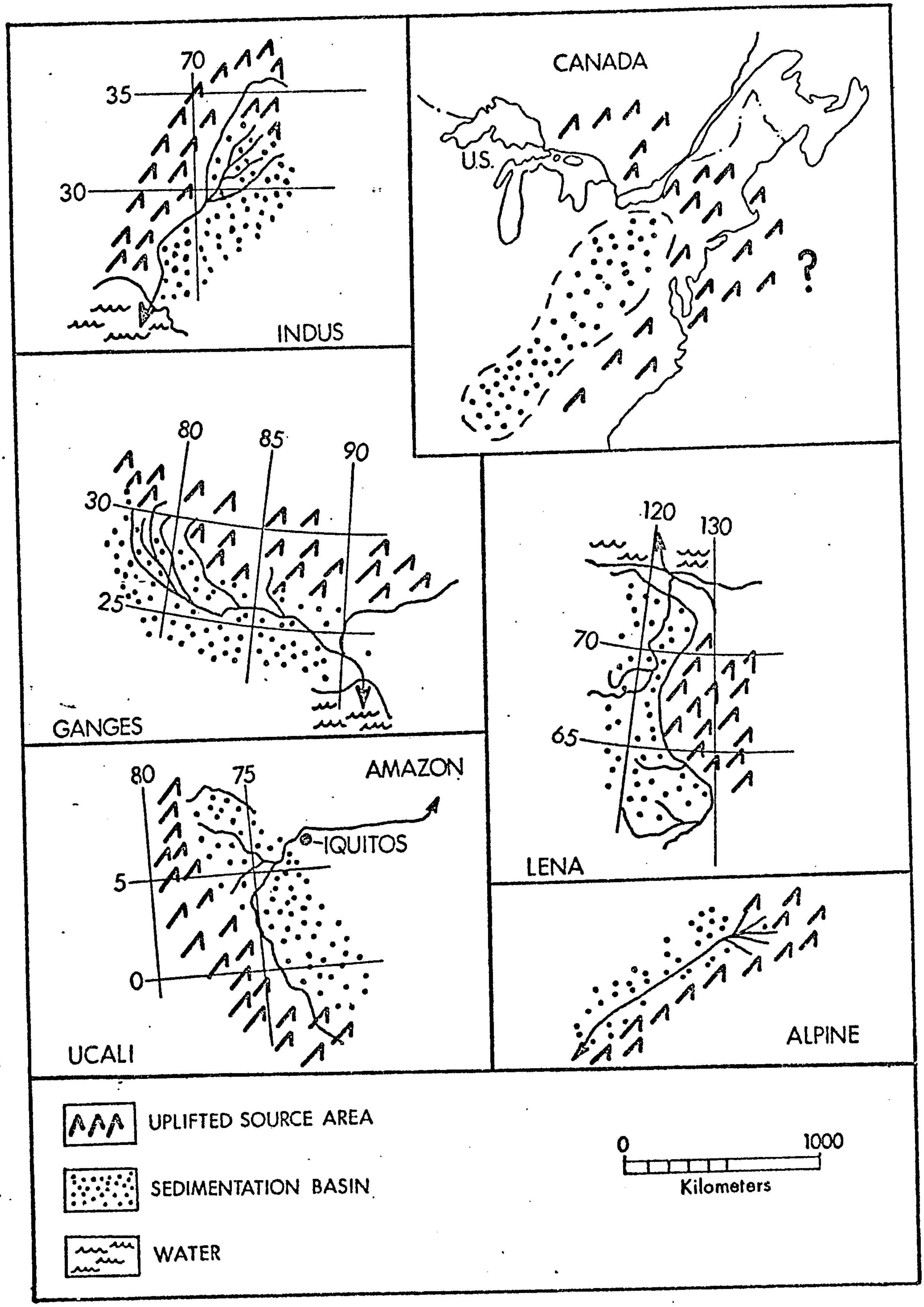

PUBLISHED STUDIES
THIS STUDY
SEDIMENT FLOW PATTERN
OUTCROP OF MIDDLE CARBONIFEROUS SEDIMENTS
AVERAGE CROSSBEDDING ORIENTATION
DECREASE IN MONOCRYSTALLINE QUARTZ
DECREASE IN PEBBLE SIZE

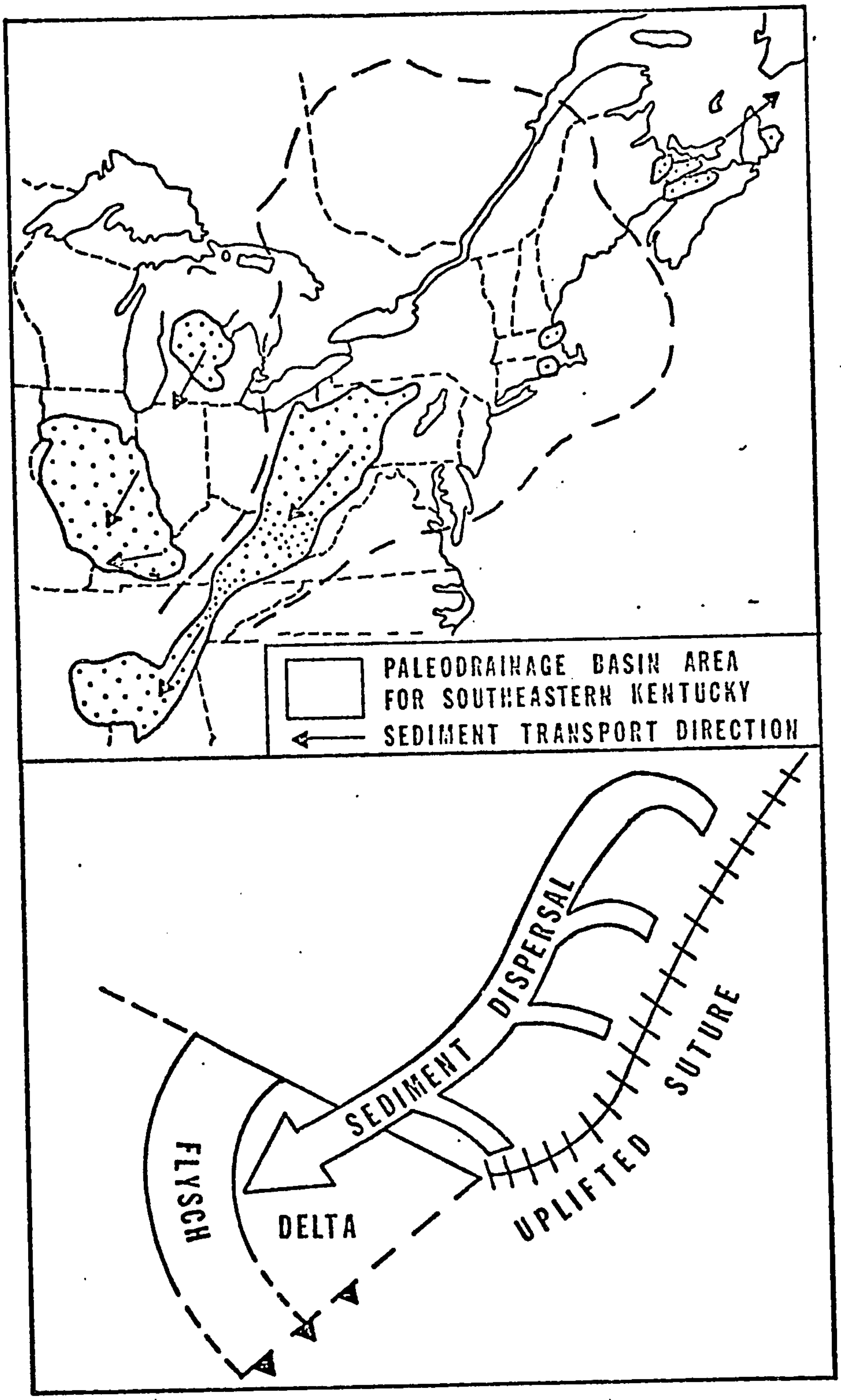
FIGURE 39. Sediment dispersal in four modern basins and one Tertiary basin. These examples were chosen because they represent uplifted areas drained by predominantly longitudinal rivers into basins characterized by a sediment dispersal system parallel to the basin axis and are similar in size to the present outcrop limit of the Appalachian Basin. The Alpine example is redrawn fron Van Houten (1974, Fig. 3).



CANADA
U.S.
70
35
30
INDUS
80
85
90
30
25
GANGES
120
130
70
65
LENA
80
75
AMAZON
IQUITOS
5
0
UCALI
ALPINE
UPLIFTED SOURCE AREA
SEDIMENTATION BASIN
WATER
0
1000
Kilometers

FIGURE 40. Outline of possible paleodrainage basin for middle Carboniferous low-sinuosity fluvial sediments. Drainage basin area is approximately 270,000 sq. kilometers. This is within the range suggested by paleohydraulic calculations (Table 16). The basins in New Brunswick and Nova Scotia were not included in drainage area because paleocurrent data indicate a northeast current direction. See Table 18 for summary of basin characteristics.

FIGURE 41. Relationship between uplifted suture zone and molasse-flysch basin sedimentation. The flysch basin associated with the middle Carboniferous molasse in the Appalachian Basin for this example would be the Ouachita Trough. The sequential north to south closing of the Proto-Atlantic would provide a mechanism for recycling the quartz pebbles, as diagrammed in Fig. 36. Redrawn from Graham et al. (1975, Fig. 6)


PALEODRAINAGE BASIN AREA
FOR SOUTHEASTERN KENTUCKY
SEDIMENT TRANSPORT DIRECTION
SEDIMENT DISPERSAL
UPLIFTED SUTURE
FLYSCH
DELTA

CONCLUSIONS

An integrated sedimentologic and stratigraphic analysis of middle Carboniferous sediments has produced the following conclusions, which are divided into three categories: stratigraphy, sedimentology and basin analysis. Figure, table and page numbers, listed in parentheses after each conclusion, indicate the location in the text where data related to that conclusion are presented.

Stratigraphy

1. The lower three members of the Lee Formation in southeast Kentucky (Chadwell, White Rocks and Dark Ridge) are equivalent, in part, to the Pocahontas Formation of Virginia and West Virginia.

   Pages: 28, 82; Figure 6; Table 3

2. The Mississippian-Pennsylvanian systemic boundary, established by conodont and spore assemblages, occurs within the Pennington Formation on the Cumberland overthrust sheet.

   Pages: 24, 78; Figure 28; Tables: 4, 5

Sedimentology

3. Middle Carboniferous sandstones were deposited in a generally regressive sequence of marine, shoreface, tidal and fluvial environments.

   Pages: 37 to 48; Figures: 27, 29

4. Constructing careful vertical profiles through sandstone bodies is the best way to determine the environment of deposition.

   Page 54; Figures: 14 to 21

5. Grain size probability curves and multivariate statistical analysis of texture and composition had variable success in determining depositional environments.

   Pages: 49 to 54; Table 13

6. Paleohydraulic calculations for the fluvial sansstones are probably within an order of magnitude of being correct. However, considerable error can result from an incorrect estimation of original water depth.

   Pages: 93 to 94; Figure 31

Basin Analysis

7. Sandstone petrography and paleocurrent data indicate that middle Carboniferous sediments in the Appalachian Basin were derived from a low-rank metamorphic and sedimentary rock source area, which lay to the northeast and east, with transport predominantly parallel to the basin axis.

   Pages: 47, 109 to 113; Figures: 24, 25, 37, 38; Table 8

8. The well rounded quartz pebbles, a striking compositional aspect of middle Carboniferous sand-ston es, were recycled from Precambrian and Lower Paleozoic sandstones.

   Pages: 109 to 111; Figures: 35, 36; Table 17

9. The Scituate, Narragansett, Boston and Woonsocket Basins of the northeastern United States, were inter-montane basins within the source area which supplied the sediments to the middle Carboniferous Appalachian Basin.

   Pages: 114 to 116; Figure 40; Table 18

10. The Cumberland, Minas, Moncton and Sydney Basins of eastern Canada, which were intermontane basins, sloped to t the northeast and did not contribute sediments to the Appalachian Basin.

    Pages: 114 to 116; Figure 40; Table 18

11. The intermontane basins were formed in an uplifted area caused by the suturing of Africa to North America. Sediments derived from the uplifted area were deposited either as molasse sediments in the Appalachian Basin or as flysch in the Ouachita Trough.

Page 117; Figure 41

REFERENCES CITED

Allen, J. R. L., 1963, Asymmetrical ripple marks and the origin of water-laid cosets of cross-strata: Liverpool Manchester Geol. Jour., v. 3, p. 187-231

_____, 1965, Origin and characteristics of recent alluvial sediments: Sedimentology, v. 5, p. 89-191

_____, 1970a, Physical processes of sedimentation: Elsevier, New York, 248 p.

_____, 1970b, Studies in fluvial sedimentation: A comparison of fining upward cyclothems, with specific reference to coarse member composition and interpretation: Jour. Sed. Petrology, v. 40, p. 298-323

Allen, D. R., 1975, Identification of sediments from well logs, in Chilingarian, G. V. ed., Compaction of Coarse Grained Sediments: Developments in Sedimentology 18A, Elsevier, New York, p. 349-402

Arkle, T., 1974, Stratigraphy of the Pennsylvanian and Permian of the central Appalachians, in Brigs, G. ed., Carboniferous of the southeastern United States: Geol. Soc. America Sp. Paper 148, p. 5-29

Ashley, G. H. and Glenn, L. C., 1906, Cumberland Gap coal field: U. S. Geol. Survey Prof. Paper 49, 240 p.

Baars, D. L., 1961, Permian blanket sandstones of the Colorado Plateau, in Peterson, J. A. and Osmond, J. C. eds., Geometry of sandstone bodies: Am. Assoc. Petroleum Geologists- A Symposium, p. 179-208

Banks, N. L., 1973, Tide-dominated offshore sediments, Lower Cambrian, North Norway: Sedimentology, v. 20, p. 213-228

Belt, E. S., 1965, Stratigraphy and paleontology of Mabou Group and related Middle Carboniferous facies, Nova Scotia, Canada: Geol. Soc. America Bull., v. 76, p. 777-802

Bigarella, J. J; Mabescone, J. M.; Caldaslins, C. J. and Mota, F. O., 1965, Paleogeographical features of the Sierra Grande and Piementera Formations (Parnaiba Basin, Brasil): Paleogeography, Paleoclimatology, Paleoecology, v. 1, p. 259-296

Bird, J. M. and Dewey, J. F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: Geol. Soc. America Bull., v. 81, p. 1031-1060

Blatt, H., 1967, Original characteristics of clastic quartz grains: Jour. Sed. Petrology, v. 37, p. 401-424

Brenner, R. L. and Davies, D. K., 1974, Oxfordian sedimentation in western interior United States: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 407-428

Boothroyd, J. C., 1969, Crane Beach, Field trip guidebook coastal environments of northeastern Massachusetts and New Hampshire, Contributions 1, CRG, Geol. Dept., University of Massachusetts, Amherst, p. 146-173

Butts, C., 1914, The coal resources and general geology of the Pound quadrangle in Virginia: Va. Geol. Survey, Bull. IX, 61 p.

_____, 1940, Geology of the Appalachian Valley in Virginia: Va. Geol. Survey, Bull. 52, 568 p.

Campbell, C. V., 1971, Depositional model-Upper Cretaceous Gallup beach shoreline, Ship Rock area, northwestern New Mexico: Jour. Sed. Petrology, v. 41, p. 395-409

_____ and Oaks, R. Q., 1973, Estuarine sandstone filling tidal scours, Lower Cretaceous Fall River Formation, Wyoming: Jour. Sed. Petrology, v. 43, p. 765-778

Campbell, M. R., 1893, Geology of the Big Stone Gap coal field of Virginia and Kentucky: U. S. Geol. Survey, Bull. 111, 106 p.

_____, 1896, Description of the Pocahontas sheet (Virginia-West Virginia): U. S. Geol. Survey, Geologic Atlas Folio 26

_____, 1925, The valley coal fields of Virginia: Va. Geol. Survey, Bull. 25, 300 p.

_____ and Mendenhall, W. C., 1896, Geologic section along the New and Kanawha Rivers in West Virginia: U. S. Geol. Survey, Annual Report no. 17, Part 2, p. 479-519

Carr, D. D., 1973, Geometry and origin of oolite bodies in the St. Genevieve Limestone (Mississippian) in the Illinois Basin: Ind. Geol. Survey, Bull. 48, 81 p.

Caston, V. N. D., 1972, Linear sand banks in the southern North Sea: Sedimentology, v. 18, p. 63-78

Chen, C. S. and Goodell, H. G., 1964, The petrology of the Lower Pennsylvanian Sewanee Sandstone, Lookout Mountain, Alabama and Georgia: Jour. Sed. Petrology, v. 34, p. 46-72

Clifton, H. E.; Hunter, R. E. and Phillips, R. L., 1971, Depositional structures and processes in the nonbarred high-energy nearshore: Jour. Sed. Petrology, v. 41, p. 651-670

Cotter, E., 1971, Paleoflow characteristics of a late Cretaceous river in Utah from analysis of sedimentary structures in the Ferron Sandstone: Jour. Sed. Petrology, v. 41, p. 129-138

Crandall, A. R., 1889, Report on the Geology of Whitley County and part of Pulaski County: Ky. Geol. Survey, 44 p.

Davidson-Arnott, R. G. A. and Greenwood, B., 1974, Bedforms and structures associated with bar topography in the shallow water wave environment: Jour. Sed. Petrology, v. 44, p. 698-704

Davies, D. K. and Ethridge, F. G., 1975, Sandstone composition and depositional environment: Am. Assoc. Petroleum Geologists Bull., v. 59, p. 239-264

Davis, J. C., 1973, Statistics and data analysis in geology: John Wiley and Sons, New York, 550 p.

Davis, M. W. and Erlich, R., 1974, Late Paleozoic crustal composition and dynamics in the southeastern United States, in Briggs, G. ed. Carboniferous of the Southeastern United States: Geol. Soc. America, Sp. Paper 148, p. 171-185

DeRaaf, J. F. M. and Boersma, J. R., 1971, Tidal deposits and their sedimentary structures: Geol. Mijnbouw, v. 50, p. 479-504

Derr, M. E., 1974, Sedimentary structure and depositional environment of paleochannels in the Jurrasic Morrison Formation near Green River, Utah: Brigham Young University Geology Studies, v. 21, p. 3-39

Dever, G. R., 1973, Stratigraphic relationships in the Lower and Middle Newman Limestone (Mississippian), east-central and northeastern Kentucky: unpublished M.S. Thesis, University of Kentucky, Lexington

Dickinson, W. R., 1974, Tectonics and sedimentation: Soc. Econ. Paleontologists and Mineralogists Sp. Publication 22, 204 p.

_____, 1974b, Plate tectonics and sedimentation, in Dickenson, W. R. ed., Tectonics and sedimentation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publicatior 22, p. 1-27

Dodge, C. F., 1965, Genesis of an Upper Cretaceous offshore bar near Arlington, Texas: Jour. Sed. Petrology, v. 35, p. 22-35

Doeglas, D. J., 1946, Interpretation of the results of mechanical analysis: Jour. Sed. Petrology, v. 10, p. 19-40

Donaldson, A. C., 1974, Pennsylvanian sedimentation of Central Appalachians, in Briggs, G. ed., Carboniferous of the south-eastern United States: Geol. Soc. America, Sp. Paper 148, p. 47-78

Dott, R. H., 1974, Geosynclinal concept, in Dott, R. H. and Shaver, R. H. eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 19, p. 1-13

Dott, R. H. and Shaver, R. H., 1974, Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 19, 380 p.

Eby, J. B., 1923, Geology and mineral resources of Wise County and the coal bearing portion of Scott County: Va. Geol. Survey, Bull. 24, 617 p.

Eisbacher, G. H.; Carrigy, M. A. and Campbell, R. B., 1974, Paleodrainage and late-orogenic basins of the Canadian Cordillera, in Dott, R. H. and Shaver, R. H. eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 19, p. 143-166

Englund, K. J., 1964, In the Cumberland Mountains of Kentucky, Stratigraphy of the Lee Formation: U. S. Geol. Survey, Prof. Paper 501-B, p. B30-B38

_____, 1968, Geology and coal resources of the Elk Valley area, Tennessee and Kentucky: U. S. Geol. Survey Prof. Paper 572, 59 p.

_____, 1969, Relationship of the Pocahontas Formation to the Mississippian-Pennsylvanian Systemic boundary in southeast Virginia and southern West Virginia: Geol. Soc. America, Abs. with Programs, Pt. 4, Southeastern Section, p. 21

_____, 1971, Displacement of the Pocahontas Formation by the Russell Fork Fault, southwest Virginia: U. S. Geol. Survey Prof. Paper 750-B, p. B13-B16

_____, 1974, Sandstone distribution patterns in the Pocahontas Formation of southwest Virginia and southern West Virginia, in Briggs, G. ed., Carboniferous of the southeastern United States: Geol. Soc. America, Sp. Paper 148, p. 31-45

_____ and Harris, L. D., 1961, Geologic features of the Cumberland Gap area, Kentucky, Tennessee and Virginia: Ky. Geol. Survey Guidebook

_____ and Delaney, A. O., 1966, Intertonguing relations of the Lee Formation in southwestern Virginia: U. S. Geol. Survey Prof. Paper 550-D, p. D47-D52

Ferm, J. C.; Horne, J. C.; Swinchatt, J. P. and Whaley, P. W., 1971, Carboniferous depositional environments in northeast Kentucky: Ky. Geol. Survey Guidebook, Annual Spring Field Conference, 30 p.

Ferm, J. C., 1974, Carboniferous environmental models in eastern United States and their significance, in Briggs, G. ed., Carboniferous of the southeastern United States: Geol. Soc. America, Sp. Paper 148, p. 79-95

Folk, R. L., 1968, Petrology of sedimentary rocks: Hemphills, Austin, Texas, 170 p.

Friedman, G. M., 1961, Distinction between dune, beach and river sands from textural characteristics: Jour. Sed. Petrology, v. 31, p. 514-529

_____, 1967, Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands: Jour. Sed. Petrology, v. 37, p. 327-354

Friend, P. F. and Moody-Stewart, M., 1972, Sedimentation in the Wood Bay Formation (Devonian) of Spitsbergen: Regional analysis of a late orogenic basin: Norsk Polarinstitutt, Skrifter NR 157, 77 p.

Froelich, A. J., 1973, Preliminary report of the oil and gas possibilities between Pine and Cumberland Mountains, southeastern Kentucky: Ky. Geol. Survey, Report of Investigations no. 14, 12 p.

Gellatly, D. C., 1970, Cross-bedded tidal megaripples from King Sound (Northwest Australia): Sedimentary Geology, v. 4, p. 185-191

Giles. A. W., 1921, The geology and coal resources of Dickenson County, Virginia: Va. Geol. Survey, Bull. 21, 224 p.

_____, 1925, Geology and coal resources of the coal bearing portions of Lee County, Virginia: Va. Geol. Survey, Bull. 24, 216 p.

Ginsburg, R. N., 1975, Tidal deposits: a case book of recent examples and fossil counterparts, Springer-Verlag, New York, 428 p.

Glaister, R. P. and Nelson, H. W., 1974, Grain-size distributions, an aid in facies identification: Bull. Canadian Petroleum Geology, v. 22, p. 203-240

Graham, S. A.; Dickenson, W. R. and Ingersoll, R. V., 1975, Himalayan-Bengal model for flysch dispersal in the Appalachian-Ouachita System: Geol. Soc. America Bull., v. 86, p. 273-286

Gussow, W. C., 1953, Carboniferous stratigraphy and structural geology of New Brunswick, Canada: Am. Assoc. Petroleum Geologists Bull., v. 37, p. 1713-1816

Hatcher, R. D., 1972, Development model for southern Appalachians: Geol. Soc. America Bull., v. 83, p. 2735-2760

Harms, J. C.; Southard, J. B. and Spearing, D. R., 1975, Depositional environments as interpreted from primary sedimentary structures and stratigraphic sequences: Soc. Econ. Paleontologists and Mineralogists, Short Course no. 2, 161 p.

Hauser, R. E.; Walker, F. H. and Nelson, V. E., 1957, Itinerary, some stratigraphic and structural features of the Middlesboro Basin: Road log, Geol. Soc. Kentucky and Appalachian Geological Society, 35 p.

Harbaugh, J. W. and Merriam, D. F., 1968, Computer applications in stratigraphic analysis, John Wiley and Sons, New York, 282 p.

Harnsberger, T. K., 1919, The geology and coal resources of the coal bearing portion of Tazewell County: Va. Geol. Survey, Bull. 19, 195 p.

Harris, L. D. and Miller, R. L., 1958, Geology of the Duffield quadrangle, Virginia: U. S. Geol. Survey, Geologic Quadrangle GQ-111

Hobday, D. K., 1969, Upper Carboniferous shoreline sequences in northern Alabama: Ph. D. Thesis, Louisiana State University, 75 p.

_____ and Reading, H. G., 1972, Fair weather versus storm processes in shallow marine sand bar sequences in the Late Precambrian of Finmark, North Norway: Jour. Sed. Petrology, v. 42, p. 318-324

Horne, J. C.; Ferm, J. C. and Swinchatt, J. P., 1974, Depositional model for the Mississippian-Pennsylvanian boundary in northeast Kentucky, in Briggs, G. ed., Carboniferous of the southeast United States: Geol. Soc. America, Sp. Paper 148, p. 97-114

Houbolt, J. J. H. C., 1968, Recent sediments in the southern bight of the North Sea: Geol. Mijnbouw, v. 47, p. 245-273

Hoyt, J. H., 1962, High angle beach stratification, Sapelo Island, Geotgia: Jour. Sed. Petrology, v. 32, p. 309-311

_____ and Henry, V. J., 1967, Influence of island migration on barrier island sedimentation: Geol. Soc. America Bull., v. 78, p. 77-86

Hulsemann, J., 1955, Grossrippeln und schrag-schichtungsgefuge in Nordess-Watt und in der molasse: Sencken bergiana Lethaea, v. 36, p. 359-388

Imbrie, J. and Purdy, E. G., 1962, Classification of modern Bahamian carbonate sediments, in Ham, W. E. ed., Classification of carbonate rocks: Am. Assoc. Petroleum Geologists Mem. 1, p. 253-272

Jillson, W. R., 1919, The oil and gas resources of Kentucky: Ky. Geol. Survey, Ser. 5, Bull. 1, 630 p.

_____, 1922, Oil field stratigraphy of Kentucky: Ky. Geol. Survey, Ser. 6, v. 3, 738 p.

Joering, E. A., 1972, A theory for indirectly estimating streamflow characteristics, Ph. D. Thesis, University of Cincinnati, College of Engineering

Joppling, A. V., 1965, Laboratory studies of the distribution of grainsizes in cross-bedded deposits, in Middleton, G. V., ed., Primary sedimentary structures and their hydrodynamic interpretation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 12, p. 53-65

Johnson, H. D., 1975, Tide- and wave-dominated inshore and shoreline sequences from the Late Precambrian, Finmark, North Norway: Sedimentology, v. 22, p. 45-77

Jones, M. L., 1972, Littoral paleocurrents in Gizzard and Crabb Orchard Mountains Groups, southern Cumberland Plateau and Walden Ridge, in Ferm, J. C.; Milici, R. C. and Eason, J. E. eds., Carboniferous depositional environments in the Cumberland Palteau of southern Tennessee and northern Alabama: Tennessee Div. Geology, Report of Investigations 33, 32 p.

Jordan, G. F., 1962, Large submarine sandwaves: Science, v. 136, p. 939-948

Jordan, R. R., 1964, Columbia (Pleistocene) sediments of Delaware: Del. Geol. Survey, Bull. 12, 69 p.

Kay, M., 1951, North America geosynclines: Geol. Soc. America Mem. 48, 143 p.

Klein, G. DeVries, 1967, Paleocurrent analysis in relation to modern marine sediment dispersal patterns: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 366-382

_____, 1970a, A sedimentary model for determining paleotidal range: Geol. Soc. America Bull., v. 82, p. 2585-2592

_____, 1970b, Depositional and dispersal dynamics of intertidal sand bars: Jour. Sed. Petrology, v. 40, p. 1095-1127

Klovan, J. E., 1966, The use of factor analysis in determining depositional environments from grain size distributions: Jour. Sed. Petrology, v. 36, p. 115-125

Kolmogorov, A. N., 1951, Solution of a problem in probability theory connected with the problem of the mechanism of stratification: Am. Math. Soc. Trans., v. 53, p. 171-177

Krumbein, W. C. and Graybill, F. A., 1965, An introduction to statistical models in geology: McGraw-Hill Co., New York, 475 p.

Kuenen, P. H., 1957, Longitudinal filling of oblong sedimentary basins: Geol. Mijnbouw, v. 18, p. 189-195

_____, 1966, Geosynclinal sedimentation: Geologische Rundschau, v. 56, p. 1-19

Kumar, N. and Sanders, J. E., 1974, Inlet sequence: a vertical succession of sedimentary structures and textures created by the lateral migration of tidal inlets: Sedimentology, v. 21, p. 491-532

Land, L. S. and Hoyt, J. H., 1966, Sedimentation in a meandering estuary: Sedimentology, v. 6, p. 191-208

LeBlanc, R. J., 1972, Geometry of sandstone resevoir bodies, in Cook, T. D., ed., Underground waste management and environmental implications: Am. Assoc. Petroleum Geologists Mem. 18, p. 133-190

Leeder, M. R., 1973a, Fluvatile fining-upwards sequences and the magnitude of paleochannels: Geol. Magazine, v. 10, p. 265-276

______, 1973b, Sedimentology and paleogeography of the Upper Old Red Sandstone in the Scottish Boarder Basin: Scottish Jour. Geology, v. 9, p. 117-144

Leopold, L. B.; Wolman, H. G. and Miller, J. P., 1964, Fluvial processes and geomorphology: W. H. Freeman and Company, San Francisco, 551 p.

Lovinenko, N. Y. and Remizov, I. N., 1964, Sedimentology of beaches on the northern coast of the sea of Azov: in Developments in Sedimentology, Elsevier Publishing Company, Amsterdam, v. 1, p. 245-256

Mackenzie, D. B., 1972, Tidal sand flat deposits in Lower Cretaceous Dakota Group near Denver, Colorado: Mount. Geologist, v. 9, p. 269-277

Malde, H. E., 1968, The catastrophic Late Pleistocene Bonneville flood in the Snake River Plain: U. S. Geol. Survey Prof. Paper 596, 52 p.

Martin, R. V., 1975, Petrology of the Carter Caves Sandstone, Mississippian, northeast Kentucky, M. S. Thesis, University of Cincinnati, 66 p.

Martini, I. P., 1971, A test of validity of quartz grain orientation as a paleocurrent and paleoenvironmental indicator: Jour. Sed. Petrology, v. 41, p. 60-69

Maughan, E. K. and Tazelaar, J. F., 1973, Geologic map of the Rose Hill quadrangle, Kentucky: U. S. Geol. Survey, Geologic Quadrangle GQ-1121

McGrain, P. and Crawfoed, T. J., 1959, High silica sandstone and conglomerate on Pine Mountain, Kentucky: Ky. Geol. Survey, Ser. 10, No. 1, 5 p.

Meckel, L. D., 1967, Origin of Pottsville conglomerates (Pennsylvanian) in the Central Appalachians: Geol. Soc. America Bull., v. 78, p. 223-258

Metzger, W. J., 1965, Pennsylvanian stratigraphy of the Warrior Basin, Alabama: Alabama Geol. Survey Circular 30, 80 p.

McCubbin, D. G., 1969, Cretaceous strike valley sandstone resevoirs, northwestern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 53, p. 2114-2140

Miall, A. D., 1974, Paleocurrent analysis of alluvial sediments: a discussion of directional variance and vector megnitude: Jour. Sed. Petrology, v. 44, p. 1174-1185

_____, (in press), Paleocurrent and paleohydraulic analysis of some vertical profiles through a Cretaceous braided stream deposit, Banks Island, Arctic Canada: Sedimentology

Michelson, P. C. and Dott, R. H., 1973, Orientation analysis of cross stratification in Upper Cambrian sandstones of western Wisconsin: Jour. Sed. Petrology, v. 43, p. 784-794

Middleton, G. V., 1965, Primary sedimentary structures and their hydrodynamic interpretation, ed.: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 12, 265 p.

Milici, R. C., 1974, Stratigraphy and depositional environments of Upper Mississippian and Lower Pennsylvanian rocks in the southern Cumberland Plateau of Tennessee, in Briggs, G. ed., Carboniferous of the southeast United States: Geol. Soc. America, Sp. Paper 148, p. 115-143

Miller, M. S., 1974, Stratigraphy and coal beds of Upper Mississippian and Lower Pennsylvanian rocks in southwestern Virginia: Va. Geol. Survey, Bull. 84, 211 p.

Miller, R. L., 1969, Pennsylvanian formations of southwest Virginia: U. S. Geol. Survey Bull. 1280, 69 p.

Milling, M. E. and Behrens, E. W., 1966, Sedimentary structures of beach and dune deposits, Mustang Island, Texas: Inst. Marine Sci., v. 11, p. 135-148

Mitchum, R., 1954, Pottsville strata of part of the Central Appalachians coal field, Ph. D. Thesis, Northwestern University, Evanston, 348 p.

Mizutani, S. and Hattori, I., 1972, Stochastic analysis of bed-thickness distribution of sediments: Math. Geology, v. 4, p. 123-144

Moiola, R. J. and Weiser, D., 1968, Textural parameters- an evaluation: Jour. Sed. Petrology, v. 38, p. 45-53

Moody-Stewart, M., 1966, High and low sinuosity stream deposits, with examples from the Devonian of Spitsbergen: Jour. Sed. Petrology, v. 30, p. 1102-1117

Mrakovich, J. V. and Coogan, A. H., 1974, Depositional environment of the Sharon Conglomerate Member of the Pottsville Formation in northeastern Ohio: Jour. Sed. Petrology, v. 44, p. 1186-1199

Mutch, T. A., 1968, Pennsylvanian nonmarine sediments of the Narragansett Basin, Massachusetts-Rhode Island, in Klein, G. Dev., ed., Late Paleozoic and Mesozoic continental sedimentation, northeast North America: Geol. Soc. America, Sp. Paper 106, p. 177-209

Nanz, R. H., 1955, Grain orientation in beach sands: a possible means for predicting resevoir trend: Jour. Sed. Petrology, v. 25, p. 130

Noorthoorn, V. D.;Kruijft, J. L. and Lagaaij, R., 1960, Displaced faunas from inshore estuarine sediments in the Haringvliet (Netherlands): Geol. Mijnbouw, v. 39, p. 711-723

Off, T., 1963, Rhythmic linear sand bodies caused by tidal currents: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 324-341

Oomkens, E. and Terwindt, J. H. J., 1960, Inshore estuarine sediments in the Haringvleit (Netherlands): Geol. Mijnbouw, v. 39, p. 701-710

_____, 1974, Lithofacies relations in the Late Quaternary Niger Delta complex: Sedimentology, v. 21, p. 195-222

Parks, J. M., 1966, Cluster analysis applied to multivariate geologic problems: Jour. Geology, v. 74, p. 703-715

Passega, R., 1957, Texture as characteristic of clastic deposition: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 152-184

_____, 1964, Grain size representation by CM patterns as a geologic tool: Jour. Sed. Petrology, v. 34, p. 830-847

Pelletier, B. R., 1958, Pocono paleocurrents in Pennsylvania and Maryland: Geol. Soc. America Bull., v. 69, p. 1033-1064

Pettijohn, F. J., 1956, Sedimentary rocks: Harper and Bros., New York, 526 p.

_____, Potter, P. E. and Siever, R., 1972, Sand and sandstone: Springer-Verlag, New York, 618 p.

Poole, W. H., 1967, Tectonic evolution of the Appalachian region of Canada, in Collected papers on the geology of the Atlantic Region, Hugh Lilly Memorial Volume: Geol. Assoc. Canada, Sp. Paper 4, p. 9-51

Potter, P. E. and Siever, R., 1956, Sources of basal Pennsylvanian sediments in the Eastern Interior Basin: Part I, Crossbedding: Jour. Geology, v. 64, p. 225-244

_____; Schimp, N. F. and Withers, J., 1963, Trace elements in marine and fresh water argillaceous sediments: Geochim. Cosmochim. Acta., v. 27, p. 669-694

_____ and Pettijohn, F. J., 1963, Paleocurrents and basin analysis: Springer-Verlag, Berlin, 296 p.

Pryor, W. A., 1961, Sand trends and paleoslope in Illinois Basin and Mississippi Embayment, in Peterson, J. A. and Osmond, J. C. eds., Geometry of sandstone bodies: Am. Assoc. Petroleum Geologists-A Symposium, p. 119-133

_____, 1971, Petrology of the Permian Yellow sands of northeastern England and their North Sea Basin equivalents: Sedimentary Geology, v. 6, p. 221-254

Purdy, E. G., 1963, Recent calcium carbonate facies of Great Bahama Bank: 1. Petrography and reaction groups: Jour. Geology, v. 71, p. 334-355

Read, C. B. and Mamay, S. H., 1964, Upper Paleozoic floral zones and floral provinces of the United States: U. S. Geol. Survey Prof. Paper 454-K, p. K1-K35

Reger, D. B., 1926, Mercer, Monroe and Summers Counties: W. Va. Geol. Survey Bull., 936 p.

Reineck, H. E., 1963, Sedimentgefuge im Bereich der Sudlichen Nordsee: Senckenberg Naturf. Gesell Abh., No. 504, 64 p.

_____ and Singh, I. B., 1973, Depositional sedimentary environments: Springer-Verlag, New York, 439 p.

Rodgers, J., 1970, The tectonics of the Appalachians: Wiley-Interscience, New York, 271 p.

Sahu, B. K., 1964, Depositional mechanisms from the size analysis of sediments: Jour. Sed. Petrology, v. 34, p. 73-83

Salsman, G. G.; Tolbert, W. A. and Villars, R. G., 1966, Sand ridge migration in St. Andrew Bay, Florida: Marine Geology, v. 4, p. 11-19

Schlee, J., 1963, Early Pennsylvanian currents in the southern Appalachian mountains: Geol. Soc. America Bull., v. 74, p. 1439-1451

Schumm, S. A., 1968, River adjustment to altered hydrologic regime-Murrumbidgee River and paleochannels: U. S. Geol. Survey Prof. Paper 598, 65 p.

_____, 1972, Fluvial paleochannels, in Rigby, J. K. and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 16, p. 98-107

Scott, G. L., 1965, Heavy mineral evidencs for source of some Permian quartzose sandstones, Colorado Plateau: Jour. Sed. Petrology, v. 35, p. 391-400

Seeland, D. A., 1961, Stratigraphy and cross-bedding of the Aladdin Sandstone, Black Hills, South Dakota: M. S. Thesis, University of Minnesota, 124 p.

Selley, R. C., 1967, A classification of paleocurrent models: Jour. Sed. Petrology, v. 75, p. 99-110

Seibold, E., 1963, Geological investigation of nearshore sand-transport; examples of methods and problems from Baltic and North Seas, in Sears, M. ed., Progress in oceanography, v. 1, Pergamon Press, New York, p. 1-70

Seiver, R. and Potter, P. E., 1956, Source of basal Pennsylvanian sediments in the Eastern Interior Basin: 2. Sedimentary petrology: Jour. Geology, v. 64, p. 317-334

Shelton, J. W., 1965, Trend and genesis of lowermost sandstone unit of Eagle Sandstone at Billings, Montana: Am. Assoc. Petroleum Geologists Bull., v. 49, p. 1385-1397

_____, 1973a, Models of sand and sandstone deposits: a methodology for determining sand genesis and trend: Okla. Geol. Survey, Bull. 118, 122 p.

_____, 1973b, Frio sand complex, Oligocene, Texas, Gulf Coast (17), in Shelton, J. W., models of sand and sandstone deposits: Okla. Geol. Survey, Bull. 118, p. 87-91

Shepard, F. P. and Young, R., 1961, Distinguishing between beach and dune sands: Jour. Sed. Petrology, v. 31, p. 196-214

Shepard, R. A. and Dobrovolny, E., 1962, Mississippian-Pennsylvanian boundary in northeast Kentucky: U. S. Geol. Survey Prof. Paper 450-E, p. 45-47

_____, 1964, Geology of the Tygarts Valley quadrangle: U. S. Geol. Survey, Geologic Quadrangle GQ-289

Simons, D. B.; Richardson, E. V. and Nordin, C. F., 1965, Sedimentary structures generated by flow in alluvial channels, in Middleton, G. V., ed., Primary sedimentary structures and their hydrodynamic interpretation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 12, p. 34-52

Sindowski, H. H., 1957, Die synoptische methode des kornkurven-vergleiches zur ausdeutung fossiler sedimentationsraume: Geol. Jahrbuch, Bd. 73, p. 235-275

Smith, N. D., 1970, The braided stream depositional environment, comparison of the Platte River with some Silurian clastic rocks, north central Appalachians: Geol. Soc. America Bull., v. 81, p. 2993-3014

Solohub, J. T. and Klovan, J. E., 1970, Evaluation of grain-size parameters in lacustrine environments: Jour. Sed. Petrology, v. 40, p. 81-101

Stearns, R. G. and Mitchum, R. M., 1962, Pennsylvanian rocks of the Southern Appalachians, in Branson, C. C. ed., Pennsylvanian System of the United States: Am. Assoc. Petroleum Geologists-A Symposium, p. 74-96

Steel, R. J., 1974, New Red Sandstone floodplain and piedmont sedimentation in the Hebridean Province, Scottland: Jour. Sed. Petrology, v. 44, p. 336-357

Stride, A. H., 1963, Current swept sea floors near the southern half of Great Britain: Geol. Soc. London Quart. Jour., v. 119, p.175-199

Sundborg, A., 1967, Some aspects of fluvial sediments and fluvial geomorphology: 1. General views and graphic methods: Geogr. Ann., v. 49A, p. 333-343

Swett, K.; Klein, G. Dev. and Smit, D. E., 1971, A Cambrian tidal sand body of northwest Scottland, an ancient-recent analog: Jour. Geology, v. 79, p. 400-415

Tanner, W. F., 1955, Paleogeographic reconstruction from cross-bedding studies: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 2471-2483

Terwindt, J. H. J., 1963, Sediment movement and sediment properties in the tidal area of the Lower Rhine (Rotterdam Waterway) : Konokl. Netherlands Geol. Mijnb. Verh., Geol. Ser., v. 21, p. 243-258

______, 1971, Lithofacies of inshore estuarine and tidal inlet sediments: Geol. Mijnbouw, v. 50, p. 515-526

Thompsom, W. O., 1937, Original structures of beaches, bars and dunes: Geol. Soc. America Bull., v. 48, p. 723-752

Towe, K. M., 1959, Petrology and source of sediments in the Narragansett Basin of Rhode Island and Massachusetts: Jour. Sed. Petrology, v. 29, p. 503-512

Vail, P. R., 1959, Stratigraphy and lithofacies of Upper Mississippian rocks in the Cumberland Plateau: Ph. D. Thesis, Northwestern University, Evanston, 143 p.

Van Houten, F. B., 1974, Northern Alpine molasse and similar Cenozoic deposits of southern Europe, in Dott, R. H. and Shaver, R. H. eds., Modern and ancient geosynclinal sedimentation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 19, p. 260-273

Van Stratten, L. M. J. U., 1953, Megaripples in the Dutch Wadden Sea and in the basin of Arcahon (France): Geol. Mijnbouw, v. 15, p. 1-11

Visher, G. S., 1965, Fluvial processes as interpreted from ancient and recent fluvial deposits, in Middleton, G. V. ed., Primary sedimentary structures and their hydrodynamic interpretation: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 12, p. 116-132

_____, 1969, Grain size distributions and depositional processes: Jour. Sed. Petrology, v. 39, p. 1074-1106

_____, 1972, Physical characteristics of fluvial deposits, in Rigby, J. K. and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Soc. Econ. Paleontologists and Mineralogists, Sp. Publication 16, p. 84-97

Wanless, H. R., 1939, Pennsylvanian correlations in the Eastern Interior and Appalachian coal fields: Geol. Soc. America, Sp. Paper 17, 130 p.

_____, 1946, Pennsylvanian geology of a part of the Southern Appalachian coal field: Geol. Soc. America Mem. 13, 162 p.

_____, 1947, Regional variation in Pennsylvanian lithology: Jour. Geology, v. 55, p. 237-253

_____, 1962, Pennsylvanian rocks in the Eastern Interior Basin, in Branson, C. C. ed., Pennsylvanian System in the United States: Am. Assoc. Petroleum Geologists- A Symposium, p. 4-59

_____, 1967, Marine and non-marine facies of the Upper Carboniferous of North America: Int. Nat. Congr. on Carboniferous Stratigraphy and Geology, No. 6, v. 1, p. 293-336

Weaver, C. E., 1960, Possible uses of clay minerals in search for oil: Am. Assoc. Petroleum Geologists Bull., v. 44, p. 1505-1518

Weber, K. J., 1971, Sedimentological aspects of oil fields in Niger Delta: Geol. Mijnbouw, v. 50, p. 559-576

Wentworth, C. W., 1922, The geology and coal resources of Russell County, Virginia: Va. Geol. Survey, Bull. 22, 178 p.

______, 1927, The geology and coal resources of the Middlesboro Basin in Kentucky: Ky. Geol. Survey, Ser. 6, v. 29, p. 155-235

Wermund, E. G., 1965, Cross-bedding in the Meridian Sand: Sedimentology, v. 5, p. 69-80

White, D., 1903, Deposition of the Appalachian Pottsville: Geol. Soc. America Bull., v. 15, p. 267-282

White, I. C., 1891, Stratigraphy of the bituminous coal field in Pennsylvania, Ohio and West Virginia: U. S. Geol. Survey Bull. 65, 212 p.

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

Wilson, C. W., 1956, Pennsylvanian geology of the Clark Range, Obey City, Campbell Junction and Isoline quadrangles: Tenn. Div. of Geology, Folio 1, 13 p.

Woodward, H. P., 1961, Preliminary subsurface study of southeastern Appalachian Interior Plateau: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 1634-1655

APPENDIX 1

LOCATION OF WELLS AND MEASURED SECTIONS

Appendix 1 summarizes the locations of the control data points used to construct the cross sections and isopach maps. The number of each location corresponds to its location on the index map shown in Figure 5. Much of the data is published in the literature, and reference is made to all source material. Sections measured by the writer are described in Appendix 2.

Number	Location	Source	Data Type
1.	Brodie & Son #1 Williamson, 10-L-84, Pike Co., Ky.	Jillson (1922, p. 591)	Drillers Log
2.	Gulf Oil #1 Bradley, 17-L-81, Floyd Co., Ky.	Jillson (1922, p. 147)	Drillers Log
3.	Elkhorn Coal #1, 3-J-82, Floyd Co., Ky.	Jillson (1919)	Drillers Log
4.	Rice Oil #1, 10-I-76, Perry Co., Ky.	Jillson (1919)	Drillers Log
5.	Ohio Oil Co. #3 Osborn, 25-J-71, Menifee Co., Ky.	Jillson (1922, p. 518)	Drillers Log
6.	Ohio Oil Co., #4 Osborn, 6-H-71, Menifee Co., Ky.	Jillson (1922, p. 519)	Drillers Log
7.	Va.-Ky. Oil #1 Rice, 1-G-70, Johnson Co., Ky.	Jillson (1922, p. 225)	Drillers Log
8.	Atlanta Oil & Gas #1 Watkins, 7-H-67, Laurel	Jillson (1922, p. 236)	Drillers Log
9.	Petroleum Exp. #1 Fry, 20-F-67, Knox Co., Ky.	Wiser Oil Co. Corbin, Ky.	Sample Description
10.	Delta Drilling, Gatliff Coal Co. #1, D-65 Whitley Co., Ky.	Englund (1968)	Sample Description
11.	Saxton, 12-B-65, Whitley Co., Ky.	Jillson (1922, p. 712)	Drillers Log
12.	Gibson Petro. #1 Jayne, 5-D-70, Johnson Co., Ky.	Jillson (1922, p. 225)	Drillers Log

Number	Location	Source	Data Type
13.	North Am. Petr., Asher Coal Co., 16-E-72, Bell Co., Kentucky	Ky. Geol. Survey	Drillers Log
14.	Archer Branch to Laurel Fork, Campbell Co., Tenn.	Englund (1968)	Outcrop
	I-75 Roadcut, Campbell Co., Tenn.	BeMent (1976) Sec. 14, App. 5	Outcrop
15.	Columbia Carbon, East Tenn. Iron and Coal #2, Campbell Co., Tenn.	Englund (1968)	Sample Description
16.	Big Creek Gap, LaFollette, Tenn	White (1906)	Outcrop
17.	Gilbert and Moulton, 21-A-67, Clairboune Co., Tenn.	Englund (1968)	Drillers Log
18.	Henry Bowlin Gap, 8-B-67, Whitley and Bell Co., Ky.	BeMent (1976) Sec. 18, App. 2	Outcrop
19.	Pineville, 22-D-70 Bell Co., Kentucky	Houser (1957) BeMent (1974)	Outcrop Outcrop
20.	United Fuel & Gas #2 Knuckles, 5-C-71, Bell Co., Ky.	Clarkson (1962) Geol. Surv.	Sample Description
21.	Benedum Trees, L. B. Hurst, 21-C-70, Bell Co., Ky.	Ky. Geol. Survey	Sample Description
22.	Cumberland Gap, Bell Co., Ky.	Ashley and Glen (1906); Englund (1964)	Outcrop
23.	Columbia Fuel & Gas #1 Kentenia, 16-D-74, Harlan Co., Ky.	Ky. Geol. Survey	Drillers Log
24.	Columbia Fuel & Gas #1 Ky Bailey, 3-D-74, Harlan Co.,	Ky. Geol. Survey	Drillers Log
25.	Highway 421, 7-S-75 Harlan Co., Ky.	BeMent (1976) Sec. 25, App. 2	Outcrop

Number	Location	Source	Data Type
26.	Pennington Gap, Lee Co., Va.	Giles (1925) Campbell (1925)	Outcrop
27.	Hurricane Gap, 2-F-78, Letcher Co., Ky.	BeMent (1976) Sec. 27, App. 2	Outcrop
28.	U. S. Steel #4 Bierer and Sons, 11-F-79, Harlan Co., Ky.	Ky. Geol. Survey Files	Drillers Log
29.	Highway 119, Stokeley and Assoc. core holes #1, 2, 6, 4-G-81, Letcher Co., Ky.	Ky. Geol. Survey Files	Sample Description, Outcrop
30.	Callahan Creek, F-81 Lee Co., Va.	Miller (1974)	Drillers Log
31.	Big Stone Gap, Wise Co.,	Campbell (1893) Eby (1923) Miller (1969) BeMent (1976) Sec. 31, App. 2	Outcrop
32.	Little Stone Gap, Wise Co., Va.	Eby (1923)	Outcrop
33.	Clinchfield Coal #187, Wise Dev. Co., Wise Co., Va.	Englund and Delaney (1966)	Sample Description
34.	Bond Gap, Wise and Scott Co., Va.	Englund and Delaney (1966)	Outcrop
35.	Clinchfield Coal #189, J. F. McElhaney, Russel	Englund and Delaney (1966)	Sample Description
36.	Hart-Alvy Section, Russell Co., Va.	Englund and Delaney (1966)	Outcrop
37.	Cranesnest River, Clinchfield Coal, Dickenson Co., Va.	Eby (1923)	Sample Description
38.	Blue Head Branch Section, Pike Co., Ky.	Miller (1967)	Outcrop
39.	Clinchfield Coal, J. H. Sutherland, Dickenson Co., Va.	Miller (1974)	Sample Description

APPENDIX 2

DESCRIPTIONS OF MEASURED SECTIONS

This section contains the descriptions of four measured sections through the Pennington and Lee Formations. The section number corresponds to the locations shown in Fig. 5 and listed in Appendix 1.

Section 27 Hurricane Gap, Letcher Co., Kentucky

Section begins at top of Newman Limestone on east side of road along northwest side of Pine Mountain. Base of section is 1951 meters from east line and 1646 meters from north line, Louellen quadrangle, Letcher Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent, June 23, 1973.

Pennington Formation:	Meters
1. Covered	42.6
2. Shale, silty; red to greenish gray; slightly calcareous; ripple bedded; interbedded with some thinly rippled, gray siltstones; sandy near top	4.3
3. Covered	7.3
4. Sandstone, tan to dark gray; fine grained; calcareous in part; massive bedded	1.2
5. Siltstone, light brown to light gray; rippled; lower part is interbedded with tan, fine grained, massive bedded sandstone; upper part is predominantly siltstone with some scattered beds of sandstone	18.3
6. Shale, dark gray, brown or red; silty; horizontally laminated with some rippled units	4.6
7. Sandstone, gray to tan; silty; fine grained; rippled or massive bedded; transitional base; contains some scattered interbeds of light gray, micaceous, rippled siltstone; crossbedded near top	7.6
8. Sandstone, tan to light gray; fine to very fine grained; predominantly rippled bedded with some scattered thin, massive bedded units of fine grained sand; contains some thin, interbedded gray siltstones showing load cast structures; basal part of unit contains clay pebbles; upper part is interbedded with thinly laminated black shale	8.1

9. Sandstone, light gray to tan; fine to very fine grained; lower part is somewhat coarser grained, crossbedded, micaceous in part with laminations of opaque minerals; middle third is crossbedded or rippled and interbedded with thin beds of light gray to black shale; upper third is tan, micaceous, rippled with heavy mineral laminations 28.8

10. Covered 0.9

11. Shale, greenish gray to black; slightly silty; horizontally laminated; interbedded with thinly rippled, micaceous gray siltstone 29.6

12. Shale, greenish yellow to gray to black; calcareous; contains scattered fossils of brachiopods and thin, black carbonate wackestone near top 13.7

13. Sandstone, tan to greenish gray; lower part is very fine grained, rippled and interbedded with laminated black shale; middle part is fine grained, micaceous, with concentrations of opaque minerals; upper part scours into underlying units, is medium to fine grained, quartzose and massive bedded 10.4

14. Sandstone, gray; very fine grained; silty and micaceous; crossbedded at base and rippled near top 4.0

15. Shale, silty; lower half is red or gray, contains iron-stone concretations and is interbedded with laminated gray siltstone; upper part is red to green and horizontally laminated 5.5

16. Siltstone; lower part is yellow to green, slightly sandy, micaceous with scattered concentrations of macerated plant fragments; middle part is shaley, red to green, with scattered interbeds of fine grained sandstone; upper part is sandy, brown to green, rippled and interbedded with horizontally laminated black shale 9.1

17. Shale, partly covered; silty; red to green; burrowed 3.9

18. Siltstone, tan to greenish gray; shaley; micaceous; interbedded with thin gray shale and very fine grained, rippled sandstone 12.5

19. Shale, red to green; silty, horizontally laminated 2.3

20. Siltstone, yellow to green; lower part is shaley, in part micaceous and ripple bedded; upper part is interbedded with red shale 13.6

(Pocahontas ?)

21. Siltstone; lower part is shaley, interbedded with thin beds of fine grained, gray sandstone; thin carbonaceous zone and green shale present in middle; upper part is light gray, rippled, and grades into overlying light gray, very fine grained, burrowed sandstone 12.6

22. Covered 6.1

23. Sandstone; lower part is tan, fine grained, micaceous in part, rippled and crossbedded; contains gray to black carbonaceous shale and shaley coal near center; upper part is tan to brown, medium grained, cross-bedded at base and rippled near top 3.8

Lee Formation (in part)

24. Sandstone, white; coarse grained; conglomeratic, erosional base; crossbedded with some scattered massive beds 5.3

Total 256.1

Section 18 Henry Bowlin Gap, Whitley and Bell Cos., Kentucky

Section begins at top of Newman Limestone on east side of road along northwest side of Pine Mountain. Base of section if 3581 meters from west line and 2286 meters from south line, Frakes quadrangle, Whitley Co., Kentucky. Section continues up hill, through gap and into Bell Co., measured with Jacob staff and tape by W. O. BeMent, June 21, 1973. This section is shown in Figure 16.
Conodonts sampled from Unit 9. Maceration 2095 from Unit 11.

Meters

Pennintgon Formation:

1. Covered 6.1

2. Siltstone, light gray to green to reddish green; shaley; mostly rippled with some flaser bedding; carbonaceous in lower part; interbedded with laminated gray to green shale 28.3

3. Sandstone, light gray; silty; fine grained; lower part is rippled, has conformable base and contains scattered clay pebbles; upper part is massive bedded 6.1

4. Siltstone, light gray to dark green; sandy; predominantly ripple bedded; interbedded with light gray, fine grained, crossbedded sandstones containing clay clasts 26.8

5. Sandstone, tan; medium to fine grained; lower part has erosional base, clay pebble conglomerate and is massive bedded; upper part is mostly ripple bedded with some massive beds 10.5

6. Shale, dark gray; silty; carbonaceous; mostly laminated with some rippled zones 7.6

7. Sandstone, tan; fine grained; lower part is massive bedded, burrowed along base; upper part is rippled ... 4.6

8. Shale, silty; upper half is yellow, laminated; lower half is rippled 12.2

9. Limestone, light gray; wackestone; contains abundant brachiopod and crinoid debris; sharp bounding contacts.. 3.1

10. Shale, yellow; silty; laminated 2.1

11. Sandstone, tan to white; fine to very fine grained; micaceous in part; rippled; interbedded with rippled gray siltstone; contains thin coal bed in upper part 24.3

12. Sandstone, pink to tan; medium to fine grained; lower part is rippled and horizontally laminated and contains some thin beds of dark gray silty shale; middle part is medium grained and massive bedded; upper part is fine grained and rippled 6.0

This part of the section begins the vertical profile shown in Figure 15B.

13. Shale, dark gray to black; laminated 3.1

14. Sandstone, red to light gray, medium to fine grained; micaceous and quartzose with heavy mineral concentrations; mostly crossbedded with some horizontal bedding near top; massive bedded sand near base contains abundant matrix, sharp basal contact with underlying shale 8.2

15. Shale, light gray, laminated; scattered thinly ripple bedded gray siltstone 0.5

16. Sandstone, white to red, coarse to fine grained; micaceous with local concentrations of heavy minerals; rippled near top, some horizontal bedding near center; clay pebbles and quartz granules in massive beds in lower part 12.9

17. Siltstone, dark gray; rippled with 50 percent interbedded gray shale; scattered thinly ripple bedded very fine sand 3.1

18. Sandstone, red to tan, medium to fine grained; micaceous and quartzose in part; crossbedded with scattered ripple beds near top and lower quarter of unit; clay pebbles in crossbedded units 7.0

19. Covered .... 4.0+

This part of the section begins the vertical profile shown in Figure 17.

20. Shale, light gray, silty, predominantly laminated with scattered rippled units .... .1+

21. Sandstone, upper third is light pink to light gray, micaceous in part, predominantly trough crossbedded with some scattered ripple beds near the top; lower two thirds are orange to light gray, coarse to medium grained, slightly pebbliferous with lenses of quartz pebbles, crossbedded with thicknesses ranging from 20 to 200 centimeters; erosion base 9.1

22. Covered, probably shale or siltstone 0.6

23. Sandstone, red to light pink; fine grained, micaceous in part; upper part is trough crossbedded; lower part is thinly ripple bedded with transitional base 2.1

24. Covered .... .5+

Total 194.4

Section 25 Highway 421, Harlan Co., Kentucky

Section begins at top of Newman Limestone on south side of road along northwest face of Pine Mountain. Base of section is 5181 meters from west line and 2743 meters from south line, Bledsoe quadrangle, Harlan Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent, June 19, 1973. Units 24 to 39 are shown in Figure 21. Conodonts sampled from Unit 3.

		Meters
Pennington Formation:		
1.	Covered	7.6
2.	Shale, red and greenish gray; silty; fossiliferous; interbedded with thinly rippled light gray siltstone; abundantly burrowed..................................	7.4
3.	Limestone; wackestone, light gray to brown; fossiliferous with brachiopod and crinoidal debris .... (sampled for conodonts - see Table 4)	3.1
4.	Covered	18.3
5.	Siltstone, dark gray; rippled; interbedded with laminated or rippled dark gray silty shale	3.1
6.	Sandstone, tan to white; fine grained; erosional base; lower part is crossbedded and contains pebbles of underlying silty shale; upper part is massive or low angle crossbedded	4.6
7.	Siltstone, light gray; rippled and flaser bedded; interbedded with dark gray shale	7.6
8.	Sandstone, light gray; fine grained; lower part is horizontally bedded, contains concentrations of coaly debris; upper part is tan, massive bedded with sharp top	9.5
9.	Siltstone, light gray; rippled and flaser bedded; interbedded with light gray silty shale and thinly bedded, tan to light gray fine grained sandstone; contains one bed of tan to pink, medium to fine grained, crossbedded sandstone near center of unit; grades upward into thinly bedded, light gray, fine to very fine grained rippled sandstone	25.9

This part of the section begins the vertical profile shown in Figure 15A.

10. Sandstone, light gray, fine grained; massive bedded 0.9

11. Siltstone, light gray to dark green; flaser bedded and rippled with 50 percent interbedded gray shale; loadcasts abundant; 2.0 meters near center contains scattered massive beds of fine grained sand with clay pebbles, 10 percent interbedded gray shale 7.6

12. Sandstone, tan, medium grained; massive bedded with scattered crossbeds; erosional base 2.1

13. Siltstone, light gray; rippled with thin interbeds of gray shale 0.9

14. Sandstone, white to tan, fine to very fine grained; crossbedded with scattered rippled units 6.1

15. Sandstone, white, medium grained, friable, massive bedded in units 8 to 25 cm; burrowed in upper part ... 5.8

16. Sandstone, light tan to gray, fine to very fine grained; horizontally bedded in upper part with ball-and-willow structure; lower part is horizontally bedded with a few scattered ripples and low angle crossbeds 6.1

17. Sandstone, light gray, medium to fine grained; massive bedded with clay pebbles 2.4

18. Sandstone, pink to ligh gray, fine grained; rippled with thin crossbeds containing clay pebbles; some interbedded thin siltstones and gray shale 11.0

19. Sandstone, light tan to white, medium grained; massive bedded 1.5

(Pocahontas Formation ?)

21. Covered 3.1

22. Siltstone, light gray; rippled; interbedded with dark gray shale 6.1

23. Coal rash with rootlet zone 0.2

Lee Formation: (Middlesboro Member)

24. Sandstone, tan to white; medium grained; erosional base; crossbedded and massive in lower part; contains some ripple bedded and horizontally laminated light gray

siltstone near center; upper third is thinly ripple bedded and passes gradually into overlying gray, rippled siltstone containing interbedded gray shale and thinly rippled sandstone 18.3

25. Coal, with underclay 0.2

26. Sandstone, white to light gray; medium grained; sparsely conglomeraticl erosional base; predominantly planar crossbedded with lesser amounts of massive bedding and horizontal lamination; contains a 10.6 meter interval in upper third which is predominantly rippled 67.1

27. Siltstone, light gray; micaceous; horizontally laminated; contains scattered dessication cracks; interbedded with light gray, fine to very fine grained, micaceous, rippled sand 33.5

28. Covered 4.6

29. Sandstone, white; coarse to medium grained; conglomeratic; massive and planra crossbedded 9.2

30. Siltstone, light gray; sandy and rippled; contains one bed of fine grained, massive bedded sand near base and 3.0 meter interval of tan, fine grained, crossbedded sand near top 32.7

31. Sandstone, white to light gray; medium to fine grained; erosional base; predominantly crossbedded in lower part; upper part may be 50 percent ripple bedded; interbedded with very fine grained, rippled sandstone 25.9

32. Siltstone, light gray; rippled 7.5

Hensley Member

33. Sandstone, white to tan; lower part is rippled and fine grained; upper part is medium grained and predominantly crossbedded 18.9

34. Siltstone, light gray; sandy; mostly rippled with scattered horizontal lamination 4.6

35. Sandstone, white; medium grainedl crossbedded throughout; erosional base; sparsley conglomeratic; transitional with overlying unit 3.2

36. Sandstone, tan to light gray; fine to very fine grained; ripple bedded and horizontally laminated with carbonaceous zones 12.2

37. Sandstone, pink; medium to fine grained; erosional base; predominantly planar crossbedded; contains a 4.2 meter unit of light gray, thinly rippled siltstone in lower third 33.2

38. Covered (Position of Tunnel Coal) 3.1

Bee Rock Sandstone Member

39. Sandstone, white to light gray; medium to fine grained; erosional base; conglomeratic in lower part; predominantly planar crossbedded 15.2

Total 440.2

Section 31 Big Stone Gap, Wise Co., Va.

Section measured along east and west side of gap along Louisville and Nashville and Southern Railroads. Base of section is on east side of gap, beginning at north end of tunnel on Southern Railroad, north of limestone quarry. Measured with Jacob staff and tape by W. O. BeMent, December 19, 1973.

	Meters
Pennington Formation (in part):	
1. Sandstone, light gray; fine to very fine grained; micaceous; ripple bedded	18.3
2. Covered	10.6
3. Sandstone, light gray to green; silty and fine grained; rippled; interbedded with gray, thinly rippled siltstone	30.5
4. Covered	4.6
5. Shale, light to dark gray; calcareous; fossiliferous, contains abundant brachiopods	3.7
Pocahontas Formation ?	
6. Covered	146.0

On west side of gap, in Louisville and Nashville railroad cut, near west end of trestle over river.

7. Sandstone, brown to light gray; lower part is fine grained, crossbedded; upper part is very fine grained and rippled	6.1
8. Covered	3.4
9. Siltstone; lower half is gray to dark green, horizontally laminated; upper part is sandy, interbedded with greenish gray, very fine grained, rippled sandstone..	12.8
10. Covered	4.3
11. Sandstone, white; erosional base; lower third is very coarse grained, conglomeratic, massive and crossbedded; upper part is medium grained, sparsley conglomeratic and planar crossbedded	12.8
12. Covered	4.3

13. Sandstone; erosional base; lower half is white to brown, medium grained, sparsley conglomeratic, predominantly crossbedded; upper part is light green, medium grained at base and coarse grained at top with some pebbles, crossbedded in lower portion and massive bedded at top 17.9

14. Covered 59.1

Along east side of gap, near south end of Louisville and Nashville tunnel.

15. Sandstone; lower two thirds are greenish gray, fine to very fine grained, micaceous, and crossbedded; upper part is gray, fine grained, micaceous, horizontally laminated and contains plant impressions 8.8

16. Coal 0.8

Lee Formation

17. Sandstone, light green to white; medium grained; basal conglomerates consist of clay pebbles and plant impressions in massive bedded units; remainder of unit is crossbedded 20.1

18. Shale; silty; lower half is light to dark gray, interbedded with fine grained, gray rippled sandstones; thicker shale intervals contain ironstone concretions; upper part is dark gray, horizontally laminated and contains a 1.4 meter coal and underclay 12.8

19. Sandstone, reddish orange to light gray; lower part is medium grained, massive bedded, has erosional base with basal conglomerate of clay pebbles; upper part is fine to very fine grained, partly brown, and rippled 10.4

20. Covered 15.5

Along west side of gap, in Louisville and Nashville cuts, starting at trestle over river.

21. Sandstone, red to pink to orange; coarse grained; sparsley pebbliferous with some massive bedded conglomeratic units; predominantly crossbedded 14.0

22. Covered 36.6

23. Sandstone, gray to pale orange; erosional base; lower part is coarse grained, conglomeratic, massive or crossbedded; upper part is medium grained and crossbedded 23.1

24. Shale, dark gray; slightly silty; contains ironstone concretions 2.1

25. Sandstone, gray to brown; medium grained; speckled (?) due to weathering of opaques; partly micaceous; thinly ripple bedded 10.7

Along west side of gap in new railroad cut.

26. Sandstone, orange to tan; medium grained; crossbedded in lower part; upper part is light gray, very fine grained, micaceous and rippled or horizontally laminated 7.6

27. Siltstone, light to dark gray; micaceous; slightly sandy; rippled 3.9

28. Sandstone, light orange to tan, medium grained; erosional base; crossbedded 2.3

29. Siltstone, dark gray; slightly micaceous, horizontally laminated; contains ironstone concretions and plant fossils 2.2

30. Shale, dark gray; slightly silty; fissle; scattered rippled units 9.1

31. Sandstone, light gray; medium grained; predominantly crossbedded; contains opaque mineral laminations; some zones are massive bedded 42.1

32. Covered 92.0

33. Sandstone, light gray; very fine grained; horizontally laminated with scattered massive beds 12.5

34. Shale; silty; lower third is dark gray and interbedded with thinly ripple bedded dark gray siltstone; upper part is horizontally laminated 15.2

Bee Rock Sandstone Member

35. Sandstone; lower part is tan to gray, fine grained, crossbedded; upper part is white or tan, medium grained, micaceous in part, predominantly crossbedded 28.9

711.3

APPENDIX 3

FIELD AND LABORATORY METHODS AND PROCEDURES

To facilitate the comparison of my data with that of other workers, a brief description of data aquisition and sample preparation for construction of vertical profiles, sieve analysis, thinsection petrography, heavy mineral preparation and x-ray analysis of clays is given below.

Vertical profiles through sandstones were made at field stations every 6 to 10 kilometers along Pine and Cumberland Mountains. Bedding type, crossbed thickness, paleocurrent data and estimates of grainsize with grainsize comparator and handlense were observed and recorded through 2482 meters of sandstone. These data were supplemented by detailed profiles through and additional 675 meters at localities 14, 18, 19 and 25 (Fig. 5). Detailed profiles included measurement of bed thickness, bedding type, vertical variation of paleocurrent data and collection of samples for grainsize analysis with binocular microscope. Representative profiles are shown in Figures 14 to 20. Sandstones in the overlying Breathitt Group were observed at several locations within the overthrust sheet totaling 170 meters with one detailed profile constructed through a 15.1 meter sequence for comparison purposes.

Crossbedding directions of both planar and trough crossbeds were rotated using a steronet according to the method described by Potter and Pettijohn (1963, p. 260). A total of 1621 measurements were made at 72 sites. In the overlying Breathitt sandstones, 270 measurements were made at 27 sites. The vector mean, magnitude and variance were calculated for each sample site and for each sandstone type. Thicknesses were measured for 1417 crossbeds and the vector mean and variance were recalculated using the cube of the thickness as a weighting factor (Miall, 1974, p. 1180). As can be seen in Table 9, there is no significant difference between the weighted and unweighted values.

Unconsolidated samples of sandstone were collected at 10 locations, split into 100 gram samples and prepared for sieving (Folk, 1968, p. 17). Eighteen samples were sieved into quarter phi intervals and standard statistical grainsize parameters were calculated using data obtained from log-probability curves (Table 7).

One hundred and fifteen thinsections were prepared from sandstones collected at 16 localities and stained for feldspar (Friedman, 1971, p. 524). Thirty two were selected for detailed petrographic analysis which included 200 point counts for composition and measurement of 50 monocrystalline quartz grains long axes for estimating quartz grainsize (Griffiths, 1967, p. 64-66).

Samples collected from lower, middle and upper sandstones in the sedimentary sequence at eight localities were disagregated and the 125 to 250 micron fraction was separated by sieving. Heavy minerals were removed with bromoform using standard preparation procedures (Carver, 1971, p. 429-433).

Granules (2 to 4 mm.) were separated from the gravel fraction of conglomeratic sandstones at three localities, thinsectioned and classified as one of five types of quartz, sandstone or siltstone. Granules from Middle Carboniferous conglomeratic sandstones in the Northern Appalachian Basin (Elkins, Randolph Co., W. Va.) and the Illinois

Basin (Sweeden, Edmonson Co., Ky.) were prepared for comparison (Table 17).

Samples of shale were ultrasonically disaggregated and prepared by centrifuging for x-ray diffraction using the smear-on-glass technique of Gibbs (1971). Samples were analyzed on General Electric equipment with Cu Kα radiation at 2°/minute. Additional runs were made after the samples were subjected to glycolation and heating (Griffin, 1971). Crystallinity of illite was estimated using the method of Weaver (1960). Representative traces indicating the relative peak heights of kaolinite and illite are shown in Figures 16 and 21.

APPENDIX 4A

LISTING OF SPORE TAXA

Coal samples were collected at ten localities and sent to Dr. R. A. Peppers, Illinois Geological Survey, for spore analysis. Macerations made by Dr. Peppers were also sent to Dr. R. M. Kosanke, U. S. Geological Survey, Denver. The spore assemblages of seven of the samples are listed in this appendix. Assemblages and locations for the other three samples can be found in Table 5 and Fig. 28. None of the samples contain definitive Mississippian taxa such as TRIPARTITES and ROTOSPORA.

Maceration 2118

Tennessee, Campbell County, 1280 meters from west line and 5243 meters from north line, Jacksboro quadrangle. Coal is located at top of hill, along east side of access road to main quarry of the Silica Sand Company. Coal is 3 to 5 centimeters thick, contains a thin underclay, and is overlain by a conglomeratic, crossbedded, quartzose sandstone ranging in thickness from 5 to 8 meters.

AHRENSISPORITES GUERICKEI (Horst) Potonie and Kremp
CALAMOSPORA sp.
CAMPTOTRILETES sp.
DENSOSPORITES ANNULATUS (Loose) Smith and Butterworth
D. IRREGULARIS Hacquebard
D. cf. D. SINUOSUS Kosanke
D. SPHAEROTRIANGULARIS Kosanke
GRANULATISPORITES PRIDDYI (Berry) S. W. and B.
G. sp.
LYCOSPORA GRANULATA Kosanke
L. PSEUDOANNULATA Kosanke
RAISTRICKIA sp.
REINSCHOSPORA SPECIOSA (Loose) S. W. and B.
SCHULZOSPORA RARA Kosanke
SPENCERISPORITES RADIATUS (Ibrahim) Winslow

A preliminary generic count follows:

CAMPTOTRILETES	1 percent
CRISTATISPORITES	1
DENSOSPORITES	29
GRANULATISPORITES	9
LYCOSPORA	42
RAISTRICKIA	1
SCHULZOSPORA	16
Total	100 percent

Age: Pennsylvanian

Maceration 2194

Tennessee, Campbell County, 1067 meters from west line and 5486 meters from north line, Jacksboro quadrangle. Coal is located in ditch on northwest side of access orad into main quarry of Silica Sand Company. At the present time, this location is at the outside ditch of the first switch back. Coal is less than 2 centimeters thick and no developed underclay was observed. Coal is within a red and green siltstone and shale sequence.

Only CALAMOSPORA sp. could be identified from this sample. Several other taxa were observed but poor preservation prevented even generic assignment. Cuticle and fine opaque matter are present in modest abundance.

Age: Pennsylvanian

Maceration 2197-2198

2197 - Kentucky, Harlan County, 5486 meters from west line and 579 meters from south line, Bledsoe quadrangle. Coal is located at base of the Bee Rock Sandstone of the Lee Formation, on the west side of U. S. Highway 421 across from the road-side park. Coal ranges in thickness from 8 to 20 centimeters, and is associated with a thin underclay. Coal and underclay overlie a black to dark gray, silty shale, and are overlain by a sparsley conglomeratic, massive and crossbedded sandstone ranging in thickness from 15 to 20 meters.

2198 - Kentucky, Bell County, 5060 meters from west line and 549 meters from north line, Middlesboro North quadrangle. Coal is located at base of the Bee Rock Sandstone, along the west side of U. S. Highway 25E. Sample was taken at outcrop 250 meters south of U. S. Highway junction 25E and 119. Coal is approximately 18 centimeters thick with a poorly developed underclay. Coal overlies a dark gray, silty, rippled shale, and is disconformably overlain by a predominantly crossbedded, medium to fine grained sandstone. This sandstone is shown in Fig. 20-A and is described in Appendix 5 as Section 20-A.

Both macerations contain a great deal of semi-opaque to opaque matter and few spores. 2198 has more translucent matter but has fewer spores. Only LYCOSPORA and one specimen of APICULATISPORIS were observed.

Age: Pennsylvanian

Maceration 2199

Kentucky, Pulaski County, 2250 meters from west line and 1125 meters from north line, Burnside quadrangle. Coal is located on east side of U. S. Highway 27 at base of crossbedded sandstone. Coal is approximately 10 centimeters and is associated with an underclay ranging in thickness from 10 to 35 centimeters.

DENSOSPORITES ANNULATUS (Loose) Smith and Butterworth

D. cf. D. SINUOSUS Kosanke

D. cf. D. TENUIS (Loose) Potonie and Kremp

GRANULATISPORITES PALLIDUS Kosanke

G. cf. G. PRIDDYI (Berry) S. W. and B.

SCHULZOSPORA RARA Kosanke

Age: Pennsylvanian

MACERATION 2200

Kentucky, McCreary County, 3886 meters from west line and 2926 meters from north line, Barthell quadrangle. Coal is located on east side of Kentucky Highway 92, near base of sandstone on inside of curve. Coal is 15 centimeters thick and has a thin underclay.

DENSOSPORITES ANNULATUS (Loose) Smith and Butterworth

D. TRIANGULARIS Kosanke

DICTYOTRILETES cf. D. BIRETICULATUS (Ibrahim)

LYCOSPORA GRANULATA Kosanke

Age: Pennsylvanian

Maceration 2201

Kentucky, Laurel County, 4541 meters from west line and 945 meters from south line, Lily quadrangle. Coal is located on southeast side of U. S. Highway 25W at base of ripple bedded sandstone. Coal is 16 centimeters thick, is associated with a thin underclay, and overlies a light gray, silty, rippled shale with thinly interbedded, rippled, fine grained sandstone.

CRASSISPORA KOSANKEI (Potonie and Kremp)

DENSOPORITES cf. D. TENUIS (Loose) Potonie and Kremp

LAEVIGATOSPORITES DESMOINENSIS (Wilson and Coe)

L. OVALIS Kosanke

Age: Pennsylvanian

Maceration 2195-B

Tennessee, Campbell County, 45 meters from east line and 1550 meters from south line, Ivydell quadrangle. Located on east side of U. S. Highway 25W, north of Lafollette. Coal is 7 centimeters thick and has thin underclay. Coal is overlain by a medium to coarse grained, cross-bedded sandstone approximately 8 meters thick. Coal and underclay overlie a 10 meter thick sequence of thinly interbedded red and green siltstones and shales.

See Table 5 for complete taxa listing

Age: Pennsylvanian

Maceration 2095

Kentucky, Bell County, 3960 meters from west line and 2140 meters from south line, Frakes quadrangle. Located on east side of road on north-west side of Pine Mountain in Henry Bowlin Gap. See section description in Appendix 2 (Section 18). Coal is less than 5 centimeters thick and does not have a developed underclay. Coal overlies a thinly bedded, rippled gray siltstone (Unit 11, Section 18, Appendix 2, and is overlain by a medium to fine grained, rippled or laminated sandstone (Unit 12, Section 18, Appendix 2).

See Table 5 for complete taxa listing.

Age: Pennsylvanian

Maceration 2121

Virginia, Wise County, 640 meters from west line and 3660 meters from south line, Jenkens East quadrangle. Located at base of south wall of main quarry of Southwest Sand Co., Pound Gap, Virginia. Quarry is on east side of U. S. Highway 23, on woutheast side of Pine Mountain. Coal is less than 10 centimeters thick, and is associated with a thin underclay. Coal and underclay overlie a thin, gray, rippled siltstone, and are overlain by a conglomeratic massive and crossbedded, coarse grained quartzose sandstone.

See Table 5 for complete taxa listing.

Age: Pennsylvanian

APPENDIX 4B

LOCATION OF CONODONT SAMPLES

Samples of limestone and calcareous shale were collected at four localities and were dissolved in acid using standard techniques. Conodonts were picked from the residue and sent to Dr. C. B. Rexroad, Indiana Geological Survey, Bloomington, Indiana for identification. A listing of the fauna taxa is given in Table 4. Three of the samples are shown in stratigraphic sections with dated spore assemblages in Figure 28.

Henry Bowlin Gap, Whitley Co., Kentucky

Base of section shown in Fig. 28 is 3600 meters from west line and 2266 meters from south line, Frakes quadrangle, Whitley Co., Kentucky. Samples come from Unit 9, Section 18, Appendix 2.

Age: Chesterian

Big Stone Gap, Wise Co., Virginia

Sample location is along east side of Southern Railway, north of limestone quarry and 47.6 meters north from railroad tunnel. Sample comes from Unit 5, Section 31, Appendix 2.

Age: Chesterian

I-75, Jellico, Campbell Co., Tennessee

Sample location is 2446 meters from west line and 4892 meters from south line, Jellico West quadrangle, Campbell Co., Tennessee. Sample comes from Unit 1, Section 14, Appendix 5.

Age: Chesterian

Pound Gap, Wise Co., Virginia

Base of section shown in Fig. 28 is 63 meters from east line and 4373 meters from south line, Jenkins West quadrangle, Wise Co., Virginia. Sample location is 61 meters from east line and 4416 meters from south line in ditch along north side of dirt road, Jenkins West quadrangle, Wise Co., Virginia.

Age: Chesterian

LaFollette, Campbell Co., Tennessee

Section shown in Fig. 28 is composit through Big Creek Gap, Campbell Co., Tennessee. Base of section is 44 meters from east line and 1530 meters from south line, Ivydell quadrangle, Campbell Co., Tennessee.

Age: Chesterian

APPENDIX 5

VERTICAL PROFILES THROUGH PENNINGTON AND LEE SANDSTONES

This portion of the Appendix contains the sandstone descriptions associated with the vertical profiles shown in Figures 14 to 20. The section number corresponds with the figure number in the text.

Section 15A Highway 421, Harlan, Kentucky

Section measured from top of hill at Little Shepard Trail turnoff (BM 2641), north through road cut. Top of section is 5334 meters from west line and 2667 meters from south line, Bledsoe quadrangle, Harlan Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent and Paul Edwin Potter, March 1, 1975.

Pennington Formation:	Meters
12. Covered	3.0+
11. Sandstone, light tan to white, medium grained; massive bedded	1.5
10. Sandstone, pink to light gray, fine grained; rippled with thin crossbeds containing clay pebbles; some interbedded thin siltstones and gray shale	11.0
9. Sandstone, light gray, medium to fine grained; massive bedded with clay pebbles	2.4
8. Sandstone, light tan to gray, fine to very fine grained; horizontally bedded in upper part with ball-and-pillow structure; lower part is horizontally bedded with a few scattered ripples and low angle crossbeds	6.1
7. Sandstone, white, medium grained, friable, massive bedded in units 8 to 25 cm; burrowed in upper part	5.8
6. Sandstone, white to tan, fine to very fine grained; crossbedded with scattered rippled units	6.1
5. Siltstone, light gray; rippled with thin interbeds of gray shale	0.9

Section 15A (Continued)

		Meters
4.	Sandstone, tan, medium grained; massive bedded with scattered crossbeds; erosional base	2.1
3.	Siltstone, light gray to dark green; flaser bedded and rippled with 50 percent interbedded gray shale; loadcasts abundant; 2.0 meters near center contains scattered massive beds of fine grained sand with clay pebbles, 10 percent interbedded gray shale	7.6
2.	Sandstone, light gray, fine grained; massive bedded	0.9
1.	Siltstone, light gray; flaser bedded and rippled with 50 percent interbedded gray shale	2.5+
	Total	46.9

Section 15B Henry Bowlin Gap, Whitley Co., Kentucky

Section measured on east side of road cut through crest of Pine Mountain. Base of section if 3901 meters from west line and 2286 meters from south line, Frakes quadrangle, Whitley Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent and M. Loudin, February 15, 1975.

Penning Formation:	Meters
7. Covered	4.0+
6. Sandstone, red to tan, medium to fine grained; micaceous and quartzose in part; crossbedded with scattered ripple beds near top and lower quarter of unit; clay pebbles in crossbedded units	7.0
5. Siltstone, dark gray; rippled with 50 percent interbedded gray shale; scattered thinly ripple bedded very fine sand	3.1
4. Sandstone, white to red, coarse to fine grained; micaceous with local concentrations of heavy minerals; rippled near top, some horizontal bedding near center; clay pebbles and quartz granules in massive beds in lower part	12.9
3. Shale, light gray, laminated; scattered thinly ripple bedded gray siltstone	0.5
2. Sandstone, red to light gray, medium to fine grained; micaceous and quartzose with heavy mineral concentrations; mostly crossbedded with some horizontal bedding near top; massive bedded sand near base contains abundant matris, sharp basal contact with underlying shale	8.2
1. Shale, dark gray to black, laminated	1.2+
Total	32.9

Section 14 - Highway I-75, Jellico, Tennessee

Section measured up northwest face of road cut. Base of section is 2446 meters from west line and 4892 meters from south line, Jellico West quadrangle, Campbell Co., Tenn. Measured using Jacob staff and tape by W. O. BeMent, R. Elias and Ho-shing Yu, May 17 and July 1, 1975.

Pinnacle Overlook Member of the Lee Formation	Meters
11. Siltstone, gray; rippled with thin interbeds of gray shale	1.0+
10. Shale, gray; oxidized and iron stained; bleached white in upper part	2.0
9. Sandstone, tan to light gray, fine grained; upper part rippled and flaser bedded with thinly cross-bedded clay pebble units; lower part is rippled and horizontally bedded with sdattered clay pebbles	6.0
8. Shale, dark gray to black; uniform and horizontally laminated with thin siltstone interbeds; siltstones show ball-and-pillow structures; scattered ironstone concretions	20.5
7. Sandstone, tan, fine grained; massive or crossbedded in units from 20 to 60 cm. in thickness	2.0
6. Shale, yellow in upper third with thin gray siltstone interbeds; lower two thirds is gray with scattered ironstone concretions; thin beds of burrowed siltstone or fine grained, rippled sand with clay pebbles also present	13.0
5. Sandstone, upper 3.5 meters is thin ripple bedded, fine to very fine grained with clay drapes; next 2.5 meters—thinly crossbedded with clay pebbles and interbedded gray shale and siltstone; lower 5.0 meters are gray, fine to medium grained, rippled or crossbedded with clay pebbles, heavy mineral concentrations and burrows	11.0
4. Shale, gray, laminated with thin interbedded gray siltstones showing ball-and-pillow structure; scattered beds of very fine grained, light gray sandstone with clay pebbles	2.2
3. Sandstone, upper 5.5 meters are yellow, fine grained, crossbedded with clay pebbles and scattered concentrations of heavy minerals; next 10.0 meters are	

		Meters
	white to yellow, fine to medium grained, massive or crossbedded; lowest 7.7 meters are medium to coarse grained, pebbly, massive or crossbedded with scattered horizontal bedding, erosional base	23.2
2.	Shale, brown to dark gray with finely disseminated pyrite	1.2
1.	Shale, dark gray with thin calcareous packstone interbeds of fossil hash; thinly bedded, rippled fine grained sandstone lenses in lower part	7.1
	Total	89.2

Section 17 Henry Bowlin Gap, Bell Co., Kentucky

Section measured on east side of road, just below crest of Pine Mountain on south side of hill. Base of section is 3962 meters from west line and 2225 meters from south line, Frakes quadrangle, Bell Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent and M. Loudin, February 15, 1975.

	Meters
Lee Formation:	
5. Covered	0.5+
4. Sandstone, red to light pink; fine grained, micaceous in part; upper part is trough crossbedded; lower part is thinly ripple bedded with transitional base	2.1
3. Covered, probably shale or siltstone	0.6
2. Sandstone, upper third is light pink to light gray, micaceous in part, predominantly trough cross-bedded with some scattered ripple beds near the top; lower two thirds are orange to light gray, coarse to medium grained, slightly pebbliferous with lenses of quartz pebbles, crossbedded with thicknesses ranging from 20 to 200 centimeters; erosional base	9.1
1. Shale, light gray, silty, predominantly laminated with scattered rippled units	0.1+
Total	12.4

Section 18 Highway 25 E, Pineville, Bell Co., Ky.

Section measured along west side of road. Base of section is 5029 meters from west line and 61 meters from north line, Middlesboro North quadrangle, Bell Co., Kentucky. Measured by W. O. BeMent with Jacob staff and tape, March 9, 1975.

		Meters
Lee Formation:		
6.	Shale, slightly silty in part; gray; laminated	0.1
5.	Sandstone, white to light gray, micaceous in part; lower third is fine grained with clay pebble conglomerate along scoured base, massive and crossbedded; upper two thirds are white to light gray, fine to very fine grained, predominantly trough crossbedded with scattered ripple beds, plane bedded near top	9.8
4.	Sandstone, white; silty with thin shaley zones; fine to very fine grained; ripples	2.4
3.	Angular disconformity	.1
2.	Sandstone, white to light gray; medium to fine grained; alternating units of crossbedding and horizontal lamination, some scattered rippled zones	5.1
1.	Shale, black; silty; contains thin beds of very fine grained rippled sandstone, scattered ironstone concretions	1.0+
	Total	18.5

Section 19A Henry Bowlin Gap, Bell Co., Kentucky

Section measured along east side of road. Base of section is 4100 meters from west line and 1676 meters from south line, Frakes quadrangle, Bell Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent and M. Loudin, February 15, 1975.

		Meters
Lee Formation:		
7.	Siltstone, shaley, gray to black; horizontally laminated, partly covered	1.0
6.	Sandstone, pink to light gray; fine to medium grained; composed of three massive bedded units separated by crossbedded units; lowest crossbedded unit contains quartz pebbles	14.1
5.	Sandstone, pink; fine to medium grained; predominantly crossbedded with scattered horizontally bedding	2.4
4.	Sandstone, pink; medium grained; pebbly; massive bedded	2.1
3.	Sandstone, pink; fine to medium grained; horizontally laminated	0.3
2.	Sandstone, pink; coarse to medium grained; pebbly; erosional base	1.3
1.	Shale, silty; gray to dark green; thin coal and underclay	1.0+
	Total	22.2

Section 19B Henry Bowlin Gap, Whitley Co., Kentucky

Section measured on north side of road. Base of section is 4008 meters from west line and 1768 meters from south line, Frakes quadrangle, Whitley Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent and M. Loudin, February 15, 1975.

	Meters
Lee Formation:	
7. Covered	1.0+
6. Siltstone, light gray, thin bedded, rippled and horizontally laminated	0.3
5. Sandstone, red; fine to medium grained; composed of two massive bedded units with disconformable bases separating crossbedded units	3.5
4. Sandstone, red to light gray; micaceous in part; fine to medium grained; predominantly crossbedded with some massive bedded units near center	7.9
3. Sandstone, white to light gray; very fine grained; horizontally laminated	0.5
2. Sandstone, mostly red but light gray in lower .5 meter; medium to fine grained; crossbedded; erosional base .	3.5
1. Shale, dark gray to black, laminated partly covered	1.2
Total	17.9

Section 20A Highway 25 E, Pineville, Bell Co., ky

Section measured along west side of road, south of intersection of Highways 25E and 119. Base of section is 5060 meters from west line and 305 meters from north line, Middlesboro North quadrangle, Bell Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent, February 2, 1975.

	Meters
Lee Formation:	
9. Shale, silty, light gray, laminated	1.0
8. Sandstone, tan; silty, rippled; interbedded with thin beds of gray rippled siltstone	2.3
7. Sandstone, white to tan; medium to fine grained; cross-bedded; sandbody may be divided into three wedge shaped units ranging in thickness from 1.5 to 4.6 meters; crossbed thicknesses range from 15 to 160 centimeters	23.2
6. Siltstone, slightly sandy; dark gray; rippled with some scattered horizontal lamination	8.1
5. Sandstone, tan; fine grained; crossbedded	1.3
4. Siltstone, dark gray; rippled; contains thin underclay and coal 25 to 75 centimeters thick (Tunnel Coal) ..	3.1
3. Sandstone, white; medium to fine grained; predominantly planar crossbeddedl reactivation surfaces common; micaceous in part; contains scattered laminations of coaly material	11.2
2. Sandstone, white to light gray, light pink in part; medium grained; massive bedded; contains heavy mineral laminations and concentrations of coaly material	5.2
1. Shale, dark gray to black; interbedded with thinly bedded, light gray to green, rippled siltstones	1.0+
Total	56.4

Section 20B Henry Bowlin Gap, Bell Co., Kentucky

Section measured along east side of road along inside of curve. Base of section is 4054 meters from west line and 1372 meters from south line, Frakes quadrangle, Bell Co., Kentucky. Measured with Jacob staff and tape by W. O. BeMent and M. Loudin, February 16, 1975.

		Meters
Lee Formation:		
6.	Covered	0.5+
5.	Sandstone, white to tan; fine grained crossbedded with scattered massive beds; clay pebbles of dark gray shale near base	1.1
4.	Sandstone, white to pink; medium to fine grained; predominantly planar crossbedded; reactivation surfaces and wedging of units are common with scattered overturned crossbeds; contains scattered units which are horizontally bedded; micaceous in part with laminations of opaque minerals and coaly material ..	33.0
3.	Sandstone, pink; coarse to medium grained; conglomeratic; upper part contains scattered pebbles and is crossbedded; lower part is massive bedded with pebbles arranged in bands, fragments of coaly material near top	5.5
2.	Sandstone, pink to light gray; medium grained; sparsely pebbliferous; crossbedded, erosional base	2.1
1.	Shale, silty; light gray; predominantly horizontally laminated with scattered rippled units	1.0+
	Total	43.2

APPENDIX 6

This section of the Appendix contains the locations of the sandstone outcrops used for the paleohydraulic calculations listed in Tables 16A and 16B.

2-75-B

Outcrop is 3559 meters from west line and 1963 meters from south line, Frakes quadrangle, Bell Co., Kentucky. Outcrop is located on east side of road through Henry Bowlin Gap, approximately 182 meters southwest of where power line crosses road. This sandstone is described in Section 18, Appendix 2, Units 20 to 24.

3-93-1

Outcrop is 3000 meters from east line and 4150 meters from south line, Norton quadrangle, Wise Co., Virginia. Outcrop is located on southwest side of Virginia Highway 610, approximately 3.1 kilometers south of the intersection of Virginia Highway 610 and U. S. Highway 23.

3-71-1

Outcrop is 5697 meters from west line and 716 meters from north line, Benham quadrangle, Harlan Co., Kentucky. Outcrop is located along east side of creek, approximately 378 meters north of U. S. Highway 119. Creek crosses Highway 119 at Blair, Harlan Co., Kentucky.

3-74-1

Outcrop is 3026 meters from east line and 1368 meters from south line, Roxana quadrangle, Letcher Co., Kentucky. Outcrop is along west side of Win Branch Creek, approximately 917 meters north of U. S. Highway 119.

3-52-1

Outcrop is 606 meters from east line and 3154 meters from south line, Bledsoe quadrangle, Harlan Co., Kentucky. Outcrop is on east side of creek, approximately 520 meters north of U. S. Highway 119, at Rhea, Kentucky.