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**The sedimentology of the Corbin Sandstone Member, Lee
Formation, eastern Kentucky, and a comparison to age
equivalent rocks of the Illinois Basin, southwestern Indiana**

Barnhill, Mark Leonard, Ph.D.

University of Cincinnati, 1994

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THE SEDIMENTOLOGY OF THE CORBIN SANDSTONE MEMBER, LEE
FORMATION, EASTERN KENTUCKY, AND A COMPARISON TO AGE
EQUIVALENT ROCKS OF THE ILLINOIS BASIN, SOUTHWESTERN INDIANA

A dissertation submitted to the
Division of Research and Advanced Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in the Department of Geological Sciences
of the College of Arts and Sciences

1994

by

Mark L. Barnhill

B.S., Wright State University, 1979

M.S., Tulsa University, 1984

Committee Chair: Dr. Wayne A. Pryor

UNIVERSITY OF CINCINNATI

November 19 **19** 93

I hereby recommend that the thesis prepared under my supervision by Mark L. Barnhill
entitled The Sedimentology of the Corbin Sandstone Member, Lee Formation, Eastern Kentucky, and a Comparison to Age Equivalent Rocks of the Illinois Basin, Southwestern Indiana
be accepted as fulfilling this part of the requirements for the degree of Doctor of Philosophy

Approved by:

Wayne A. Pyper
J. B. Maguire
Warren H. H. H.

ABSTRACT

A geologic study of the Lee Formation (Corbin Sandstone Member) of the central Appalachian Basin and the Mansfield Formation of the eastern Illinois Basin was undertaken. Both units are Pennsylvanian (Morrowan/Atokan) in age. The Lee Formation has been variously interpreted as a barrier island, fluvial, or tidal deposit; no consensus presently exists regarding its origin. For decades, the Mansfield Formation was considered predominantly nonmarine, but the recent discovery of abundant tidal rhythmites within the unit has called this interpretation into question.

The objectives of this study were fourfold: 1) to determine the origin of the Lee Formation (Corbin Sandstone Member), 2) to determine the influence of intrabasinal tectonics on deposition of the Corbin Sandstone Member, 3) to reexamine the origin of the Mansfield Formation, and 4) to offer a comparison of the Lee and the Mansfield Formations.

The Corbin Sandstone consists, predominantly, of medium grained sandstone composed of planar and trough/tangential crossbedding. Together, they comprise almost 75 percent of the unit. Planar crossbed sets range from 7 cm to 2.3 m thick and persist laterally up to 100 m. Simple and compound, planar-tabular and planar-wedge shaped sets are observed. Planar crossbedding is interpreted as transverse bars that were deposited in a low-sinuosity or braided

river. Outcrops may contain superimposed transverse bar deposits more than 30 m thick.

Trough/tangential crossbed sets range from 7 cm to 1.8 m thick and persist laterally up to 30 m. Trough/tangential crossbedding is primarily associated with braided river channel-fill deposition. A fourfold hierarchy of braid-channels is observed: 1) A first order channel consisting of an alluvial-braidplain up to 60 km wide, 2) second order channels active during low-flow, the margins of which are observable at outcrop scale, 3) third order channels that were inactive during low-flow, easily observable at outcrop scale, and which scoured the flanks of transverse bars, and 4) fourth order channels that were inactive during low-flow, and which scoured the tops of transverse bars. Outcrops may contain multistory channel-fill successions more than 40 m thick.

A marine, tidal component caps the vertical succession in some outcrops. Tidal indicators include lenticular-bedded shale, wavy-bedded sandstone, flaser-bedded sandstone, rhythmic-bedded sandstone and medium-scale trough/tangential crossbedding containing tidal-bundles. The trace fossil Cochlichnus is the only identifiable trace fossil found in the Corbin Sandstone and was observed in the tidal facies only. No body fossils were observed in the Corbin Sandstone.

Paleocurrent rose diagrams support the depositional

interpretations. Facies interpreted as braided-fluvial show a unimodal paleocurrent pattern, whereas facies interpreted as tidal show a trimodal paleocurrent pattern. Southwest-directed paleocurrent data suggest a northeastern source for the Corbin Sandstone. Quartz pebble sizes decrease to the south-southwest supporting a northeastern source.

Coal palynology indicates that the Corbin Sandstone is early middle Morrowan in age, deposited in a rainy tropical climate.

Isopach mapping demonstrates that intrabasinal tectonic elements influenced basin evolution by controlling sediment thickness patterns, paleodispersal trends, and paleocurrent directions within the Corbin Sandstone. The documentation of faults and uplifts controlling paleodispersal trends and paleocurrent directions provides additional support for a fluvial interpretation.

Subsurface stratigraphic correlations suggest that the Irvine-Paint Creek Fault and Kentucky River Fault System further influenced basin evolution by acting as a hinge line separating a stable platform to the north from an actively subsiding basin to the south.

Examination of more than 500 gamma-ray well-logs through the Corbin Sandstone reveals that gamma-ray profiles are either blocky or upward-fining. Blocky profiles are interpreted as multistory transverse bar and third order channel-fill successions. Upward-fining profiles are

interpreted as single or multistory second order and third order channel-fill successions. The tidal facies is also recognizable (tidal mixed flats are recognized by their "spiky" gamma-ray log-response).

The Mansfield Formation within the study area in southwestern Indiana is composed of tide-dominated rocks deposited in two major depositional environments: a transgressional, tide-dominated estuarine-fill environment, and a regressional tide-influenced deltaic environment which overlies it. Separating the two is a regionally-correlatable, transgressive marine shale. Estuarine-fill successions are dominated by dark gray shale (with rare spiriferid brachiopods), lenticular-bedded shale, wavy-bedded sandstone, and rhythmic-bedded siltstone showing well-developed neap-spring-neap cyclicity. The estuarine-fill successions are capped by outer-estuarine sandy shoal deposits containing marine trace fossils. These deposits migrated landward and became centered over the interfluvial highs.

Tide-influenced deltaic deposits are lithostratigraphically complex. They are dominated by lenticular-bedded shale, wavy-bedded and flaser-bedded sandstone, crossbedded sandstone, ripple-bedded sandstone, and abundant, discontinuous coal-beds with rooted underclays. Subenvironments include subtidal to intertidal sandflats, mixed flats, and mudflats, tidal sand ridges,

fluvial distributary channels, tidal-fluvial point bars, intertidal to supratidal swamps, and supratidal coal-forming peat-swamps. The tide-dominated nature of the Mansfield Formation indicates that tides could be an important depositional process in ancient, shallow epicontinental seas.

Comparison of the Lee and the Mansfield Formations reveals significant differences. The Mansfield Formation is dominated by fine-grained deposits of predominantly tidal origin, whereas the Lee Formation is dominated by coarser grained deposits of predominantly fluvial origin. Generally speaking, the central Appalachian Basin was dominated by fluvial and fluvial-deltaic processes, whereas the eastern Illinois Basin was dominated by tidal processes during Morrowan/Atokan time. This suggests that tectonic setting influenced sedimentation during early Pennsylvanian time.

When rocks of the Lee and associated Breathitt Formation are compared to the Mansfield Formation as a whole, some similarities emerge. Mansfield rocks outside the study area contain local, braided river deposits similar to deposits of the Lee Formation. In addition, fine grained rocks of the Breathitt Formation contain tidal deposits consisting of small-scale tidal rhythmites similar to those observed in the Mansfield Formation.

The data gathered in this study suggest that the Illinois Basin and the central Appalachian Basin were

largely separated during Morrowan/Atokan time; the Cincinnati Arch was emergent and acted as a barrier. A partial linkage between the two basins is suggested by the presence of braided-river deposits in the Mansfield Formation that contain quartz pebbles, occupy northeast to southwest oriented paleovalleys, and have southwest-directed paleocurrent directions.

Correctly interpreting the depositional environment of the Lee Formation has resulted in a better understanding of the physical processes operating in the central Appalachian Basin during Morrowan/Atokan time. It has also provided an independent field check for numerical models that suggest an emergent northern source area during that time. Determining the influence of intrabasinal tectonics on sedimentation of the Corbin Sandstone has provided insight about the evolution of the central Appalachian Basin. This information may be useful in developing models for fossil fuel and groundwater exploration.

Reexamination of the Mansfield Formation has resulted in a better understanding of the significance of tides in shallow epicontinental seas. A comparison of the Lee and the Mansfield Formations has provided insight into whether the Cincinnati Arch was emergent or submergent during Morrowan/Atokan time, and the role of tectonic setting in controlling deposition.

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INTRODUCTION

General Statement

This research concerns the Corbin Sandstone Member of the Lee Formation of eastern Kentucky and the Mansfield Formation of southwestern Indiana (Fig. 1.1). These two units are Pennsylvanian (Morrowan/Atokan) in age and are dominated by detrital sediments.

The Lee Formation of eastern Kentucky consists of four major northeast to southwest trending sandstone belts that are stacked en-echelon, with the oldest to the east and the youngest to the west (Rice and Weir, 1984; Chesnut, 1988). These compositionally mature sandstone bodies are sheet-like in their geometry (Rice, 1984; Horne et al., 1974; Englund, 1964). They have relatively large sedimentary structures, almost always contain quartz pebbles, and, where well-cemented, tend to form steep escarpments (Rice, 1984; Fenn et al., 1971; Englund, 1964). Furthermore, the Lee Formation sandstones are commonly separated by shales assigned to the partially time-equivalent Breathitt Formation. The Corbin Sandstone is the youngest of the major sandstone members of the Lee Formation (table one).

The Mansfield Formation of southwestern Indiana consists, predominantly, of interbedded sandstone, siltstone, and shale with abundant, discontinuous coal beds and associated underclays (Weller, 1930). Furthermore, the

Fig. 1.1

Map showing the location of some of the large-scale structural features of the Appalachian and eastern mid-continent areas.

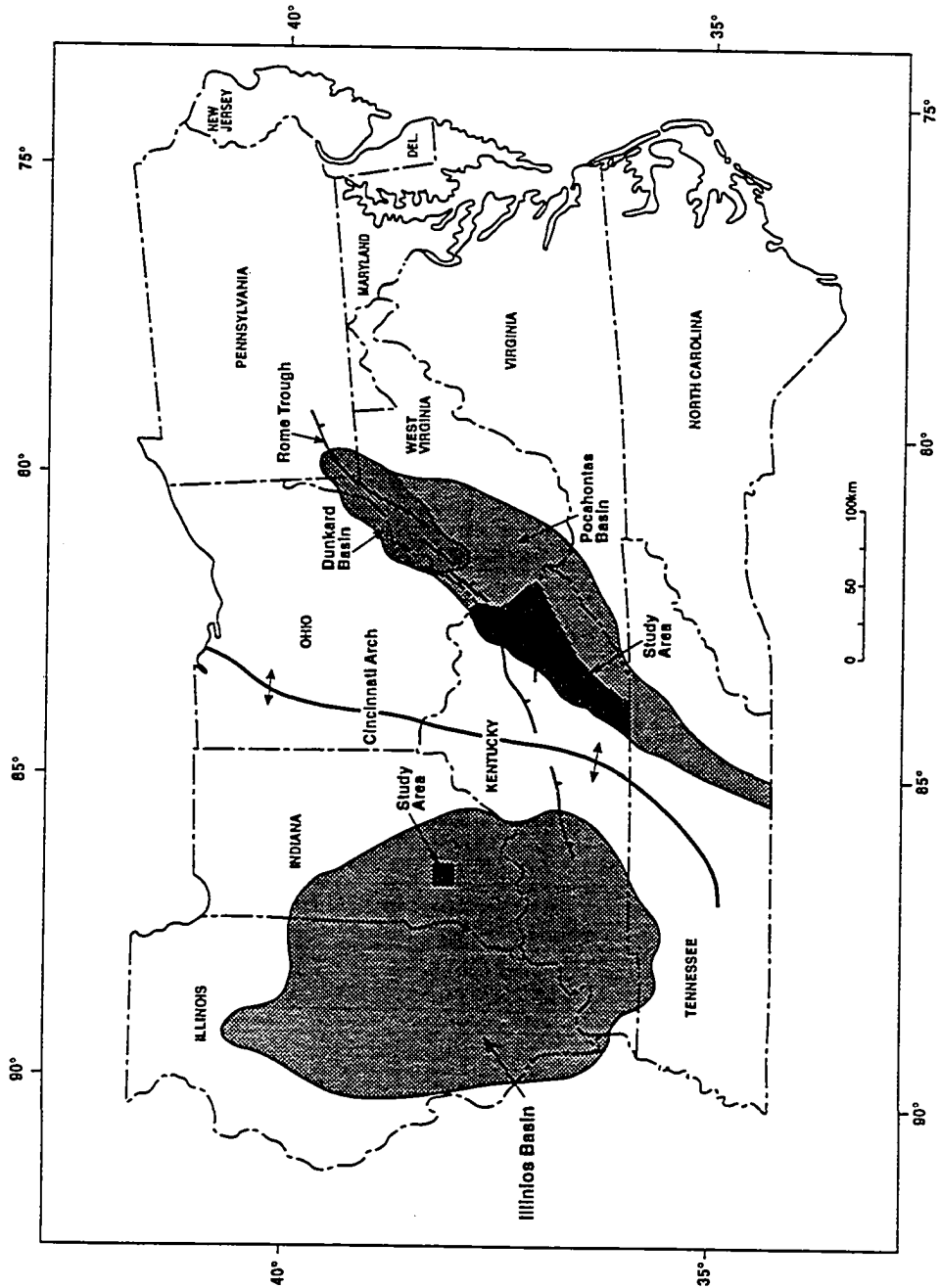
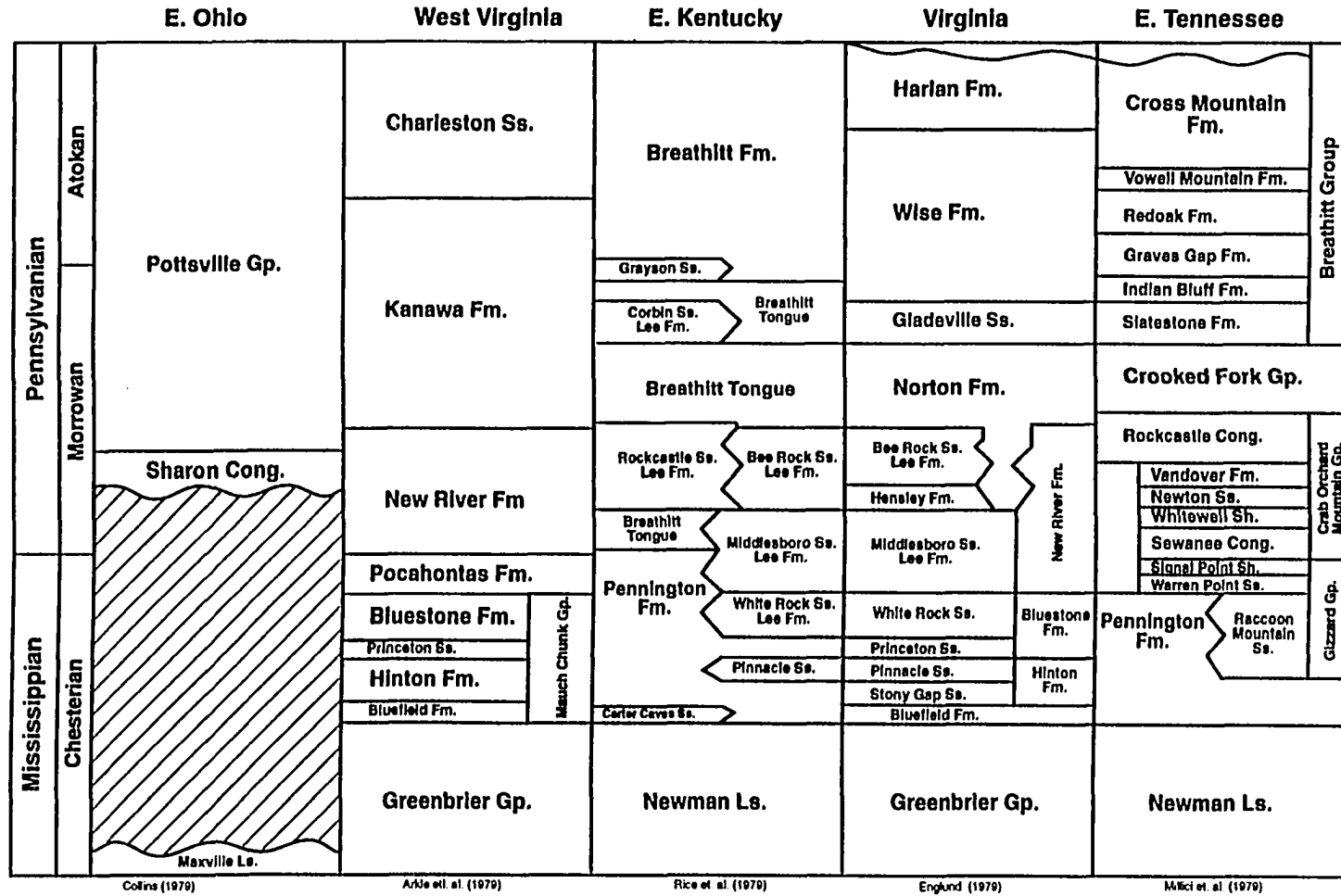


Table 1. Regional stratigraphic correlation chart for the central Appalachian Basin.



Mansfield Formation rests directly on Mississippian age rocks where it fills incised valleys, up to 250 feet or more deep, with both shale-dominated and sandstone-dominated successions (Furer, Indiana Geol.Surv. pers. comm., 1993; Barnhill, 1992; Fishbaugh et al., 1989). In the study area, the Mansfield Formation ranges from 0 to 300 feet thick and contains both incised valley-fill deposits and rocks deposited outside of valley-wall confinement.

The Lee and the Mansfield Formations are both controversial. In the case of the Lee Formation the problem involves disagreement, beginning in the early 1970's, regarding its depositional environment. This controversy began shortly after publication of the Lee-Newman Barrier Shoreline Model (Ferm et al., 1971), which presented a simple but comprehensive explanation for late Mississippian to middle Pennsylvanian sedimentation in the central Appalachian Basin. This model contained two contentious elements, the second of which concerns this research: 1) it assumed that no major unconformity exists between the Mississippian and Pennsylvanian Systems in the central Appalachian Basin, and 2) it presented the Lee Formation Members as deposits of barrier island origin, sharing a common, eastern, Appalachian source with intertonguing units of the Breathitt Formation.

The environmental interpretation of the Lee Formation presented in the Ferm et al., 1971 paper was questioned when

additional outcrop examination revealed incompatibilities with the model. For example, the predominantly southwest-directed paleocurrent directions observed in the Lee Formation suggested a northeastern source rather than the eastern, Appalachian source suggested by Ferm et al. (1971). Furthermore, the presence of autochthonous coals directly beneath some Lee Formation sandstones is inconsistent with a model which assumes a depositional continuum from offshore marine deposits of the Newman and Pennington Formations to marginal marine barrier island deposits of the Lee Formation.

Researchers have offered alternate interpretations of the Lee Formation since the Lee-Newman Barrier Shoreline Model was first proposed. Included are fluvial interpretations (e.g., Bement, 1976; Hester and Taylor, 1981; Chesnut, 1988), as well as a tidal interpretations (e.g., Englund and Thomas, 1990). Presently, there is no consensus regarding the origin of the Lee Formation. A comprehensive review of the literature on the Lee Formation is offered in chapter two.

The controversy involving the origin of the Mansfield Formation is a more recent one. Since the time of Weller (1930), the presence of abundant coal beds and rooted horizons, combined with the absence of body fossils and the paucity of trace fossils, have suggested a predominantly nonmarine origin for the Mansfield Formation. More

recently, however, Kvale et al. (1989), and Archer and Kvale (1989), have documented the presence of tidal deposits within the Mansfield Formation showing daily, monthly, and seasonal tidal periodicities. Moreover, these deposits appear to be common. As a result of this discovery, a reevaluation of the nonmarine origin for the Mansfield Formation is called for.

One of the difficulties in studying the Mansfield Formation is the lack of good outcrop exposures. The Mansfield Formation is dominated by fine-grained rocks and is a common slope-former in southwestern Indiana. Outcrops are scarce, usually covered with vegetation, and of poor quality. Recently, however, more than 5,000 feet of Mansfield Formation core, from 63 coreholes taken at the Naval Surface Warfare Center located at Crane, Indiana, has been made available for study. These cores represent an unprecedented database with which to reexamine the origin of the Mansfield Formation.

Objectives

The objectives of this study are a direct result of the problems concerning the origins of the Lee and Mansfield Formations outlined above. These objectives are: 1) to determine the depositional environment(s) of the Corbin Sandstone Member of eastern Kentucky in order to resolve the

historical controversy regarding the origin of the Lee Formation; 2) to determine what influence preexisting intrabasinal tectonic elements exerted on Corbin Sandstone deposition in the central Appalachian Basin; 3) to reexamine the origin of the Mansfield Formation of southwestern Indiana; and 4) to compare the Lee and Mansfield Formations in light of the data gathered in this study.

The primary objective of this study is to determine the depositional environment of the Corbin Sandstone. Since the publication of the Lee-Newman Barrier Shoreline Model (Ferm et al., 1971), many researchers have examined the Lee Formation or age equivalent rocks in the central and southern Appalachian Basin (e.g., Horne et al., 1974; Hobday, 1974; Hobday and Horne, 1979; Miller 1974; Bement, 1976; Millici, 1979; Carlson, 1979; Hester and Taylor, 1981; Rice, 1985; Chesnut, 1988; Wnuk and Mayberry, 1990; Wizevich, 1992). The interest in these sandstones persists because their correct interpretation has significant sedimentological implications, as well as extrabasinal tectonic implications.

In Kentucky alone, for example, there are four major Lee Formation sandstones that can be correlated across the width of the state, covering thousands of square kilometers in outcrop and in the subsurface (Rice and Weir, 1984; Chesnut, 1988). Therefore, they represent a significant stratigraphic component of the Morrowan/Atokan section in

the central Appalachian Basin. Correctly interpreting their origin provides insight into the physical processes that dominated sedimentation during Morrowan/Atokan time.

The correct interpretation of the Lee Formation may have extrabasinal tectonic implications as well. According to the numerical models of Beaumont et al., (1988), the area north of the central Appalachian Basin (including northern Ohio, western Pennsylvania, and New York State), was emergent, and a source of detrital sediments into the central Appalachian Basin during Morrowan/Atokan time. Field data from the Corbin Sandstone may provide an independent source of support or disconfirmation for the numerical models of Beaumont et al. (1988).

The second objective of this study is to determine what affect, if any, preexisting intrabasinal tectonic elements had on paleodispersal trends, sediment thickness patterns, and paleocurrent directions within the Corbin Sandstone Member. On the Appalachian Plateau of eastern Kentucky, several large uplifts and faults are present that predate the Corbin Sandstone, possibly influencing its depositional history. Since, the Lee Sandstones are sheet sandstones (Rice, 1984), the effects of preexisting structures on their depositional history can be determined relatively easily by constructing isopach maps of the individual members. Thickness values taken from subsurface well-logs and from 7.5 minute geologic quadrangle maps can accomplish this.

Determining the influence of preexisting structures on Corbin Sandstone deposition may provide valuable insight into the role intrabasinal tectonic elements play in basin evolution. Moreover, determining the degree to which preexisting structural features influence the geometry and thickness patterns of sandstone bodies has important applications in the search for fossil fuels, and groundwater. For example, if ancient lineaments such as the Kentucky River and Irvine-Paint Creek Faults Systems influence the geometry and thickness of large sandstone bodies, then delineating these structural features is critical to locating potential reservoir/aquifer bodies, especially in areas of limited well control.

The third objective of this study concerns the origin of the Mansfield Formation of southwestern Indiana. Although the Mansfield Formation contains tidal deposits in rocks previously considered nonmarine, it is unclear what tidal environments are represented. Whether the Mansfield Formation is predominantly tidal, or whether the tidal deposits are areally and stratigraphically restricted is also undetermined.

Determining the influence of tides in the Mansfield Formation may provide insight about epicontinental seas. Shaw (1964) and Irwin (1965) believed that significant tidal deposits could not be generated in epicontinental seas because in shallow cratonic basins, frictional effects would

have dampened tidal currents. Their influential theoretical work led to the conclusion that in a cratonic basin such as the Illinois Basin, tidal influence would not be significant. If the Mansfield Formation is found to be largely tidally-influenced, this suggests that tidal currents can be a dominant physical processes in cratonic basins.

The fourth objective of this research is to compare the Lee Formation (Corbin Sandstone Member) and associated rocks of the central Appalachian Basin with the Mansfield Formation of southwestern Indiana. Examining rocks of the same or similar age from different basins may lead to a better understanding of the major processes operating in the two basins during Morrowan/Atokan time. This information may lead to more important insights.

For example, the central Appalachian Basin and the Illinois Basin formed in very different tectonic settings. If the Lee Formation and age equivalent rocks appear to have been dominated by the same depositional processes as the Mansfield Formation, it would suggest that depositional processes were operating largely independent of the tectonic setting. Moreover, it would suggest that the Cincinnati Arch, the major structural feature separating the two basins, was largely submergent during Morrowan/Atokan time, and that the two basins were linked. Conversely, if the Lee Formation and age equivalent rocks of the central

Appalachian Basin appear to have been dominated by different physical processes than the Mansfield Formation of the Illinois Basin, it would suggest that physical processes were affected by the tectonic setting. It would also suggest that the central Appalachian Basin and the Illinois Basin were wholly or partially separated by the Cincinnati Arch during Morrowan/Atokan time.

Although this research attempts to resolve the problems regarding the depositional environments of the Corbin Sandstone of eastern Kentucky, and the Mansfield Formation of southwestern Indiana, its primarily concerned with the origin of the Corbin Sandstone Member of eastern Kentucky, and the bulk of this study will be devoted to its examination.

Geologic Setting of the Corbin Sandstone Member

The study area of the Corbin Sandstone Member of eastern Kentucky lies entirely within the Pocahontas Basin (Fig 1.1), a large, early to middle Pennsylvanian-age successor basin of the Appalachian Basin that extends from northern West Virginia to Tennessee (Donaldson et al., 1985; Ferm, 1974). Table 1 shows the regional stratigraphic correlation of Pennsylvanian age rocks for the Pocahontas Basin.

To the west of the Pocahontas Basin is the

Cincinnati Arch, towards which the coal-bearing rocks of the basin thin. These early to middle Pennsylvanian age rocks of the Pocahontas Basin may have been linked to Pennsylvanian age rocks in the Illinois Basin across the Cincinnati Arch. This is suggested by the presence of southwest-directed paleocurrent directions, and quartzite pebbles in Morrowan/Atokan age sandstones in the central Appalachian and Illinois Basins (Pryor and Sable, 1974; Pryor and Potter, 1979).

Northeast of the eastern Kentucky study area is the Dunkard Basin, a small successor basin dominated by clastic rocks of late Pennsylvanian to early Permian age (Englund and Thomas, 1990; Ferm, 1974). Starting in southwestern Pennsylvania and running southwestward through the Dunkard Basin, then westward through Kentucky, is the Rome Trough (Fig. 1.1). The Rome Trough developed in the late Proterozoic, and in eastern Kentucky the Kentucky River Fault System and Irvine-Paint Creek Fault make up part of this structural lineament (Donaldson and Shumaker, 1979). In the study area these faults were intermittently active throughout most of the Paleozoic. In early Pennsylvanian time they acted as a hinge line separating a stable platform to the north from the actively subsiding Pocahontas Basin to the south (Arkle, 1974; Dever, et al., 1977).

To the west of the Cincinnati Arch is the Illinois Basin. The Illinois Basin is a large cratonic basin, that

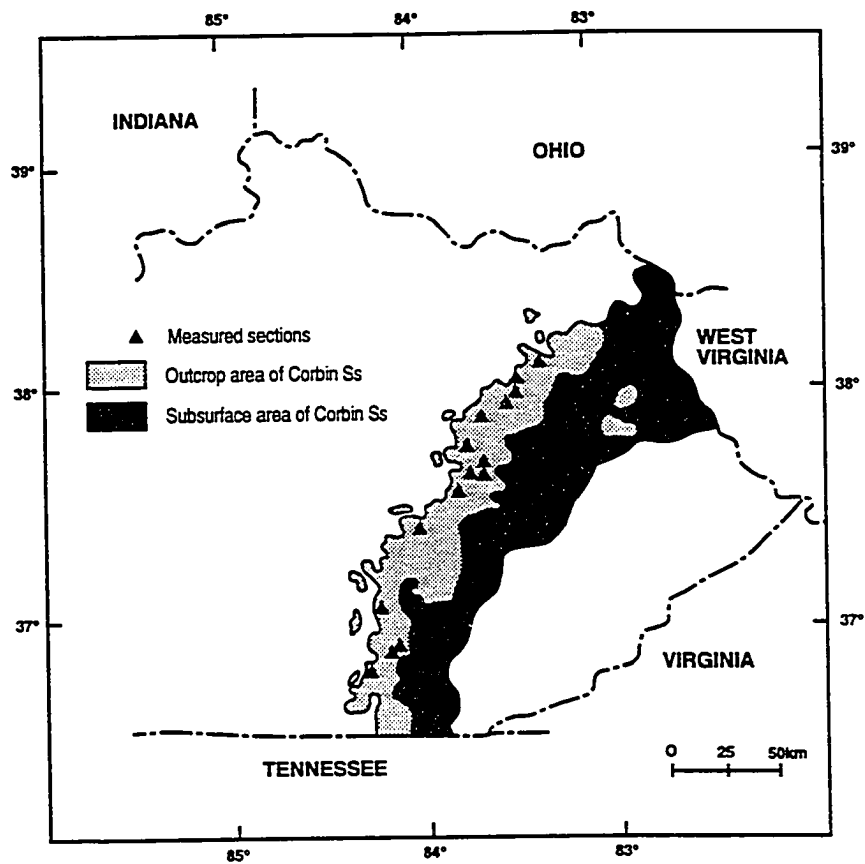
began forming in late Proterozoic to early Cambrian time (Klein and Hsui 1987), and contains up to 3,055 feet of Pennsylvanian age coal-bearing rocks (Wanless, 1975).

Location of the Corbin Sandstone Member

The lower Pennsylvanian Corbin Sandstone Member covers an area of approximately 11,700 square kilometers that includes most of the Pottsville Escarpment and the western portion of the Appalachian Plateau physiographic province of eastern Kentucky (Fig. 1.2). Here the rocks are relatively flat-lying and are intensely dissected by the numerous tributaries of the three major river systems that drain the plateau. In the north and central parts of the area respectively, the Licking and Kentucky rivers flow northwestward across the Appalachian Plateau, over the Pottsville Escarpment, and eventually to the Ohio River. Farther south, the Cumberland River flows southwestward over the Appalachian Plateau and eventually empties into the Ohio River near Paducah, Kentucky. The terrain in the outcrop area is rugged, with local relief often in excess of 300 feet, and in the Red River Gorge area of Menifee and Powell Counties, the relief often exceeds 500 feet (Weir, 1973).

The Corbin Sandstone Member outcrops at numerous places along the western portion of the plateau (Fig. 1.2), but

Fig. 1.2 Outcrop and subsurface areal distribution of
the Corbin Sandstone Member of eastern
Kentucky.



finding good quality exposures can be difficult. Where it is well cemented, the outcrops commonly form sheer cliffs that are often inaccessible, heavily weathered, and usually incomplete (Fig. 1.3). Where it is poorly cemented, the Corbin Sandstone weathers to a sandy soil and is quickly overgrown by vegetation, often by pine trees (Fig. 1.4).

The best exposures are the road-cut sections, and the best of these are located in the northern part of the field area. In many instances the entire section is exposed, is relatively unweathered, and is easily accessible. Of the measured sections shown in Fig. 1.2, all but two are road-cut sections.

Methodology

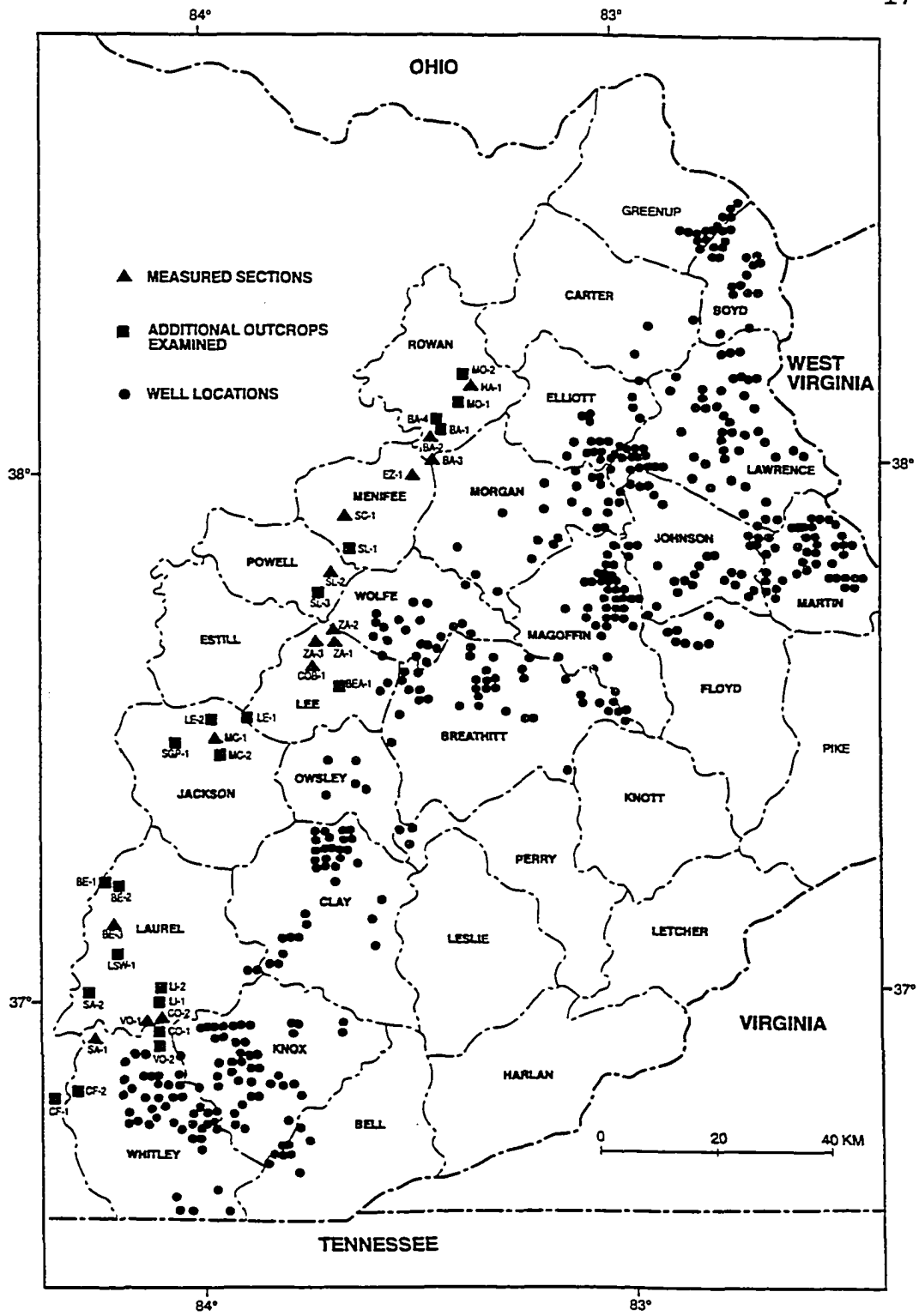
The outcrop belt of the Corbin Sandstone Member covers approximately 4,800 square kilometers. Along the length of the outcrop belt, approximately 35 outcrops were examined (Fig. 1.5). Of these 35, the 15 best were measured and described in detail. The criteria used in selecting these outcrops included the areal extent and degree of weathering of the outcrop face, the completeness of the section (i.e. were bounding contacts observed), and the vertical accessibility of the unit. Finally, location was also considered to ensure a proper representation of sections along the length of the outcrop belt.

Fig. 1.3 Large cliff of the Corbin Sandstone. This is typical of the Corbin Sandstone Member and other Lee Formation Sandstones where they are well-cemented.

Fig. 1.4 Where poorly cemented, the Corbin Sandstone weathers to a sandy soil and is quickly vegetated, usually by pine trees as shown in this photograph.



Fig. 1.5 Outcrop locations and well locations
with gamma-ray well-logs used in subsurface
analysis.



At most locations entire outcrops were photographed using a standard 50mm lens, and photographs were developed and assembled to obtain complete photomosaics of the exposures. Pertinent outcrop data were then recorded in the field on clear film overlays. These data included the two-dimensional architecture of primary sedimentary structures, macroforms, and channel-fill sequences. Also included were set and coset boundaries, and member bounding contacts. The location of grain size and paleocurrent measurements, as well as the location of trace fossils and fossil plant remains were noted as well. Of the 15 sections selected for detailed examination, nine were analyzed using this procedure. However, the remaining outcrops did not lend themselves to this treatment, and in these cases more traditional methods were employed. These exposures were measured with a stadia rod, and a vertical columnar profile of sedimentary structures, textural information, paleocurrent measurements and all other pertinent data were recorded in a field notebook.

To determine if there is a trend in quartz pebble size along the length of the outcrop belt, measurements were taken at ten sections that have a conglomeratic facies. For this procedure a piece of cardboard with an eight by twenty inch rectangular hole was placed over an area of the conglomerate that, from visual inspection, appeared to have the largest quartz pebbles. The long diameter of the ten

largest quartz pebbles located within the rectangle was then measured. In addition, a replicate set of measurements was taken for a total of 20 measurements at each location.

An extensive subsurface examination of the Corbin Sandstone Member was also undertaken. More than 500 gamma-ray well-logs were examined over the 6,900 square kilometer subsurface areal extent of the sandstone. This yields a density of approximately one well per 13.8 square kilometers. Where available, a well-log was examined in every Carter Coordinate section. However, there are large tracts where either no wells are present or no wire-line logs were run. Drillers logs were not used because a careful comparison of tops and intervals picked by drillers to the electric logs proved that they are not dependably accurate. The location of all wells with gamma-ray well-logs used in this study is shown in Fig. 1.5.

The top and base of the Corbin Sandstone Member were picked from the gamma-ray logs for each of the wells examined in order to generate a regional isopach map of the unit. In addition, three regional cross-section networks were constructed and tied together to ensure that the Corbin Sandstone interval was picked consistently throughout the area. Correlations were made by visual comparison of gamma-ray signatures from diagnostic shale, sandstone and carbonate units below the Corbin Sandstone, and from sandstone-shale packages above the unit.

As previously mentioned, this research combines both outcrop and subsurface data. An advantage of sedimentological research that combines both components is the insight one can give about the other. Data gathered from an outcrop are commonly displayed as a columnar profile showing the vertical variation in lithologies and textures as well as the thicknesses and types of primary sedimentary structures. For the Corbin Sandstone Member significant vertical variation in these components often exists from outcrop to outcrop. These variations reflect the depositional facies present at different locations at different times during Corbin Sandstone sedimentation. Clearly, then, gamma-ray well-log signatures also reflect these same depositional facies. Comparing vertical columnar profiles of outcrop data to gamma-ray well-log signatures that reflect similar or identical vertical ordering of lithologies and textures provides insight into the probable depositional facies present in specific areas in the subsurface. More importantly, gamma-ray well-log signatures that have been correlated to specific outcrops can then be used as interpretive models to help delineate depositional environments in the subsurface for other sandstones similar to the Corbin Sandstone. The fact that gamma-ray well-log signatures can be related to specific depositional environments has been well known for a significant time.

Figure 1.6 shows some typical gamma-ray signatures and

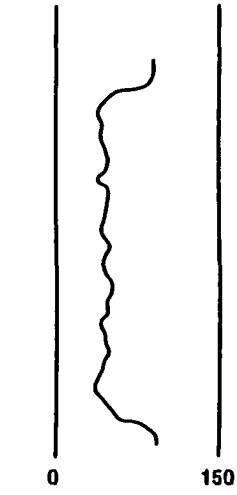
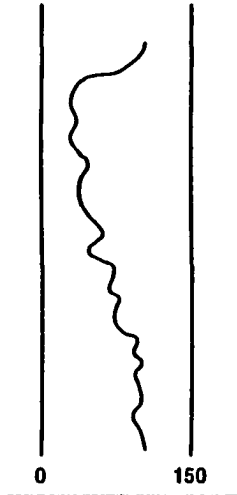
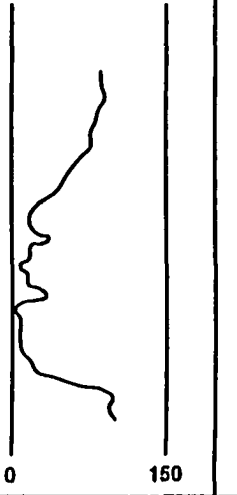
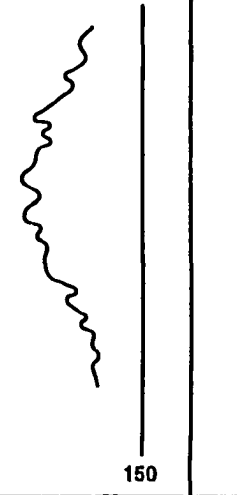
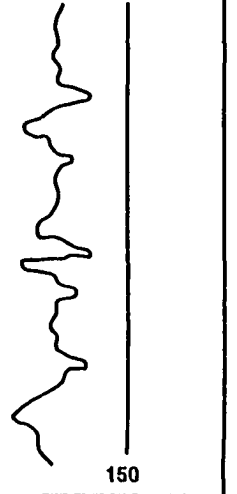
the depositional settings they represent. These profiles are highly generalized. For example, the bell-shaped profile shown in Fig. 1.6 is considered to be a typical gamma-ray well-log signature of a meandering river because the major depositional element of meandering rivers is the fining-upward point bar. However, the point bar is not the only coarse-grained deposit that may be present in a meandering system. For example, large coarse-grained chute bars may form at the toes of point bars in some rivers. These deposits form under rapid-flow conditions of extreme floods, consist of stacked accretionary events and together they may show little or no fining-upward tendency (McGowen and Garner, 1970). Therefore, the fining-upward bell-shaped profile of Fig. 1.6 is too general to serve as an adequate model for a meandering river with abundant chute bar deposits.

Models of gamma-ray well-log profiles are generalized not because the tool is incapable of reflecting subtle differences in sedimentary facies. Rather, they are generalized because not enough detailed studies that compare gamma-ray well-log signatures with outcrops and/or core have been done to develop more sophisticated models.

In summary, the Corbin Sandstone Member of the Lee Formation of eastern Kentucky is the primary focus of this research. It is suggested here that resolving the controversy surrounding the origins of Lee Formation

Fig. 1.6

Gamma-ray well-log signatures and the
depositional environments they represent
(Cant, 1984).

Cylindrical	Funnel Shaped	Bell Shaped	Symmetrical	Irregular
Clean, No Trend	Abrupt Top Coarsening Upward	Abrupt Base Fining Upward	Rounded Base and Top	Mixed, Clean and Shaley, No Trend
				
<p>aeolian, braided fluvial, carbonate shelf, reef, submarine canyon fill</p>	<p>crevasse splay, distributary mouth bar, clastic strand plain, barrier island, shallow marine sheet sandstone, carbonate shoaling- upward sequence, submarine fan lobe</p>	<p>fluvial point bar, tidal point bar, deep sea channel, some transgressive shelf sands</p>	<p>sandy offshore bar, some transgressive shelf sands, amalgamated CU and FU units</p>	<p>fluvial floodplain, carbonate slope, clastic slope, canyon fill</p>

Sandstones can best be accomplished by a combined surface and subsurface treatment of its individual members. The Lee Formation Members are very large sandstone bodies that merit individual study. In the past, researchers have attempted to study them collectively, or make generalizations regarding all the Lee Sandstone Members based on a few outcrops from a single member. Chapter two provides an up-to-date summary of previous sedimentological work on the Lee Formation, and the models proposed for its origins.

STRATIGRAPHY AND PREVIOUS SEDIMENTOLOGICAL WORK

Regional Stratigraphy

The Lee Formation was named by Campbell (1893) for a large exposure of the unit at Big Stone Gap in Lee County, Virginia. Campbell recorded a general description of the Lee Formation and noted its considerable southeastward thickening. He later (1898a, 1898b) extended the name to lithologically similar rocks in southeastern Kentucky and here subdivided the Lee Formation into three units; two coarse-grained "lentils" separated by a finer grained unit. The lower unit he named Rockcastle Sandstone for exposures along the Rockcastle River. The upper unit he named Corbin Sandstone for exposures near the town of Corbin in Whitley County, Kentucky. In addition, he also named the overlying Breathitt Formation for unusually thick exposures of that formation in Breathitt County, Kentucky.

Further stratigraphic work on the Lee Formation was done by the Tennessee and Kentucky Geological Surveys, as well as the United States Geological Survey. Conducted early in this century, this work was done to evaluate the economic potential of the coal resources of the area.

Evaluating the coal resources of early Pennsylvanian rocks on the Appalachian Plateau in southeastern Kentucky, Miller (1910) correlated outcrops of the Rockcastle Sandstone and Corbin Sandstone across a nine county area.

In northeastern Kentucky, Phalen (1912) conducted an early subsurface analysis. He used driller's logs from 21 wells scattered over a 30 minute quadrangle to correlate rocks from Devonian through Pennsylvanian age, including the Lee. Butts (1914) examined Lee Formation outcrops along Pine Mountain in southeastern Kentucky and southwestern Virginia and made stratigraphic correlations of the Lee and Breathitt Formations. In addition, he made an early attempt at regional correlation and produced a rough stratigraphic correlation section of lower and middle Pennsylvanian age rocks from the Anthracite Region of eastern Pennsylvania to the Black Warrior Basin of Alabama. Additional work done at this time included a regional correlation of Lee strata along the Cumberland Plateau of eastern Tennessee and further subdivisions of the Lee Formation in the same area by Nelson (1925). This work provided the modern stratigraphic nomenclature for the Lee Formation in that area.

In eastern Kentucky some of the first regional stratigraphic analyses of early Pennsylvanian age rocks were done by Wanless (1939, 1946). Examining outcrops along the Cumberland Escarpment, he correlated early Pennsylvanian age rocks from southeastern Ohio to the Tennessee border. In addition, he traced several members of the Lee Formation below the Corbin Sandstone from Tennessee into southeastern Kentucky and correlated the Lee Formation from the Pine

Mountain area of southeastern Kentucky into southwestern Virginia.

In the Cumberland Mountain area of southeastern Kentucky and southwestern Virginia, Englund (1964) subdivided the Lee Formation into seven mappable members based on lithologic distinctions between cliff-forming sandstones and intervening fine-grained units. Using outcrop and subsurface data, Englund (1964), and Englund and Delaney (1966) traced the Lee Formation eastward along a 200 kilometer stretch from Bell County, Kentucky to Tazewell County, Virginia. They demonstrated that early Lee Formation sandstones intertongue to the east with finer-grained rocks of the Pennington Formation, Pocahontas Formation and New River Formation. This was later confirmed by Miller (1974) who correlated late Mississippian and early Pennsylvanian sediments in the same area. This suggests that early Lee Sandstones in the deepest parts of the Pocahontas Basin are of late Mississippian age. Table 1 shows a regional stratigraphic correlations of Carboniferous rocks in the central Appalachian Basin.

A significant contribution to understanding Pennsylvanian stratigraphy in eastern Kentucky resulted from the geologic mapping program of the state. Geologic mapping in Kentucky was done at a scale of 1:24,000, and was conducted by the United States Geological Survey in conjunction with the Kentucky Geological Survey. This work,

begun in 1961 and completed in 1978, revealed the extreme vertical and lateral variations in lithology, as well as the discontinuous nature of Pennsylvanian sediments (Rice, 1984). It also demonstrated the extreme difficulty of applying a single stratigraphic nomenclature to this area. Stratigraphic relations and other aspects of the Lee Formation revealed by the mapping program are summarized by Rice (1984).

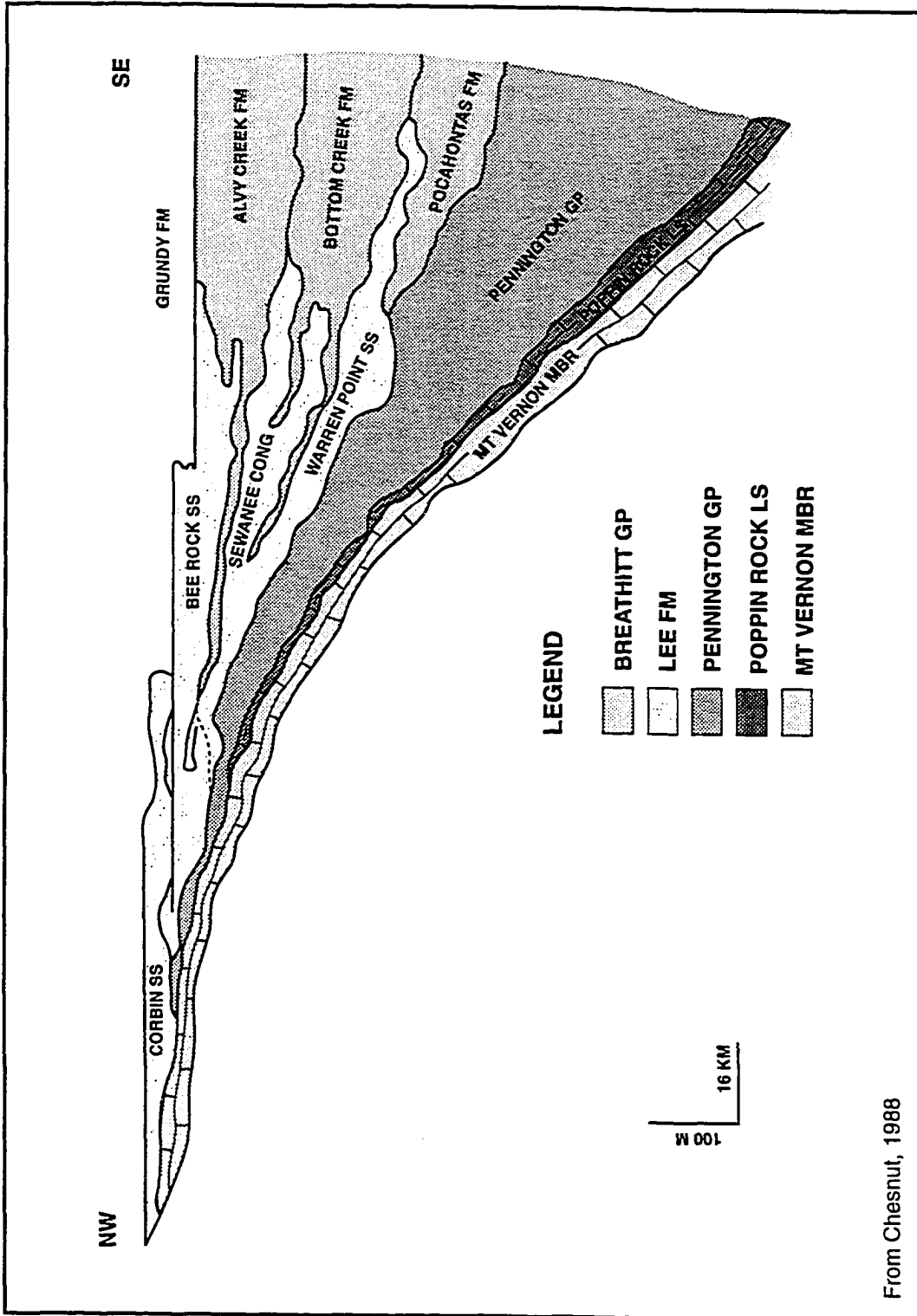
A more recent stratigraphic study has been done by Chesnut (1988) who conducted a regional subsurface correlation of Carboniferous rocks over a large area of the central Appalachian Basin. He grouped the Lee Formation sandstones into four northeast to southwest trending belts and demonstrated their stacked en-echelon arrangement. Figure 2.1 shows the stratigraphic relations of these sandstones from the Cumberland Escarpment of northeastern Kentucky to southwestern Virginia.

Pennsylvanian Stratigraphy Along the Pottsville Escarpment

Pennsylvanian sediments along the Pottsville Escarpment are assigned to either the Lee Formation or the Breathitt Formation. This distinction is primarily lithologic, as the lower Breathitt Formation intertongues with the Lee Formation, and here the two formations are time-equivalent.

The Lee Formation along the escarpment consists of four

Fig. 2.1 Regional cross-section of early Pennsylvanian strata from the from the Cumberland Plateau of northeastern Kentucky to southwestern Virginia. (Chesnut, 1988).



From Chesnut, 1988

named and several unnamed sandstone members separated by tongues of the Breathitt Formation. The named members include the Livingstone Conglomerate, the Rockcastle Sandstone, the Corbin Sandstone and the Grayson Sandstone. Of the four, only the Corbin and Rockcastle members have large areal distributions (Fig. 2.2).

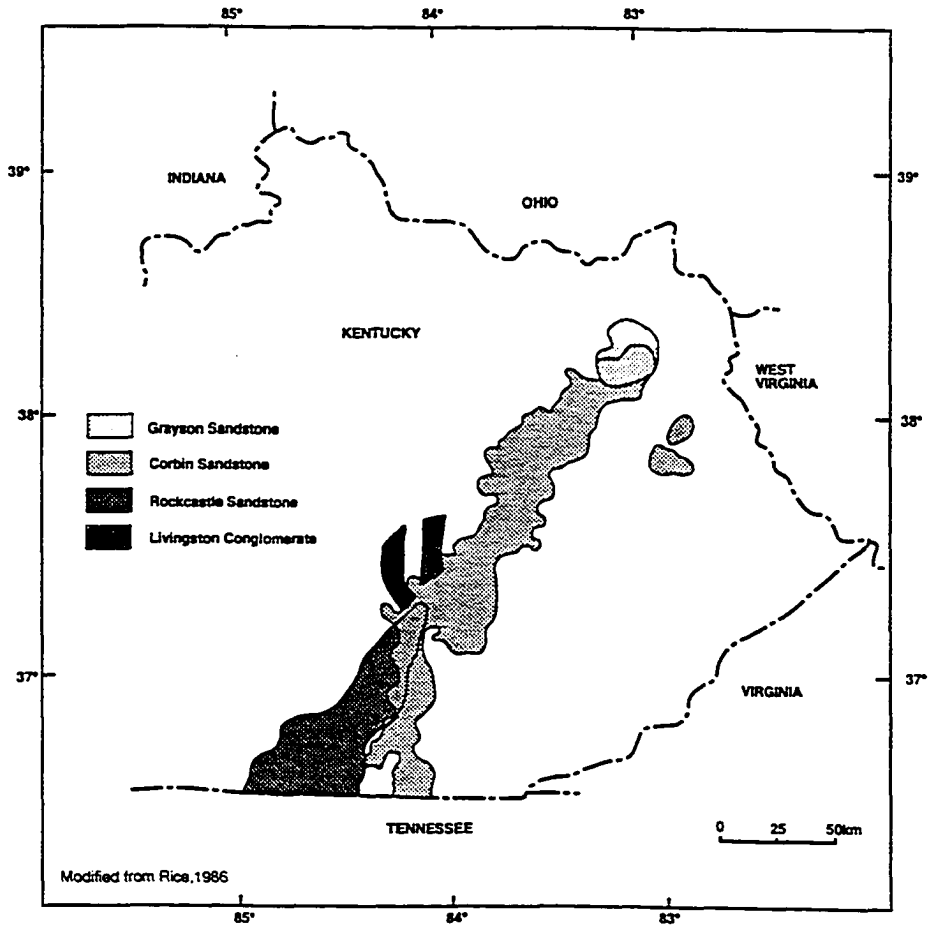
The Breathitt Formation is lithologically complex, a mixture of detrital sediments coal and thin limestones. It has not been formally subdivided because of the thin and discontinuous nature of the units.

Descriptions of the Lee Sandstone Members and the Breathitt Formation are included in the next several pages.

The Livingston Conglomerate Member

The earliest member of the Lee Formation along the Pottsville Escarpment is the Livingston Conglomerate Member. The Livingstone Conglomerate was named by Miller (1908) for exposures of the unit near Livingston, Kentucky. Its known areal distribution is limited to two paleovalleys each about 7 kilometers wide and 30 kilometers long (Rice, 1986) as shown in Fig. 2.2. The unit ranges from 0 to 36 meters thick, and consists of interbedded conglomerate and fine to coarse grained quartz-rich sandstone (Rice and Weir, 1984). The lower contact is highly erosional; in places the Livingstone Conglomerate has cut through the underlying

Fig. 2.2 Areal outcrop distribution of Lee Sandstone
members along the Cumberland Plateau in
eastern Kentucky (modified from Rice, 1986).



Pennington Formation and up to 27 meters into the Newman Limestone Formation (Brown and Osolnik, 1974).

Its origin is controversial, but Rice and Schwietering (1988) believe the unit represents part of the same fluvial drainage system responsible for the Brownsville Paleovalley of the Illinois Basin described by Pryor and Potter (1979).

The Rockcastle Sandstone Member

The Rockcastle Sandstone Member is present along the southern portion of the Pottsville Escarpment. Its outcrop distribution is southwest of the Corbin Sandstone except for a small area where the two overlap (Fig. 2.2). The thickness of the unit averages 30 to 40 meters (Greb and Chesnut, 1989; Rice and Weir, 1984), but may exceed 60 meters in places. The basal portion is erosional into the underlying Breathitt Formation where local relief often exceeds 3 meters (Hatch, 1963; Stager, 1963).

The Rockcastle Sandstone fines upward into the overlying Breathitt Formation, or sometimes into a coal zone and another Lee Sandstone as demonstrated by Greb and Chesnut (1989). Laterally the unit intertongues with shales, siltstones and ripple-bedded sandstones of the Breathitt Formation.

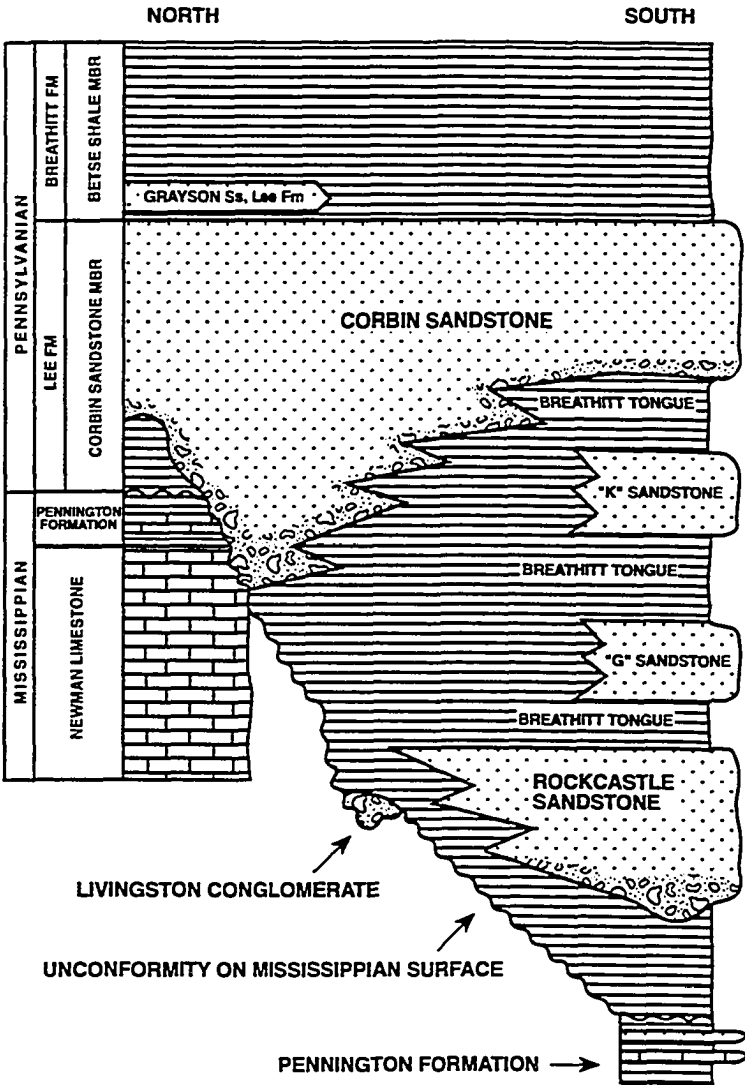
Internally the Rockcastle Sandstone consists primarily of fine to coarse grained quartzose sandstone and a basal

quartz-pebble conglomerate often containing large fossil plant fragments (Rice and Weir, 1984). Primary sedimentary structures include medium and large-scale trough crossbeds, and planar tabular and planar wedge-shaped crossbeds that may exceed six meters in thickness (Wizevich, 1991). Paleoflow measurements from crossbeds indicate a southwestward transport direction.

Unnamed Lee Sandstones

In addition to the Lee Formation Sandstones shown in Fig. 2.2, there are several local Lee Formation sandstones that have not been assigned formal names. These sandstones are limited to the southern part of the field area and occur stratigraphically between the Rockcastle Sandstone and Corbin Sandstone as shown in Fig. 2.3. Geologists mapping the area determined that these relatively thin and discontinuous sandstones did not merit formal member status and assigned these units letter designations only (e.g., Puffett, 1962, Stager, 1963). These sandstones range from 15 to 30 meters thick and are lenticular in their geometry (Rice and Weir, 1984; Greb and Chesnut, 1988). Their basal contacts are usually sharp or erosional, and they grade laterally and up-section into siltstone and shale. Internally, they consist of fine to medium grained quartzose sandstone with local quartz-pebble conglomeratic lenses near

Fig. 2.3 Stratigraphic section of Lee and Breathitt
strata from north to south along the
Pottsville Escarpment of eastern Kentucky.



the base, and occasional lenses of siltstone and shale near the top. Primary sedimentary structures include planar and trough cross-strata and ripple beds. Paleocurrent measurements suggest flow directions were to the southwest (Rice and Weir, 1984; Greb and Chesnut, 1989).

The Corbin Sandstone Member

The Corbin Sandstone Member outcrops along all but the very northern part of the Pottsville Escarpment (Fig. 2.2), and is the primary cliff-forming sandstone in the area. Generally, the unit fines upward and grades laterally into shales, siltstones and sandstones of the Breathitt Formation.

The basal portion of the unit is almost always sharp or erosional and often contains quartz-pebble conglomeratic lenses. In the northern part of the outcrop area the Corbin Sandstone is typically 60 to 90 meters thick and rests directly on Mississippian strata of the Pennington Formation or Newman Formation, or on a tongue of the Breathitt Formation (Fig. 2.3). In the southern part of the field area the Corbin Sandstone Member is thinner, averaging 30 to 45 meters thick, and here the unit rests directly on finegrained sediments of the Breathitt Formation.

The Corbin Sandstone Member is predominantly a medium grained sandstone, but grain size is highly variable and

encompasses the entire sand-size fraction. The unit is dominated by medium and large-scale trough/tangential and planar cross-strata that indicate predominantly southwest paleoflows. The Corbin Sandstone Member is the primary focus of this research, and the unit will be treated comprehensively in subsequent chapters.

The Grayson Sandstone Member

The Grayson Sandstone Member is limited to a small area in the northern part of the Pottsville Escarpment (Fig. 2.2). The unit was named by Ferm (in Thomas et al., 1955) for thin exposures near the town of Grayson, Kentucky. It was originally considered part of the Breathitt Formation (e.g., Whittington and Ferm, 1967), but it was later assigned to the Lee Formation by Delaney and Englund (1973).

The basal portion of the unit is erosional and it is sharply erosional where it overlies Mississippian age rocks (Englund and Windolph, 1975). It grades laterally into fine-grained sediments of the Breathitt Formation and upward into the Wolf Creek Coal. The Grayson Sandstone Member ranges in thickness from zero to 21 meters and occurs from one to 25 meters above the Corbin Sandstone (Rice and Weir, 1984).

The Grayson Sandstone consists of very fine to coarse grained, quartzose, micaceous sandstone and contains some

local conglomeratic lenses with well-rounded quartz pebbles up to 1.3 centimeters in diameter (Englund and Windolph, 1975). Primary sedimentary structures include large crossbeds, and wavy-bedded and ripple-bedded siltstone and sandstone (Whittington and Ferm, 1967).

The Breathitt Formation

Intertonguing with and overlying the Lee Formation are finer-grained deposits of the Breathitt Formation (Figs. 2.1 & 2.3). The Breathitt Formation is characterized by complex lithologies that display rapid lateral and vertical changes. It is this characteristic that makes stratigraphic correlation of Pennsylvanian rocks in eastern Kentucky difficult (Rice et al., 1979). Lithologies of the Breathitt Formation include shale, siltstone, sandstone, coal, underclay, and thin limestones but sandstone and shale are most abundant.

Shales of the Breathitt Formation are typically light to dark grey, micaceous and silty with abundant plant material. (Rice et al., 1979; Black, 1978; Hylbert and Philley, 1971). In addition, they commonly contain siderite nodules and disc-shaped concretions 30 centimeters or more in diameter (Rice et al., 1979; Black, 1978). Body fossils are not abundant in the Breathitt Formation, but thin zones containing brachiopods, pelecypods, cephalopods and

gastropods have been reported (Rice et al., 1979).

Sandstones of the Breathitt Formation are fine to medium-grained and typically range from one to 15 meters thick (Black, 1978; Flores, 1978). They normally cannot be traced over long distances and usually pinch-out into finer-grained deposits within a few miles (Horne et al., 1974). These sandstones are compositionally immature litharenites and sublitharenites with up to 25% mica (Flores, 1978). Common sedimentary structures include ripple beds, horizontal bedding, trough/tangential cross-strata and planar cross-strata (Close, 1985; Horne et al., 1978; Gardner, 1977).

While there is a great deal of controversy about the nature of the Lee Formation, there is a broad consensus regarding the environmental setting during Breathitt Formation sedimentation. Agreement exists that the Breathitt Formation is composed primarily of fluvial-deltaic sediments (Englund and Thomas, 1990; Donaldson et al., 1985; Close, 1985; Horne et al., 1978; Flores, 1978; Gardner, 1977; Hester, 1977; Horne et al., 1974; Ferm et al., 1971). Almost all of the environments associated with fluvial-deltaic sedimentation have been recognized.

Alluvial plain sediments consisting of point bar, crevasse splay, levee, and backswamp-marsh and lake deposits have been observed (Close, 1985; Horne et al., 1978, Flores, 1978; Hester, 1977; Gardner, 1977; Horne et al., 1974; Ferm

et al., 1971). Upper deltaic plain deposits such as distributary channel, point bar, levee, interdistributary bay, crevasse splay and backswamp-marsh have been recognized (Donaldson et al., 1985; Close, 1985; Flores, 1978; Horne, et al., 1978; Hester, 1977; Gardner, 1977; Horne, et al., 1974; Ferm, et al., 1971). And, finally, deposits of the lower deltaic plain have been documented. These include distributary channel, interdistributary bay, distributary mouth bar and pro-delta deposits (Donaldson et al., 1985; Flores, 1978, Horne et al., 1978; Gardner, 1977; Horne et al., 1974; Ferm et al., 1971).

Separating packages of fluvial-deltaic sediments in the Breathitt Formation are thin marine zones (Englund and Thomas, 1990; Chesnut, 1981; Gardner, 1977). Most of these zones are of limited areal extent, but a few, such as the Magoffin and Kendrick Members, cover large areas of eastern Kentucky. Marine zones range from 0 to 37 meters thick, contain marine and brackish water fauna, and are considered to be of bay-fill origin (Chesnut, 1981; Ketani, 1981).

Previous Sedimentological Work

Most of the early geologists who studied early Pennsylvanian sediments of the central Appalachians were interested in their coal resource potential, and few commented on how these sediments were deposited. But

examination of the literature makes clear that those who considered the question thought they were marine. The following is a quote from Campbell (1898a). Here he comments on how he thought Lee Formation sediments were deposited:

"The erosion interval undoubtedly represents a period of time in which the limestone area was dry land and the Pennsylvanian sea was located some distance eastward. Later, subsidence of the land allowed this sea to transgress upon the land, forming successive overlaps to the west; each position of the shore was marked by sand and gravel, which was sorted by the waves and finally laid down as sandstone and conglomerate, while sandy mud was being deposited offshore."
(p.3)

Nelson (1925) examined Lee Formation sediments on the Cumberland Plateau in eastern Tennessee and offered the following, almost identical interpretation:

"The old Pennsylvanian sea did not at the beginning cover all areas occupied by the coal measures. It originally occupied only the eastern and southeastern portion of the area, and from these points advanced westward and northward over the old Pennington land surface." (p.39)

One of the first geologists to offer an explanation of Pennsylvanian age sediments of the Central Appalachian Basin based on some understanding of sedimentary environments was Wanless (1946). He suggested that the Lee Formation and Breathitt Formation, together, represent a complex of environments of delta-plain origin, and suggested lake, marsh, lagoon, fluvial and distributary channel deposits as likely environments. However, he did not specify which of these environments he thought the Lee Formation represented.

A comprehensive regional study of Lee Formation sediments was conducted by Mitchum (1954). This research incorporated both outcrop and subsurface components that included stratigraphic correlation, petrographic analysis and subsurface mapping. In addition, it included one of the first regional paleocurrent studies of Lee Formation rocks in the area.

Mitchum believed the Lee Formation sandstones were marine and offered a depositional model to explain them. In this model, southwest-trending longshore currents moved large quantities of sand and gravel from offshore bars and beach deposits. Then, migration of the strandline caused these deposits to merge giving the Lee Formation sandstones their sheet-like character. He believed that strong longshore currents best explained the unimodal southwest trending crossbed dips he observed.

Mitchum considered a fluvial interpretation for the Lee Formation but dismissed it. Mitchum concluded that fluvial deposits were too discontinuous and shale-rich to account for the sheet-like sand-rich character of the Lee Sandstones.

Two paleocurrent studies of the Lee Formation followed Mitchum's work, one by Potter and Siever (1956) and the other by Schlee (1963). Potter and Siever measured paleocurrents of Lee Formation sandstones along the Pottsville Escarpment as part of a larger paleocurrent study

of early Pennsylvanian sediments in the Illinois Basin. They concluded that the Lee Formation sandstones along the Pottsville Escarpment formed part of a large southwest-trending fluvial paleodrainage network operating over much of the eastern mid-continent during the early Pennsylvanian.

Schlee (1963) worked further south and took some 1200 paleocurrent measurements from three lower Lee Formation sandstones on the Cumberland Plateau of eastern Tennessee and the Black Warrior Basin in northeast Alabama and northwest Georgia. Based on these measurements and field observations that included abundant fossil plant material and fining-upward textural trends, he concluded that the Lee Formation sandstones are fluvial.

Prior to 1970, research on early Pennsylvanian sediments in the central and southern Appalachians focused primarily on stratigraphic problems related to coal resource evaluation. Sedimentological questions, if addressed at all, were of secondary interest. After 1970 this focus shifted, and since that time a number of papers have been written on the sedimentology of Pennsylvanian deposits in the central and southern Appalachians. A large number of these studies involve the Lee Formation sandstones, and several models have been offered to explain how they were deposited.

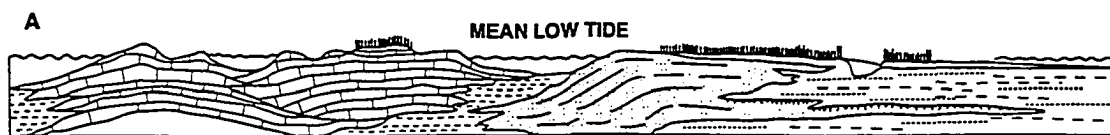
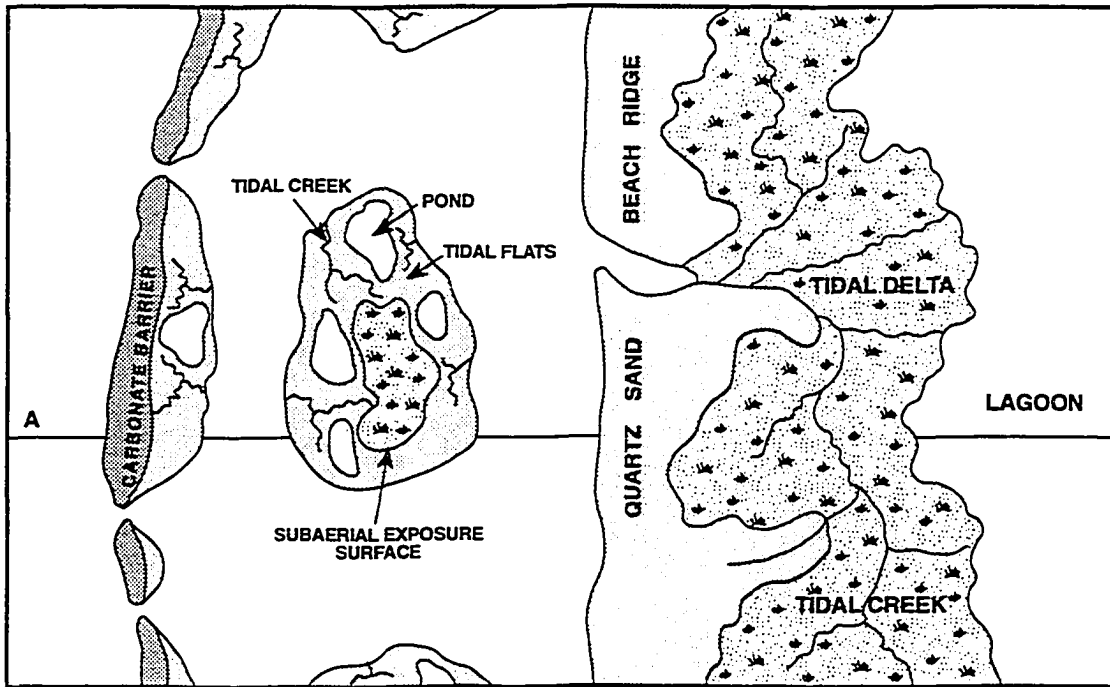
A controversial model has been proposed by Ferm et al., (1971), and Horne et al., (1974). This model, the Lee-

Newman Barrier Shoreline Model, was developed from outcrop exposures along a 35 kilometer stretch of Interstate 64 in northeastern Kentucky. According to Ferm et al., and Horne et al. late Mississippian and early to middle Pennsylvanian age rocks of the central Appalachians form three major sedimentary environments that grade laterally into one another.

Figure 2.4 shows the lateral relationship of Mississippian and Pennsylvanian sediments as envisaged by Ferm et al., (1971). Here, the Mississippian Newman and Pennington Formations form offshore carbonate barriers, carbonate mud islands and deeper water clays. Pennsylvanian Lee Formation sandstones form quartz sand barrier islands, tidal channel and tidal delta deposits, and the Pennsylvanian Breathitt Formation forms the back-barrier lagoon, and fluvial-deltaic deposits. According to the model, Pennsylvanian detrital sediments prograded westward over Mississippian carbonates and clays, thereby forming a time-regressive depositional continuum.

One objection to the Lee-Newman model concerns the nature of the Mississippian-Pennsylvanian systemic boundary. The model assumes that no regional unconformity exists between Mississippian and Pennsylvanian strata. Although the presence of a depositional continuum across the Mississippian - Pennsylvanian boundary in the deepest parts of the Pocahontas Basin has support (e.g., Englund, 1964;

Fig. 2.4 The Lee-Newman Barrier Shoreline Model for
Newman, Pennington, Lee and Breathitt
sedimentation in the central Appalachian
Basin (Ferm et al., 1971).



- | | | | |
|----------------------|----------------------------|---|--|
| Shale, red and green | Sandstone, orthoquartzitic | Carbonates, coarse-grained (oolites, skeletal fragments, carbonate clasts, and quartz grains) | Tidal flat carbonates (supratidal dolomite and algal mats) |
| Coal and seat rock | Shale and siltstone (dark) | Carbonates, (fine-grained micrite and pellets) | Subaerial zone (subaerial crusts and caliche) |

Englund and Delaney, 1966; Miller, 1974; Chesnut, 1988; Englund and Thomas, 1990), the presence of a depositional continuum for the rest of the basin has been challenged. Indeed, the reevaluation of the Mississippian-Pennsylvanian systemic boundary that has occurred since the Lee-Newman model was proposed has, for the most part, supported the presence of a major regional unconformity between the Mississippian and Pennsylvanian systems in the Central Appalachian Basin (e.g., Ettensohn, 1980, 1981; Chesnut, 1981, 1988; Kosanke, 1982; Rice, 1984, 1986, 1988).

Another controversial aspect of the Lee-Newman Barrier Shoreline Model concerns the Lee Formation sandstones. Ferm et al. (1971) and Horne et al. (1974) interpret the Lee Formation sandstones as barrier island and associated deposits based on stratigraphic position, horizontal facies relationships and sandstone body geometry. They also conclude that the high-energy depositional environment drove the Lee Formation sands towards high compositional maturity and that alone accounts for their compositional difference with intertonguing litharenitic Breathitt Sandstones.

A number of researchers have supported a barrier island interpretation for the Lee Formation sandstones. Hobday (1969, 1974) examined exposures of Lee Formation equivalent sandstones in northeast Alabama. Based on sandstone body geometry, sedimentary structures and paleocurrent dip orientations, he concluded these sandstones are barrier

island deposits. Later, Hobday and Horne (1979) examined Lee Formation equivalent rocks along a 16 kilometer stretch of highway in southern West Virginia. They interpreted exposures there to be tidally influenced barrier island deposits consisting of tidal inlets, flood and ebb tidal delta deposits, and flood channel and washover berm deposits.

Miller (1974) examined late Mississippian and early Pennsylvanian rocks in southwestern Virginia and developed a model for early Pennsylvanian sedimentation in that area similar to the Lee-Newman model. The primary distinction between Miller's model and the Lee-Newman model is that Miller invokes multiple regressions and transgressions in the early Pennsylvanian to account for the stacked Lee Formation Sandstones separated by fine-grained units typical of that area.

Further work includes that of Millici (1979), who examined outcrop exposures of the Lee along the southern portion of the Cumberland Plateau of Tennessee and suggested a barrier island origin for the Sewanee Conglomerate Member of the Lee Formation in that area. At the same time Carlson (1979) conducted subsurface analyses of lower Lee Formation Sandstones on the northern Cumberland Plateau in Tennessee and examined gamma-ray well logs, core and well cuttings. Based primarily on sandstone body geometry and facies relationships, he determined that the Lee Formation

Sandstones he examined are barrier island deposits.

Although over the last 15 years support for the barrier island interpretation for the Lee Formation has somewhat waned, a couple of small-scale studies have supported this interpretation. Hayes and Conner (1982), based on a single core through late Mississippian and early Pennsylvanian deposits in northeastern Kentucky, agreed with the barrier island interpretation for the Lee Formation. Recently, Wnuk and Mayberry (1990) examined an outcrop exposure of the Middlesboro Member of the Lee Formation in northeastern Tennessee and concluded that this unit is a barrier island deposit with associated tidal channel-fill sediments. This outcrop contains long (8 meter), vertical tube-shaped structures interpreted by Wnuk and Mayberry to be animal escape burrows. They suggest these were formed by pelecypods or possibly burrowing crustaceans such as crabs or shrimp. However, Cobb et al. (1986) examined this same exposure and concluded the structures are pteridosperm plant fossil remains that were buried in-situ.

In contrast to the barrier island interpretation, a fluvial interpretation for the Lee Formation has been proposed by a number of workers. As previously mentioned, Potter and Siever (1956) and Schlee (1963), based primarily on low variance in paleocurrent measurements, concluded that the Lee Formation sandstones are fluvial.

Bement (1976), based primarily on textural and

paleocurrent data, proposed a combined marine and fluvial model for the Lee Formation. He examined late Mississippian and early Pennsylvanian age rocks along the Cumberland overthrust sheet and concluded that early Lee Formation sandstones are marine shoreface and tidal deposits that were then overlain by later Lee sandstones that are fluvial. He concluded that all Lee Formation sandstones above and including the Middlesboro Member are fluvial.

A study of late Mississippian and early Pennsylvanian sediments in southeastern Ohio and northeastern Kentucky was conducted by Short (1978). In northeastern Kentucky, he examined data from outcrops and wells in a five-county area. Based on sandstone body geometry, paleocurrent variance and type and vertical ordering of sedimentary structures, he determined that the Corbin Sandstone of Kentucky is fluvial and fluvial-deltaic in origin.

Further support for a fluvial interpretation has been offered by Rice (1985). He examined subsurface data in the Pine Mountain area of Virginia and concluded that early Lee Formation sandstones occupied southwest-trending paleovalleys carved into the Mississippian surface. This was followed by further work in West Virginia by Rice and Schwietering (1988). Reexamination of subsurface isopach mapping of the Mississippian Greenbrier Limestone done earlier by Flowers (1956) reveal channel-shaped isopachous thins filled with quartz-rich Pennsylvanian sandstone and

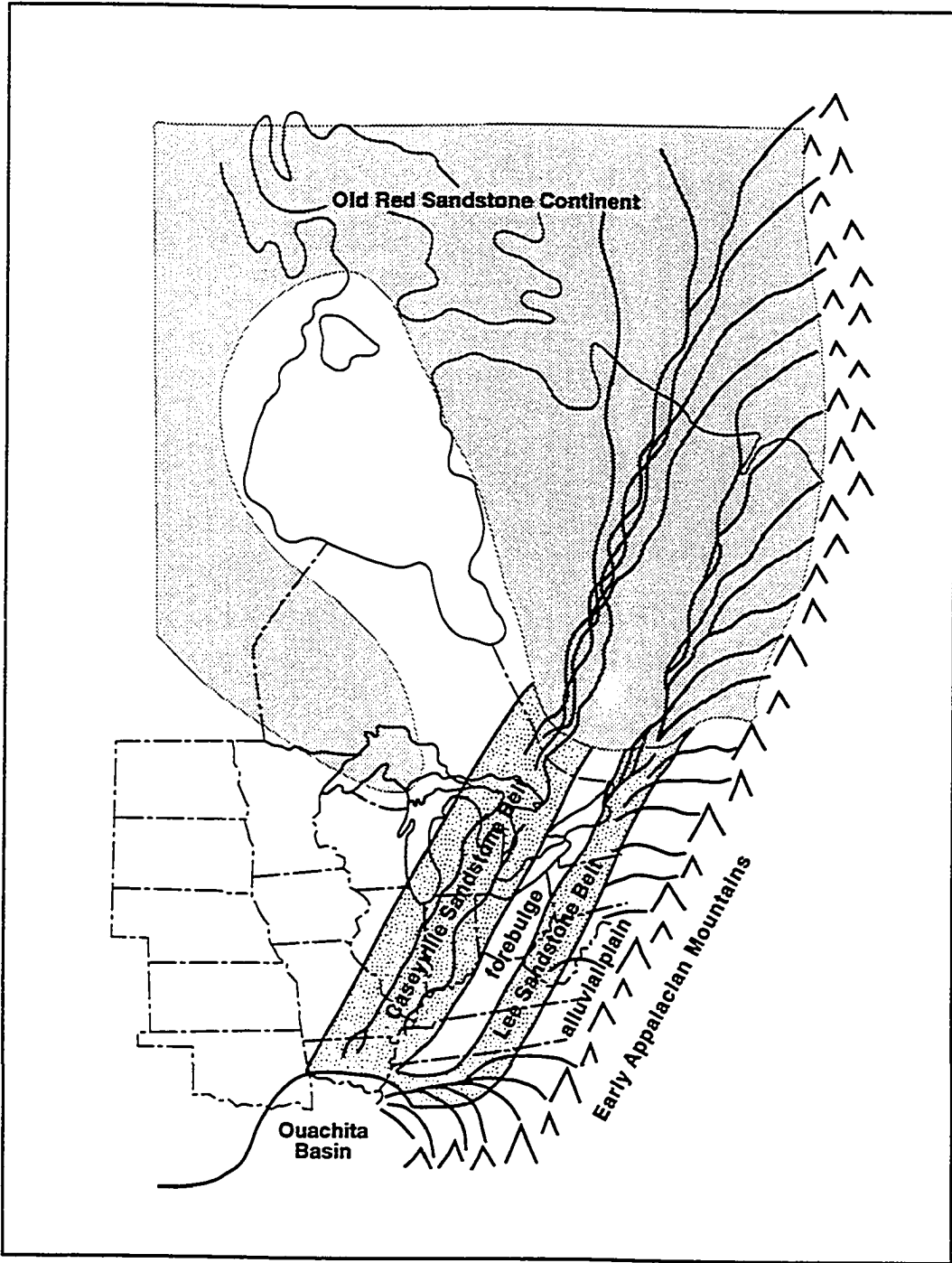
conglomerate. Rice and Schwietering conclude that the presence of these sandstone-filled south-flowing channels on the Mississippian unconformity is compelling evidence of the fluvial origin of the Lee Sandstones.

Many of those who have supported a fluvial interpretation for the Lee Formation have often considered its members to be braided fluvial deposits. Hester and Taylor (1981) examined outcrops of the Corbin Sandstone Member in a three county area in northeastern Kentucky and proposed a braided fluvial interpretation for this member. This interpretation is based on paleocurrent data, stratigraphic relationships, fining-upward textural trends, erosional lower bounding contacts, and the vertical ordering of primary sedimentary structures.

Jackson, (1984) evaluated outcrops and well-log data on the northern Cumberland Plateau in Tennessee and determined that the Rockcastle Sandstone Member (of Tennessee) is a braided-fluvial deposit.

Chesnut (1988), based on regional subsurface stratigraphic analysis and a review of the proposed models, suggested that a braided fluvial interpretation for the Lee Formation best fit the available data. He offered a paleogeographic model to explain Lee Formation sedimentation (Fig. 2.5). According to this model the primary source area of Lee Formation clastics was the Canadian Shield area that may have subsequently been stripped of the sediments that

Fig. 2.5 Paleogeographic - depositional model of Lee and Caseyville strata for the Appalachian and Eastern Interior Basins (Chesnut, 1988).



sourced these sandstones. In addition, the model assumes some contribution of sediment from the ancient Caledonide-Acadian Mountain chain to the northeast and the early Appalachians to the east. This accounts, then, for the minor lithic component present in Lee Formation sandstones.

A recent study of the Lee Formation in southeastern Kentucky and northeastern Tennessee has been conducted by Wizevich (1991 and 1992). He did lateral profiling and bounding surface analysis of several outcrops of the Lee. Based on these data he concluded that the Lee Formation sandstones were deposited by bedload dominated, single-channel low-sinuosity rivers, or multi-channel river systems where the major depositional elements were downstream accreting macroforms.

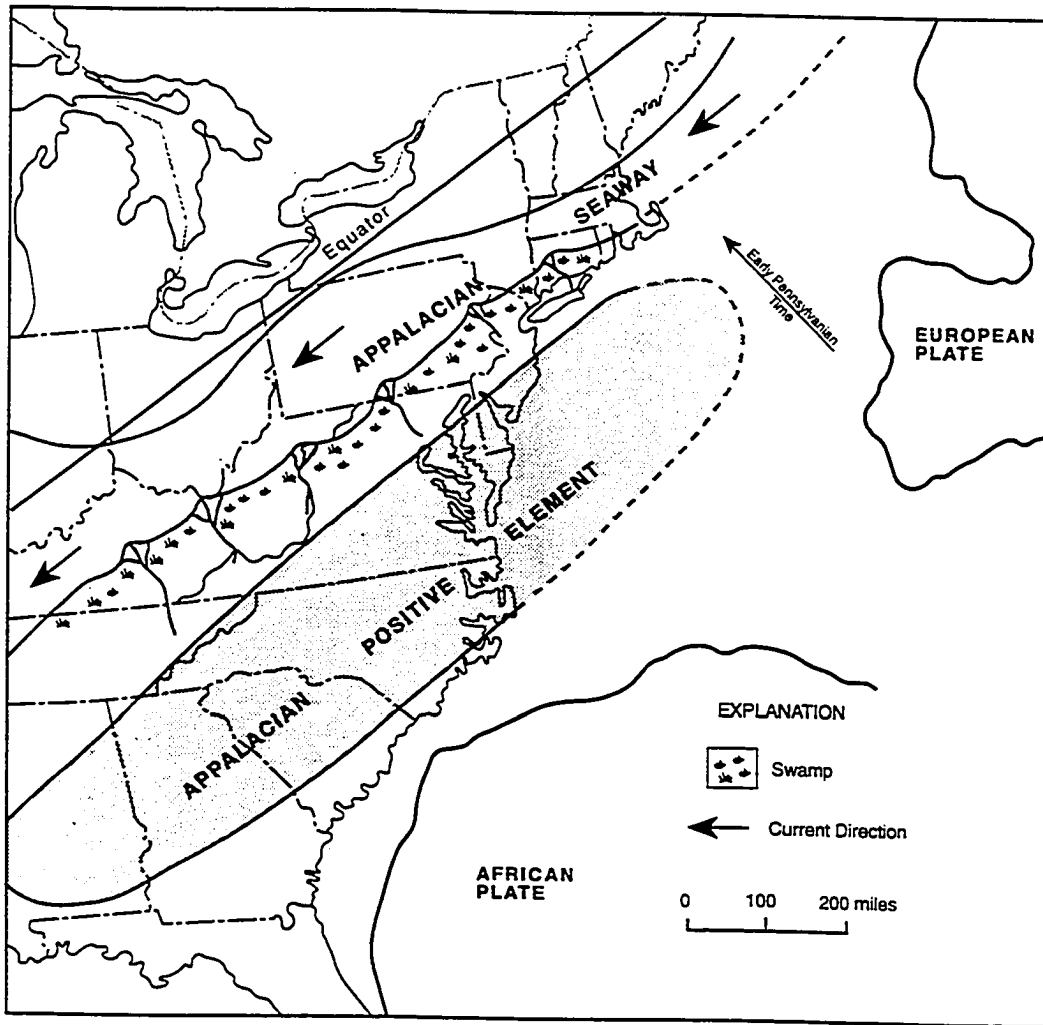
A third interpretation has been offered to explain the depositional environment of the Lee Formation. According to Cecil and Englund (1989) and Englund and Thomas (1990), quartz-rich sandstones of late Mississippian and early Pennsylvanian age are tidal deposits. They suggest estuarine, tidal flat, tidal channel and bay-fill as likely environments. They further maintain that thick quartz-rich relatively coarse-grained sandstones of the Lee Formation were deposited along a shifting basin axis by strong tidally-generated currents that attained velocities of up to 1.5 meters per second, adequate to transport coarse sand and fine gravel. Finer-grained deposits separating the quartz

sandstones occurred during periods of relatively high sea level. The modern analog proposed by the supporters of this model are the straits of Malacca. A paleogeographic model offered by England and Thomas is shown in Fig. 2.6.

In summary, then, the origins of the Lee Formation Sandstone Members has been a subject of controversy since the publication of the Lee-Newman Barrier Shoreline Model by Ferm et al., (1971) and Horne et al. (1974). Since that time many researchers have supported this model while others have suggested that a fluvial model is more consistent with the available data (e.g., Bement, 1976; Short, 1978; and Chesnut, 1988). More recently, Cecil and Englund (1989) and Englund and Thomas (1990) have supported a model that relies on an Appalachian seaway and tidally-driven currents.

The origins of the Lee Formation Sandstones are still controversial. In spite of the many papers published on the origin of the Lee Formation outcrop data that support the recent models has often been lacking, and virtually no subsurface data has been included in spite of the abundant well-data available from hydrocarbon exploration. A goal of this research is to determine whether any of the models previously proposed is supported by the abundant outcrop and subsurface information available for the Corbin Sandstone Member, or whether another model not previously proposed best fits the combined outcrop and subsurface data.

Fig. 2.6 Paleogeographic model of early Pennsylvanian sedimentation in the Appalachian Basin (Englund and Thomas, 1990).



OUTCROP ANALYSIS

Outcrop analysis reveals that the Corbin Sandstone Member consists of eight major facies. These facies are defined by both sedimentary structures and textures, and the relative abundance of each is shown in Fig. 3.1. This bar graph shows that the bulk of the facies are composed of sandstone that is either planar crossbedded, or trough/tangential crossbedded. Indeed, taken together, these two facies comprise more than 70% of the entire Corbin Sandstone Member. Although the other six facies are much less abundant, they provide valuable information for interpreting depositional environments. The ripple bedded sandstone facies and interbedded sandstone and shale facies, for example, suggest a marine component to the Corbin Sandstone not observed in the other facies.

Facies Descriptions and Interpretations

Quartz Pebble Conglomerate Facies (QPC)

The quartz pebble conglomerate facies, which comprises approximately 2.5% of the sum of all measured sections (Fig. 3.1), is confined primarily, but not exclusively, to the lower third of the Corbin Sandstone Member. This facies consists of polymodal, matrix and clast supported medium

Fig. 3.1 Bar graph showing the relative percent of the eight major facies of the Corbin Sandstone Member. Data compiled from measured sections.

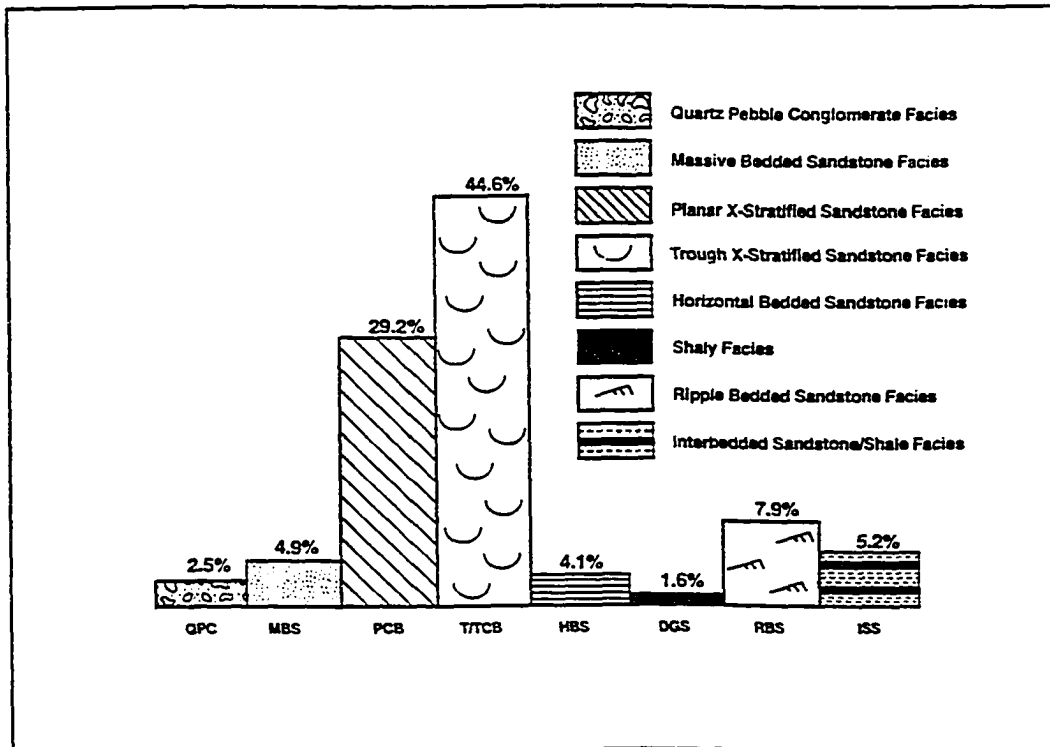
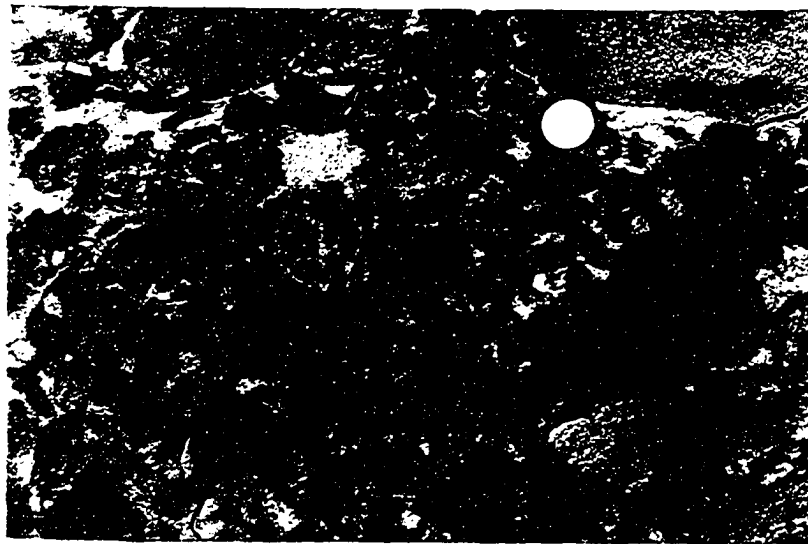
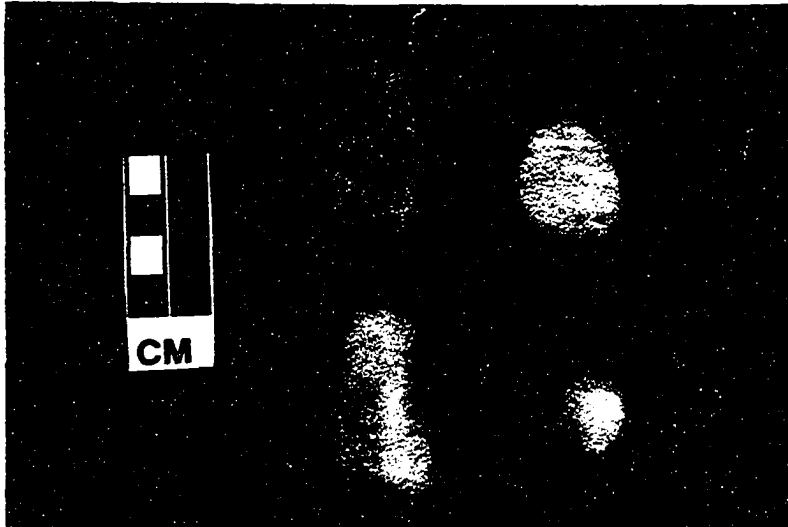


Fig. 3.2 Quartz pebble shapes from the conglomeratic facies of the Corbin Sandstone Member. Clockwise from top left are bladed, oblate, equant and prolate forms. Oblate and equant shapes are abundant, prolate forms are rare.

Fig. 3.3 Mudstone pebble conglomerate in medium-grained sandy matrix from lower portion of outcrop BA-3 (see figure 6 for location).



quartz-pebble conglomerate that is usually associated with poorly-sorted, pebbly, medium-grained quartz-rich sandstone.

Rounded to well-rounded milky (rarely rose and smokey) quartz pebbles are by far the most abundant clast type present. They range in long diameter from 4 mm to 5 cm and average 2 cm. Equant, bladed, oblate and prolate forms are all present (Fig. 3.2), but oblate and equant shapes are most common. In addition to quartz pebbles, subangular to well-rounded medium to coarse (2 to 4 cm) mudstone, shale, siltstone and very fine to fine-grained sandstone pebbles are sometimes present (Fig. 3.3). Also, large (3 cm to 4 m) brown to greenish gray, micaceous, angular mudstone and shale intraclasts incorporated into the medium quartz-pebble conglomerate were observed in one outcrop. No clast imbrication was observed in any of the conglomerates examined.

Poor to well-cemented, sometimes clayey, silty, subangular to rounded, very fine to very coarse-grained quartz-rich sand forms the matrix that binds framework clasts. In addition, poorly-sorted fine to coarse-grained subangular to rounded quartz-rich sandstone containing pea-sized rounded to well-rounded quartz pebbles is usually associated with the conglomerate. Sandstone occurs as thin (2 to 10 cm thick) discontinuous beds and small isolated pods and lenses within the conglomerate. Massive-bedded sandstone, medium and large-scale planar and

trough/tangential crossbedded sandstone, and upper flow-regime horizontal-bedded sandstone may be present directly above, below, or laterally adjacent to a given conglomeratic package.

The QPC facies has three distinct occurrences within the Corbin Sandstone Member. Discontinuous lenses are the most common occurrence and form near or at the base of the sandstone (Fig. 3.4). Ranging from zero to 60 cm in thickness, they usually pinch-out within a few meters. These basal conglomerates fill scours eroded into underlying Breathitt or Mississippian rocks. No internal organization within basal conglomerates is apparent. Horizontal, mineralized fossil tree branch and/or tree branch impressions up to 50 cm long and 20 cm wide are commonly found at the bottom of these conglomerates. Where several branches occur together, no preferred azimuth orientation was observed.

Horizontally discontinuous, tabular packages are a second, less common, form (Fig. 3.5). These conglomerates occur in the lower one third of the sandstone but above the basal contact. They range from 5 cm to 1.1 m thick, often contain poorly-sorted sandstone interbeds, and sometimes show crossbedding at the base and poorly developed horizontal bedding or massive bedding at the top. Occasionally, fossilized Calamites tree limbs or trunks are present at the base of the packages. These conglomerates

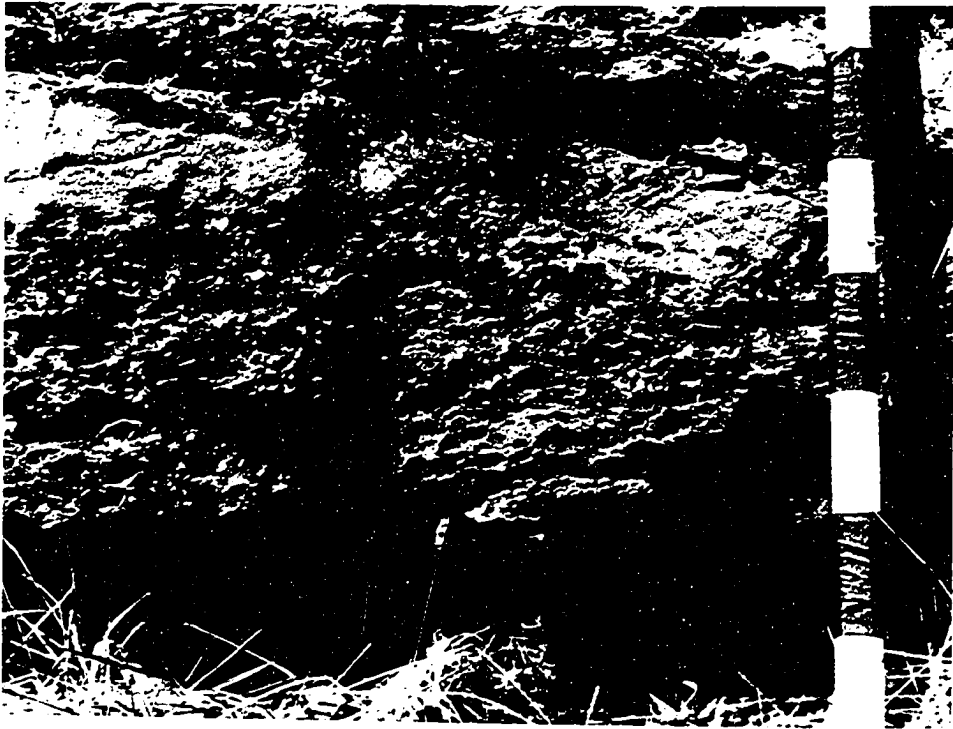
may be associated with large-scale trough/tangential crossbedded sandstone, medium and large-scale planar crossbedded sandstone, or massive-bedded sandstone units.

Finally, the QPC facies may occur as discontinuous packages that intertongue with massive-bedded sandstone (Fig. 3.8). These conglomeratic packages, observed in one outcrop only, occur near the bottom of the section where they are in erosional contact with underlying medium-scale trough/tangential crossbedded sandstone. Erosional relief locally exceeds 1.5 m. Conglomeratic packages are large (1 to 3 m thick and up to 21 m long), and contain the large mudstone and shale intraclasts previously described. Three distinct conglomeratic packages are observed intertonguing with massive-bedded sandstone. The number and size of mudstone and shale intraclasts increases within each package from north to south along the outcrop (Fig. 3.8).

Interpretation

The QPC facies has three separate occurrences in the Corbin Sandstone Member, and each occurrence represents a distinct environmental setting. Discontinuous lenses filling local scours at the base of the unit are interpreted as lag deposits that accumulated at the base of active bed-load dominated channels. Their coarse grain size, thin lenticular geometry, basal location and association with

Fig. 3.4 Basal quartz pebble conglomerate from outcrop
SC-1. See Fig. 1.5 for location.



overlying medium and large-scale trough/tangential crossbeds are characteristic of basal gravel lags in active channels. Gravel lags filling local scoured surfaces in the bottom of active channels are common, and have been documented in modern and ancient fluvial and fluvial-deltaic environments by numerous researchers (e.g., Williams and Rust, 1969; Smith, 1970; Cant and Walker, 1978; Turner, 1983; Dam and Andreasen, 1990, etc.). However, basal scour-fill gravels are not limited to fluvial channels. They are common in tidal channels and have also been observed in ancient deep-sea channels (e.g., Hein, 1984). Basal conglomerates of the Corbin Sandstone Member are not deep-sea channel scour-fill conglomerates because they can be observed in close proximity to, or directly overlying autochthonous coals.

Gravel lags in tidal channels commonly consist of mudstone clasts and/or shell fragments (Barwis, 1978; De Mowbray, 1983), whereas conglomeratic lags of the Corbin Sandstone Member are predominantly quartz pebbles with rare mudstone pebbles. No body fossils were observed anywhere in the Corbin Sandstone. Compositionally, then, gravel lags of the Corbin Sandstone are more typical of fluvial lags than tidal channel lags.

Conglomeratic units forming tabular packages have a separate origin from basal conglomerates. Considered together, their thickness, textural distribution and internal geometry, suggest that these conglomerates formed

as gravel bars that may have been medial (mid-channel) and/or lateral (bank-attached). Medial bars (the longitudinal bars of Ore (1964)) are an abundant morphological and depositional element in gravelly low-sinuosity rivers, but they can also form in predominantly sandy systems (e.g., the Lower Platte River as shown by Smith (1970)). Gravel bars in modern braided rivers range from a few tens of meters to several hundred meters in length, and from several meters to tens of meter wide (Bluck, 1979; Williams, 1971; Williams and Rust, 1969). Thicknesses typically range from .5 m to 3 m (Williams, 1971; Miall, 1977).

Commonly, there are distinct differences in grain size and sedimentary bedding features between deposits of the bar head versus those of the bar tail in gravelly, medial and bank-attached bars (Bluck, 1975, 1979; Collinson, 1978). If deposits of the bar head migrate over the bar tail, a recognizable vertical textural and stratigraphic profile is often produced. According to Rust, (1972) and Collinson, (1978), deposits of the bar head are relatively more gently inclined and experience higher flow strengths than those of the bar tail. Therefore, bar head deposits tend to be coarser-grained than bar tail deposits, and typically form massive-bedding or crudely developed horizontal-bedding (Fig. 3.5).

Conversely, the bar tail often has a steep downstream

margin that develops an avalanche face over which gravel is transported during high-flow stage, and sand is transported during waning-flow stage. As flow fluctuations are repeated, gravel and sandy crossbeds with are formed (Collinson, 1978). A common vertical stratification sequence, then, consists of crossbedded sand and gravel of the bar tail (Fig. 3.5) overlain by poorly developed horizontal-bedding or massive-bedding of the bar head (Bluck, 1979; Collinson, 1978).

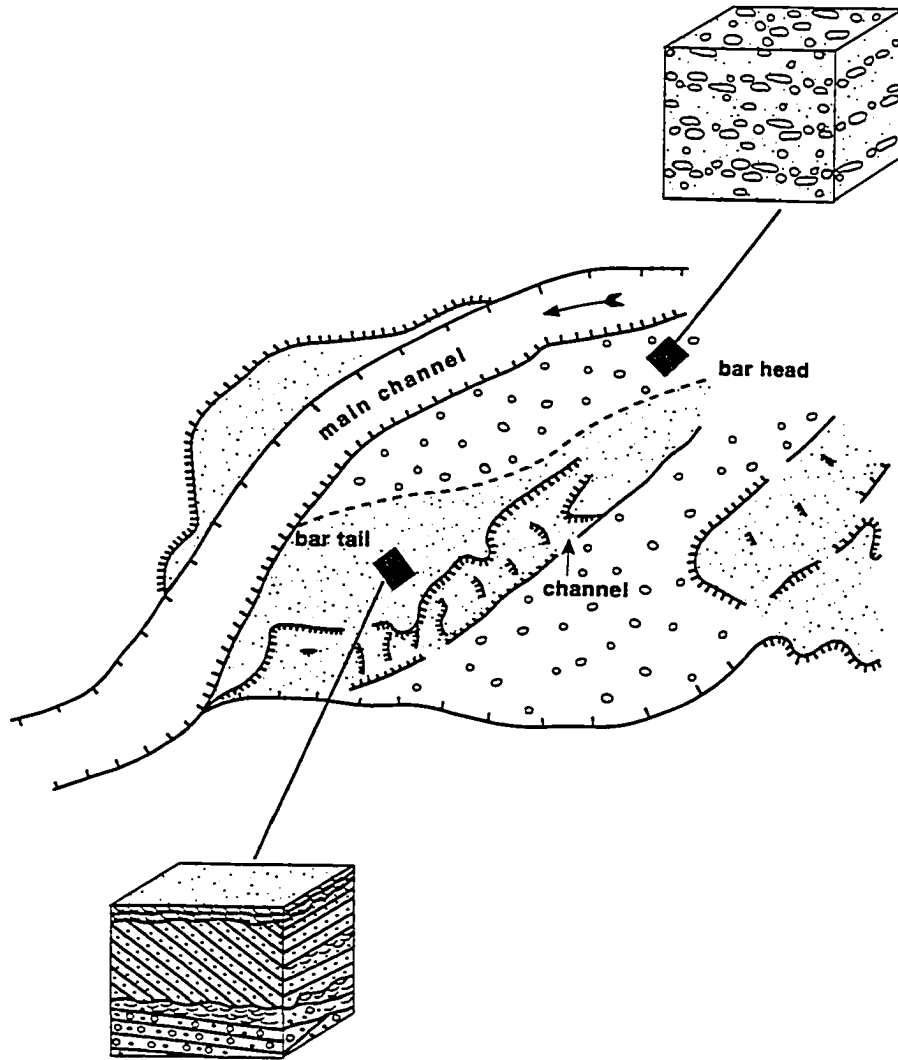
This vertical sequence is observed in tabular conglomerates of the Corbin Sandstone Member (Fig. 3.6). This highly suggests that the tabular conglomerates of the Corbin Sandstone Member formed as gravelly bars similar to those described by Bluck, (1979) and Collinson, (1978). However, determining whether these bars are medial or lateral without more detailed information regarding their geometry is not possible. Both types exhibit the internal characteristics described above.

The third occurrence of the QPC facies is genetically related to the massive-bedded sandstone facies (see Fig. 3.7). The origin of these conglomerates will be discussed along with origin of massive-bedded sandstone in the next section.

Massive-Bedded Sandstone Facies (MBS)

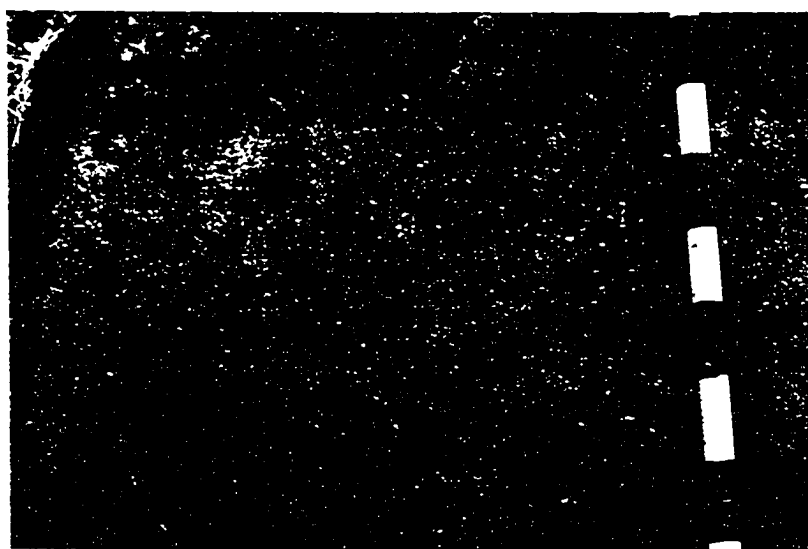
Fig. 3.5

Map showing some common morphological elements and sedimentary structures of a gravelly bar in a braided river. Bar head deposits consist of massive-bedded or poorly developed horizontal-bedded gravel and sand. Bar tail deposits consist of crossbedded gravel and sand. Migration of the bar head over the bar tail results in crossbedded sand and gravel overlain by massive or horizontal-bedded sandy gravel. Modified from Bluck (1979).



Modified from Bluck (1979)

Fig. 3.6 Tabular, quartz-pebble conglomerate.
Note alternating pebbly and sandy crossbeds
at base (arrows) overlain by poorly developed
horizontal bedding at top. Photo taken from
Outcrop ZA-3.



The massive-bedded sandstone facies is not abundant in the Corbin Sandstone Member, accounting for only 4.9% of the sum of all measured sections (Fig. 3.1). It consists of medium-grained, subangular to subrounded, poor to well-sorted, micaceous quartz-rich sand. The mean grain size of the massive-bedded sandstone is medium grained lower (280 to 350 μ), and little variation in mean grain size exists from one unit to another.

Moderate to poor-sorting is typical of the MBS facies, although occasional well-sorted units can be observed. Grain size in the sand size fraction ranges from very fine to very coarse-grained. Local pods, streaks, and lenses of very coarse sand and fine gravel may be observed in some outcrops. In addition, rounded to well-rounded pea-sized quartz pebbles are scattered sparsely throughout most units. In outcrop BA-3 (see Fig. 1.5 for location), where massive-bedded sandstone intertongues with the QPC facies, large (up to 1.5 m long), micaceous mudstone and shale intraclasts may be observed near the base of the unit (Fig. 3.7). In one outcrop (MC-1) a slight fining-upward textural trend was observed within the MBS facies.

Although bedding characteristics are not apparent, bounding contacts are usually easily observed. Flat upper contacts and erosional lower contacts are typical of the MBS facies. Generally speaking, the lack of bedding features the presence of scattered quartz pebbles within the MBS

facies provide a sharp contrast with adjacent, bedded sandstone. In the case of outcrop BA-3 (Fig. 3.7), the textural contrast between the medium-grained MBS facies and the QPC facies makes bounding contacts clear, even though both units lack bedding. This outcrop also shows pronounced interfingering of massive-bedded sandstone and conglomerate. Here, the two facies intertongue laterally up to 7 m over a 3 m vertical distance. Bounding contacts between the two facies show considerable relief (up to 1 m) across the contact. In other outcrops erosional upper contacts may be observed where the MBS facies is overlain by conglomerate, planar crossbedded sandstone, or trough/tangential crossbedded sandstone.

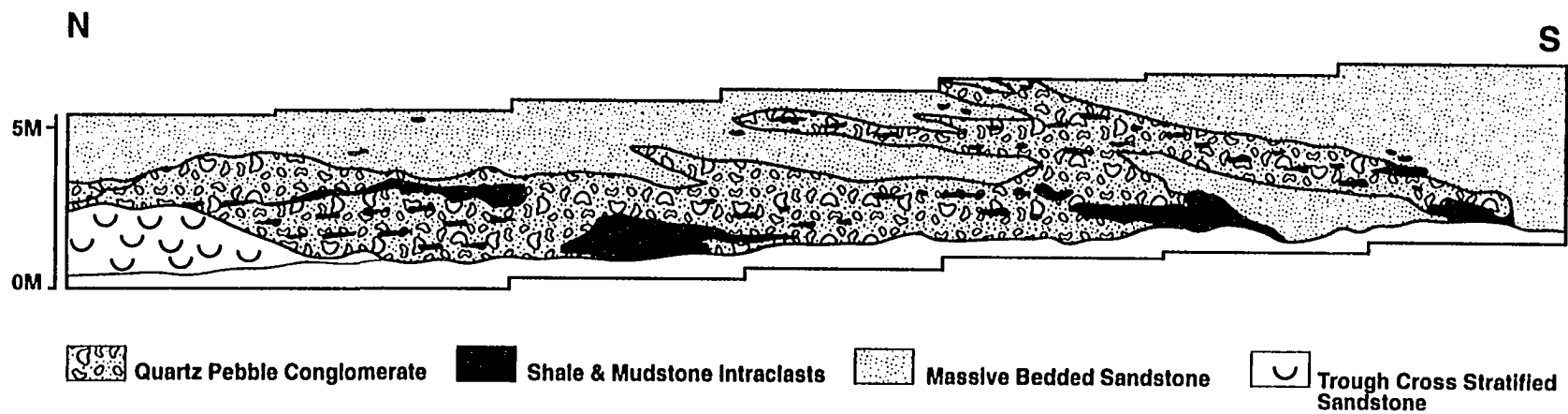
Massive-bedded sandstone units range from 1 to 6.2 m in thickness but average 2 m thick. Where present, massive-bedded units account for a relatively small percentage of the outcrop, and they are not present in the majority of the outcrops examined. Of the 15 outcrops measured and described, only six contain the MBS facies.

Interpretation

The erosional lower contacts, homogenous internal characteristics, and association with structureless conglomerates containing large, angular, mudstone and shale intraclasts, suggests that the massive-bedded sandstone

Fig. 3.7

Line drawing from photomosaic showing
intertonguing quartz-pebble conglomerate and
massive-bedded sandstone. From basal portion
of outcrop BA-3.



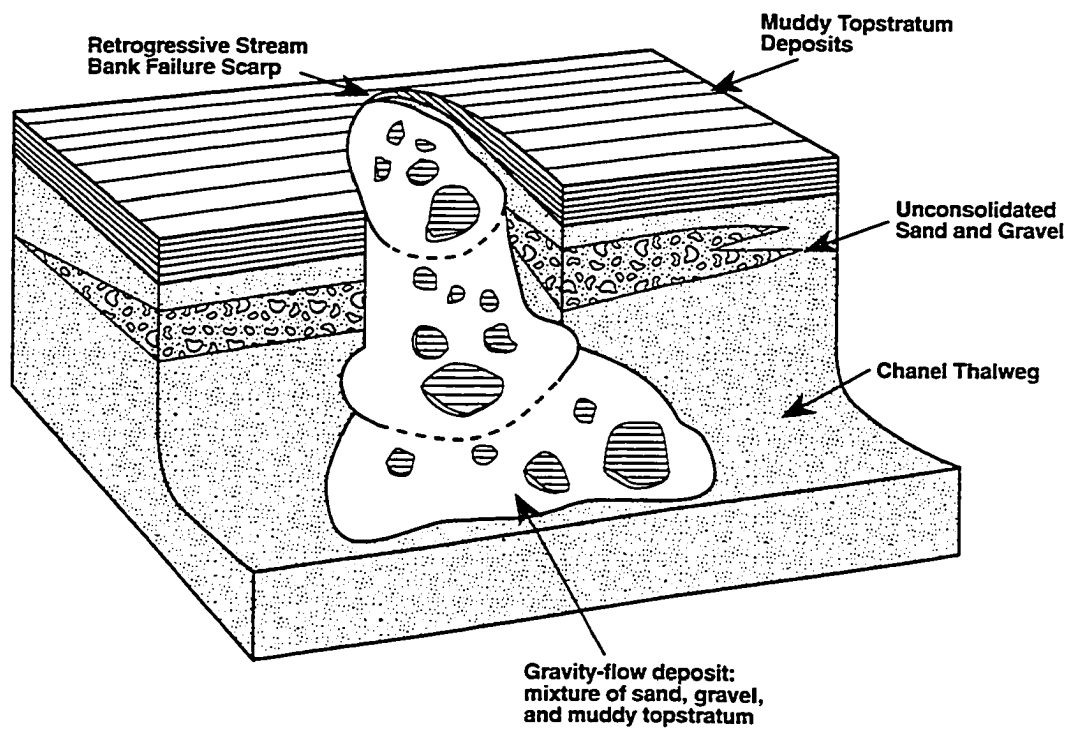
facies is the product of gravity-flow deposition. The most likely cause was retrogressive stream bank failure.

Figure 3.8 is a depositional model explaining the association of lithologies and facies shown in Fig. 3.7. Oversteepening of channel banks and elevated pore pressures in unconsolidated sand and gravel results in stream bank failure and thick gravity-flow deposition in the channel thalweg. The large, "floating", mudstone intraclasts contained within the QPC and MBS facies shown in Fig. 3.7 are best interpreted as muddy topstratum deposits. The topstratum deposits maintained their cohesiveness better than the underlying unconsolidated sand and gravel into which they were eventually incorporated as a gravity flow deposit.

Massive-bedded sandstone deposits very similar to those of the Corbin Sandstone Member have been observed in braided-fluvial deposits of the Triassic, Hawkesbury Sandstone of Australia by Conaghan and Jones (1975) and Rust and Jones (1987). There, massive-bedded sandstones with erosional lower contacts and concordant upper surfaces contain angular mudstone intraclasts up to 10 m long dispersed throughout, but lying subhorizontally within the massive-bedded sandstone matrix. Rust and Jones (1987) believe that oversteepening of channel banks from scouring caused stream bank failure along potential slip surfaces, leading to gravity-flow deposition within the active

Fig. 3.8

Depositional model for lithofacies associations shown in Fig. 3.7. Retrogressive bank failure results in gravity-flow deposition and incorporation of muddy topstratum deposits into the QPC and MBS facies.



channel, and incorporation of muddy overbank deposits into the gravity-flow deposit .

According to Laury (1971), gravity-flow deposition is most likely to occur at flood stage, where water saturation increases sediment density and elevates pore pressure, decreasing internal shear strength. Falling stage then leads to the withdrawal of water support and bank failure along slip surfaces where concentrated bank seepage is highest.

Other researchers have observed massive-bedded sandstones associated with fluvial deposits similar to the massive-bedded sandstones of the Corbin Sandstone Member. Plint (1986), observed large (up to 10 m) mudstone clasts above scoured surfaces incorporated into sandy, massive-bedded fluvial deposits of Pennsylvanian age in Nova Scotia and New Brunswick. He interpreted these as gravity-flow deposits resulting from stream bank failure. Turner and Monro (1987) noted massive-bedded sandstones filling channels up to 2.5 m thick and 10 m wide in Carboniferous rocks of northeast England and concluded that these were gravity-flow deposits resulting from stream bank failure. Dam and Andreason (1991) examined Silurian rocks in Norway that they interpreted as fluvial deposits. They described massive-bedded sandstones units similar to the MBS facies of the Corbin Sandstone Member, and interpreted these as the products of gravity-flow deposition. These units contained

basal scoured surfaces and "floating" mudstone clasts up to 15 cm long. Godin (1991) also noted massive-bedded sandstone units with basal scoured surfaces within the Jurassic age Morrison Formation in New Mexico. He interpreted the Morrison Formation these as a braided-fluvial deposit but offered no interpretation for the massive-bedded sandstone deposits.

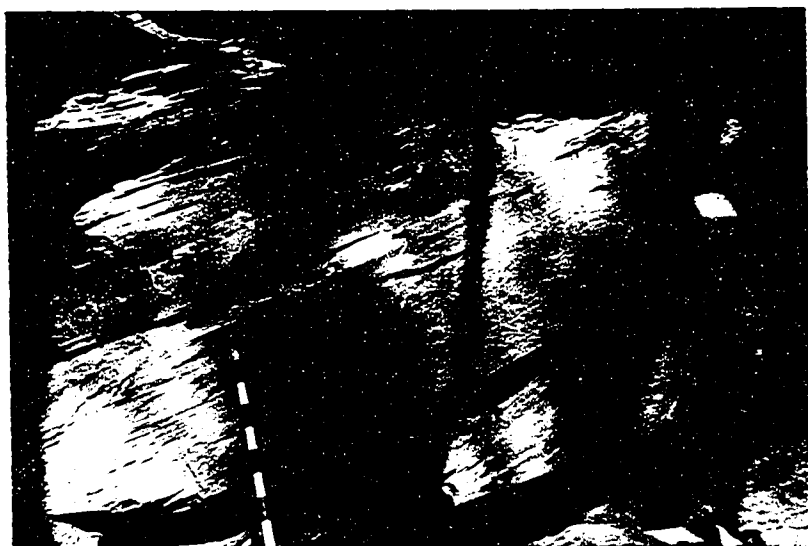
The erosional lower contacts, the lack of any observable sedimentary structures that would suggest deposition by traction sedimentation, and the association of MBS units with structureless conglomerates containing large, angular, mudstone intraclasts supports a gravity-flow interpretation for MBS units. This conclusion is further supported by the work of Wizevich (1991). He also concluded that massive-bedded sandstones he observed in the Lee Formation were the product of gravity-flow deposition.

Planar Crossbedded Sandstone Facies (PCB)

Planar crossbedded sandstone is the second most abundant facies of the Corbin Sandstone Member, accounting for approximately 29.2% of the total of all measured sections (Fig. 3.1). The PCB facies consists of poor to well-sorted, fine to medium-grained, subangular to subrounded, pebbly quartz-rich sand. Crossbed sets range in thickness from 7 cm to 2.3 m (Fig. 3.9), but large-scale

Fig. 3.9

Large-scale, planar tabular crossbed set from outcrop SL-3. This is largest PCS set observed in the Corbin Sandstone Member (2.3 m thick).



sets (.75 m to 5 m) dominate, accounting for about 42% of the facies. Small-scale sets (.07 m to .4 m thick) account for 30%, while medium-scale sets (.4 m to .75 m thick) comprise 28% of the facies.

Textural variation in the PCB facies can be considerable. It can vary from small to large-scale sets and from one set to another of the same size. It may also vary laterally and vertically within a single set. Small-scale sets are typically fine-grained and well-sorted, whereas large-scale sets are usually medium-grained and moderately-sorted. Within large-scale and medium-scale sets, crossbeds sometimes show grain-fall and grain-flow couplets of medium and coarse to very coarse-grained laminae that become more pronounced and coarser-grained toward the toe-sets. The overall effect is to highlight the cross-beds as well as the vertical segregation of textures within the set.

The range in mean grain size among PCB sets is lower fine-grained to upper medium-grained (125 to 500 μ). Locally, within a given set, it may reach very coarse sand and fine gravel (2 to 4 mm). Pea-sized rounded to well-rounded, equant quartz pebbles are common in the medium and large-scale PCB sets. They may be scattered throughout a given set or concentrated as pebble thick laminae along crossbeds. Also, oblate, rounded to well-rounded 1 cm to 30 cm diameter (2 cm to 3 cm average) claystone, mudstone and

shale clasts are scattered sparsely throughout or concentrated at the base of some sets.

The geometry of PCB sets takes one of two forms: planar tabular or planar wedge-shaped, but planar tabular sets are more common. Planar wedge-shaped sets range from small to large-scale and can be traced laterally up to 30 m before wedging out into other planar-wedge sets, being truncated by channels, or disappearing from view. Planar tabular sets are more laterally persistent than planar wedge sets. They can be traced the entire length of an outcrop, 100 m or more in some cases.

When traced laterally along an outcrop, individual sets of planar crossbeds may show considerable internal variation. For example, planar crossbeds sometimes grade down-flow into sigmoidal crossbeds. Conversely, sigmoidal crossbeds may be observed grading down-flow into planar crossbeds. In addition, planar crossbeds may grade down-flow into compound crossbeds. Dip angles of crossbeds range from 14 to 25 degrees with an average of 19 degrees.

Bounding surfaces of planar crossbed sets may be straight or erosional. Straight contacts are most commonly observed between stacked PCB sets (Fig. 3.10). A one or two laminae thick layer of pea-size quartz pebbles frequently separates PCB sets, making set boundaries easily discernable. Also, because many PCB sets are coarser grained near the toe-sets than near the top, a clear

Fig. 3.10 Stacked, large-scale, planar tabular crossbed sets (PCB) with sharp contacts. Note the difference in apparant dip angle between adjacent sets. Photofrom outcrop SL-3.



textural distinction often occurs across set boundaries.

Straight contacts also occur where medium and large-scale PCB sets are overlain by small-scale PCB sets and ripple beds. The presence of ripples capping medium and large-scale PCS sets is common in the Corbin Sandstone Member. These ripples are three-dimensional current ripples forming nested sets averaging 20 cm in thickness but reaching 40 cm in some places. Ripples may be observed capping individual sets of solitary or stacked medium and large-scale PCS sets or cosets.

Erosional upper set boundaries of PCB sets are most commonly observed where they are overlain by trough/tangential crossbeds. Medium and large-scale PCB sets can sometimes be observed in-filling local scours. In some cases one or more PCB sets may be truncated by channel-fill sequences.

The distribution of the PCB facies in the Corbin Sandstone Member is highly variable and may be abundant, common, rare or absent in a given outcrop. For example, outcrop SL-2 (see Fig. 1.5 for location) is over 54 m thick and is dominated by PCB sets. In other outcrops (e.g. VO-1) the PCB facies is virtually absent.

Interpretation

Textural characteristics, thickness variations, internal

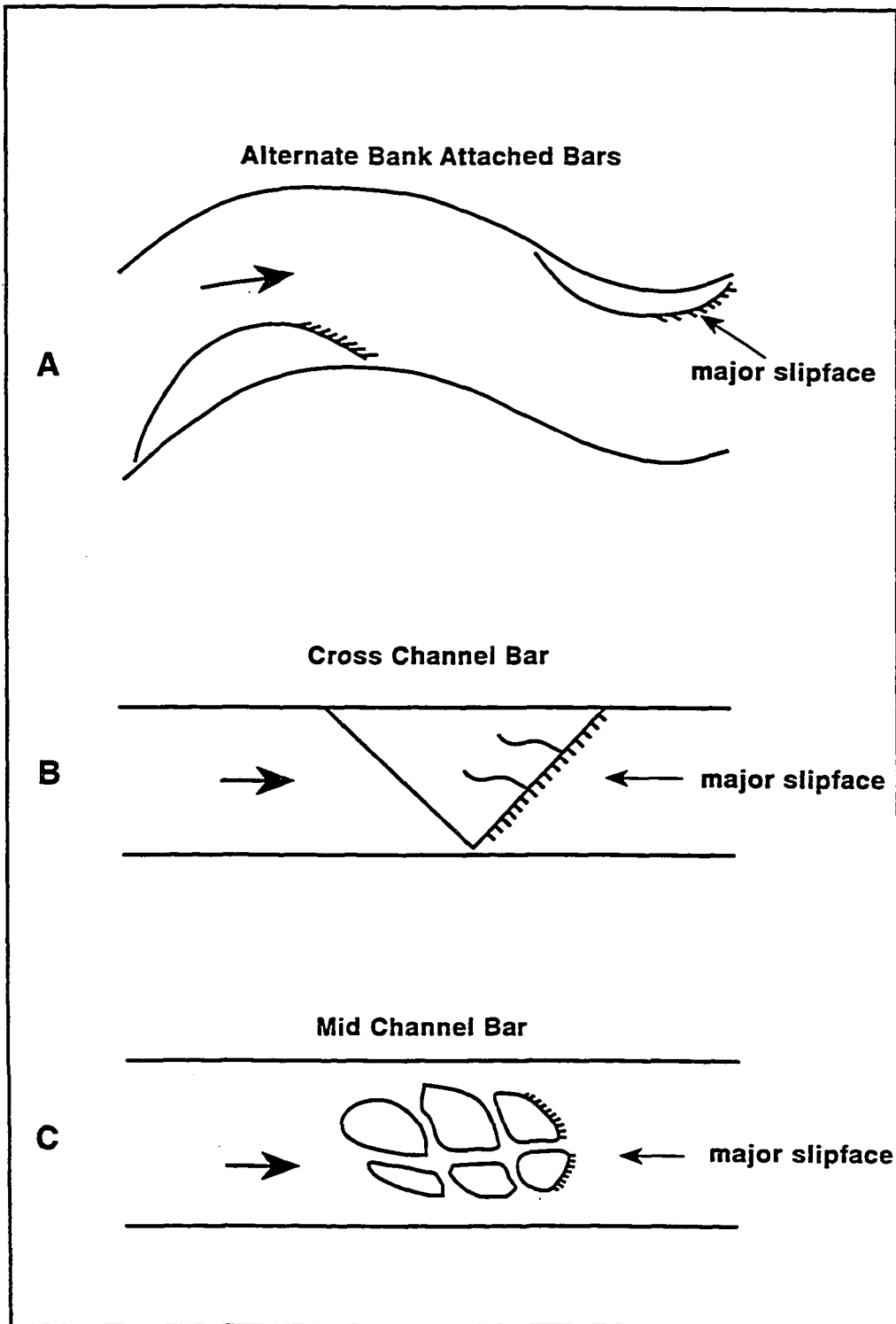
and external geometry, and lateral and vertical facies relationships, suggest that the PCB facies in the Corbin Sandstone Member is the product of transverse bar deposition in a bed-load dominated low-sinuosity or braided river.

The term transverse bar is used here in the broad context of Ore (1964) and Smith (1970) to include the cross-channel bars and linguoid bars common in sandy braided rivers, as well as the alternate bank-attached bars common in low-sinuosity non-braided rivers. All of these bars are non-equilibrium bedforms with downstream slipfaces that produce planar crossbedding (Fig. 3.11).

Transverse bars are solitary or repetitive, rhombic to lobate roughness elements with flat upper surfaces and sinuous or lobate downstream slipfaces (Smith, 1971, 1972; Cant and Walker, 1976; Miall, 1977; Blodgett and Stanley, 1980). Considerable variation in size exists. For example, Smith (1970) and Williams (1971) observed transverse bars tens of meters in length and width on the Platte River, while Collinson (1970) noted transverse bars on the Tana River up to 200 m long and wide. Thicknesses commonly range from a few centimeters to two meters (Miall, 1977), but Cant (1978) suggested that transverse bars on the South Saskatchewan River may exceed three meters thick.

During high-flow stage bar tops are covered by dunes, ripples, or upper flow-regime plane beds that serve to transport sediment to the slipface (Smith, 1970, 1971, 1972;

Fig. 3.11 Three types of transverse bars common in low-sinuosity and braided rivers that produce planar cross-stratification. Included are: alternate bank-attached bars (A), cross-channel bars (B), and mid-channel bars (C).



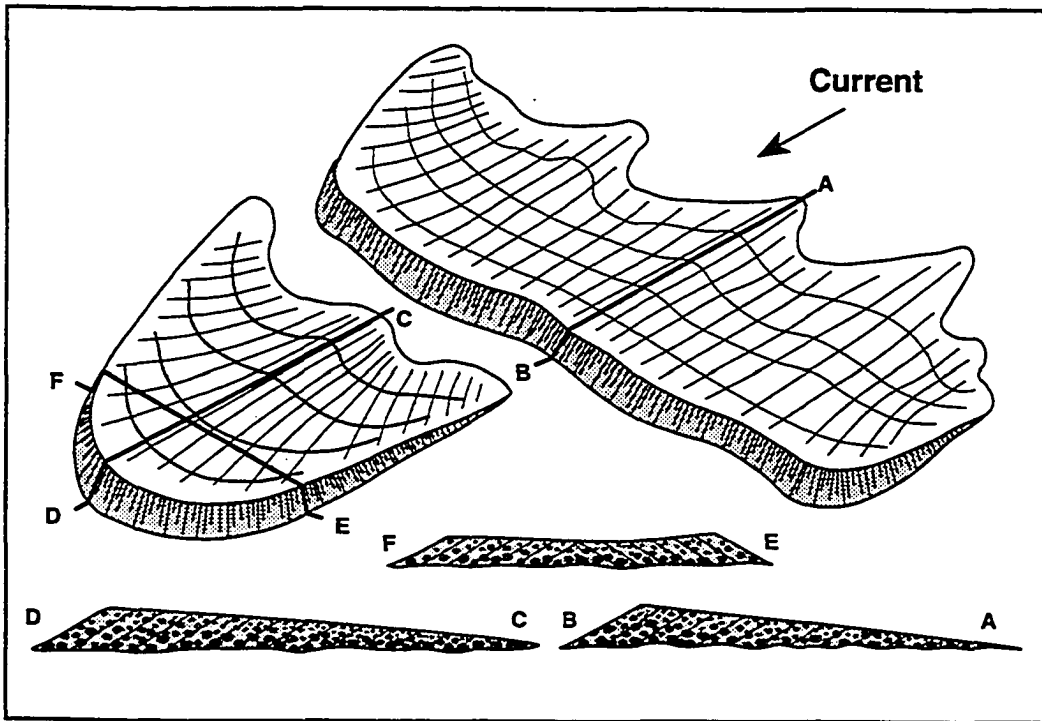
Williams, 1971; Cant and Walker, 1978). Often these bedforms can be observed during low-flow stage. However, according to Blodgett and Stanley (1980) planation without ripple preservation may occur if water level drops and flow-velocity remains high. The result is a truncation surface with a veneer of very coarse sand and gravel (Williams, 1971). If water level rise is rapid over the bar surface, another transverse bar may be superimposed on the first.

Channels adjacent to bars scour bar flanks thereby inhibiting their lateral extent and altering their shape. During low-flow stage, minor channels dissect the bar tops (Smith, 1970; Miall, 1977; Blodgett and Stanley 1980).

Internally, grain-flow and grain-fall couplets are common in transverse bars (Smith, 1972), and so is compound crossbedding (Williams, 1971). Compound crossbedding forms by ripples superimposed on the bar slipface moving perpendicular or obliquely (up to 45 degrees) to the maximum dip direction as a result of strong side currents (Williams, 1971). The result is a primary crossbedding formed from the bar avalanche face, with intrasets of small-scale crossbedding between the primary laminae, but with a different apparent dip direction.

Externally, transverse bars sometimes display a planar-wedge shaped cross-sectional profile (Williams, 1971). This is due to the lobate shape of many transverse bars, which thin toward their margins (Fig. 3.12). Planar-wedge shaped

Fig. 3.12 Inferred geometries of sandy bars from
braided river deposits of the Lower Devonian
Brownstones, Welsh Borders. Note the wedge-
shaped geometries in both bar types. Modified
from Allen, 1983.



geometries of planar crossbeds have been recognized in ancient braided-river deposits and identified as the product of transverse bar deposition (e.g., Allen, 1983).

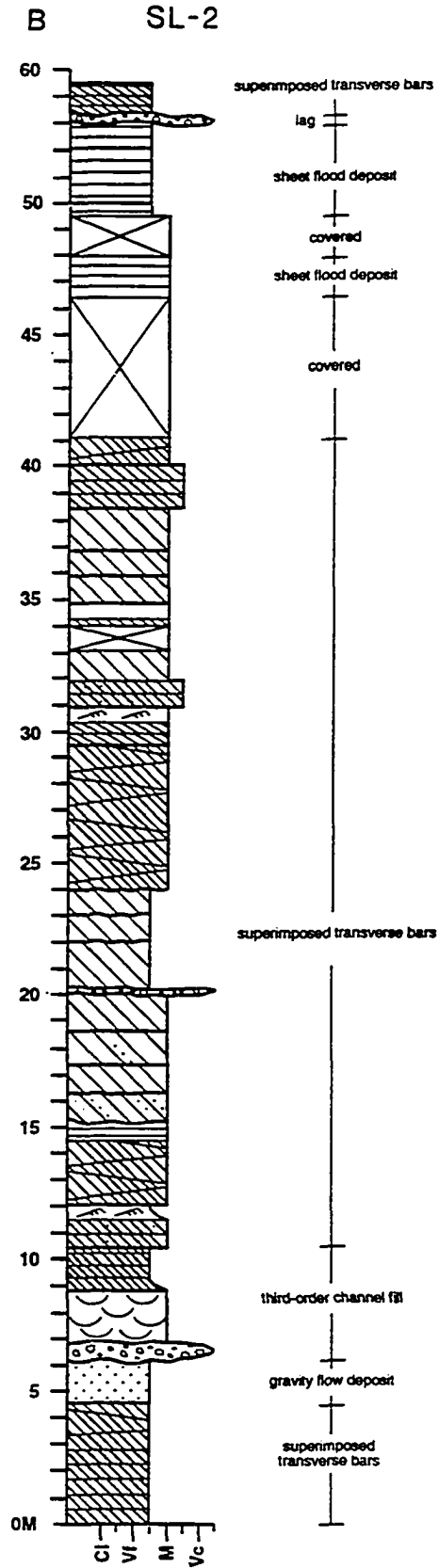
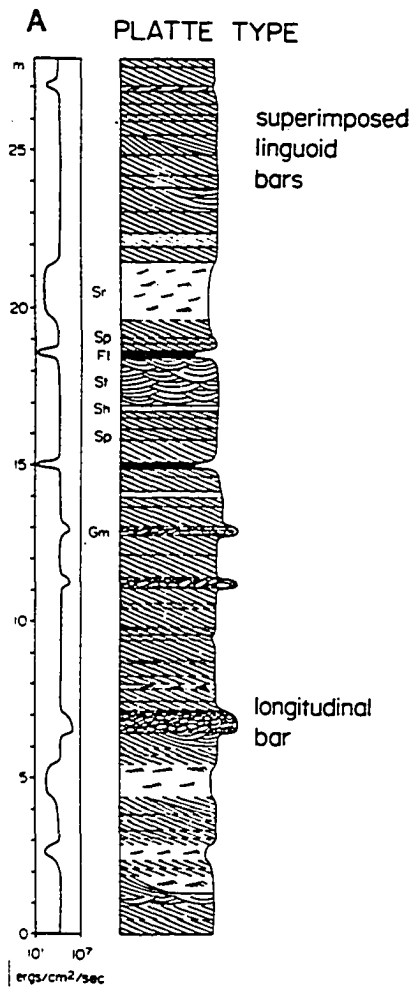
Virtually all of the characteristics of transverse bars described above are readily observed in the PCB facies of the Corbin Sandstone Member. The lateral extent and thicknesses of planar crossbedded sets, and vertical sequences of stacked PCB sets observed in some outcrops are very compatible with those of the Platte River as described by Smith (1971, 1972, 1973), and the ephemeral streams of central Australia as described by Williams (1971).

Figure 3.13 A shows a vertical facies model of the Platte River from Miall (1977). The primary morphological depositional elements in the Platte River are sandy transverse bars. Therefore the vertical sequence is dominated by stacked linguoid (transverse) bars that produce planar crossbedding. Figure 3.13 B is a vertical columnar profile of outcrop SL-2. This outcrop is interpreted to be dominated by transverse bar deposition and compares favorably with the facies model of the Platte River.

Simple, isolated or stacked PCB sets (the mesoforms of Jackson, 1975), separated by truncation surfaces with pebble lags as described above, are common in the Corbin Sandstone Member (e.g., Fig. 3.10). Large-scale PCB sets with superimposed small-scale PCB sets and/or ripples forming compound sets (the macroforms of Jackson, 1975) are also

Fig. 3.13

Figure 3.13 A is a vertical facies model of the Platte River (Miall, 1977). The primary depositional element of the Platte River is the sandy linguoid (transverse) bar that produces planar cross-stratification. Outcrop SL-2 (figure 3.13 B) is interpreted to be dominated by stacked transverse bar deposits and compares favorably with the model.



common. These are interpreted as transverse bars with superimposed smaller-scale bedforms preserved.

Simple and compound PCB sets truncated laterally by T/TCB sets associated with channel-fill sequences are also observed. These are interpreted as side channels that scoured bar flanks. Grain-fall and grain-flow couplets are common in the PCB facies, and the compound crossbeds commonly observed in planar crossbedded sets in modern transverse bars is also observed in the PCB facies of the Corbin Sandstone Member.

Planar-wedge shaped sets preserved in the Corbin Sandstone represent sections cut through lobate transverse bars wherein the thinner portions of a given set represent deposition along the bar margins while the thicker portions were deposited nearer the bar center or downstream slipface.

Trough/Tangential Crossbedded Sandstone Facies (T/TCB)

Trough/tangential crossbedded sandstone is the most abundant facies present in the Corbin Sandstone Member accounting for 44.6% of the total of all measured sections (Fig. 3.1). The T/TCB facies consists of poor to well-sorted, fine to medium-grained, subangular to subrounded quartz-rich sand. Crossbed sets, ranging in thickness from 7 cm to 1.8 m, are dominated by medium-scale sets (.4 m to .75 m thick), which comprise 42.5% of the facies. Small-

scale sets (.07 m to .4 m thick) account for 40%, while large-scale sets (.75 m to 5 m thick) comprise only 17.5% of the facies.

Textural variation is present within the T/TCB facies, but it is less extreme than in the PCB facies. Small-scale sets are typically upper fine-grained or lower medium-grained (177 to 350 μ), whereas medium and large-scale sets are typically lower to upper medium-grained (250 to 500 μ). Fine-grained medium and large-scale sets are rarely observed.

Sorting in the T/TCB facies is better than the PCB facies. Medium and large-scale sets are typically moderately to well-sorted and very well-sorted in some cases. Small-scale sets are also moderately to well-sorted but are consistently better sorted than medium and large-scale sets. Some large and medium-scale T/TCB sets show fine to coarse-grained grain-fall and grain-flow couplets that become more pronounced near the toe-sets. Generally speaking these couplets are less common in T/TCB sets than in PCB sets.

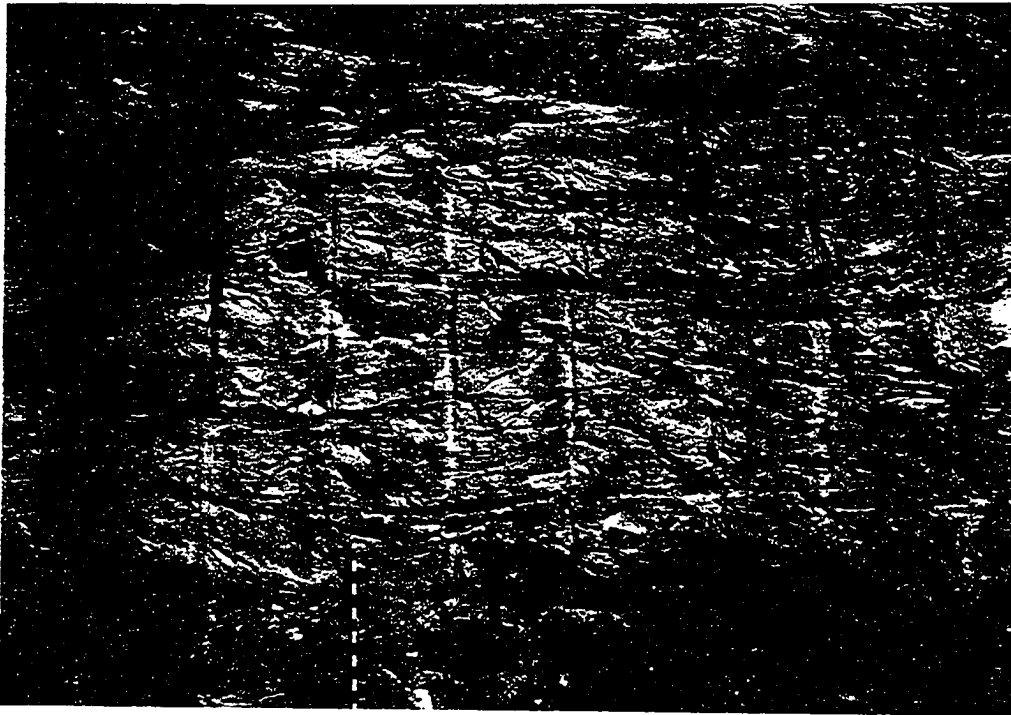
Pea-sized rounded to well-rounded, equant quartz pebbles are common in medium and large-scale sets. Pebbles may be scattered throughout a given set or concentrated along crossbeds. Also, subangular, rounded to well-rounded, oblate claystone and mudstone clasts up to 10 cm in diameter are present near the base of some medium and large-scale

sets. Finally, mineralized and/or coalified, large (up to .5 m long), fossilized tree branches may be found at the base of some medium and large-scale sets.

The internal geometry of the T/TCB sets is a function of how the plane of the outcrop exposes the preserved bedform. For example, if the outcrop face is cut parallel to the paleocurrent direction, T/TCB sets have crossbeds with curved toe-sets tangential with underlying units. T/TCB sets cut parallel to flow can be traced up to 30 m in some outcrops. More commonly, however, they can be traced only 3 m to 10 m before pinching-out. In outcrops cut perpendicular to flow, T/TCB sets are trough-shaped and usually nested (Fig. 3.14).

The greatest variability in geometry in the PCB facies occurs within individual sets in outcrops cut parallel to flow. However, in T/TCB sets variability in geometry is most pronounced among sets cut perpendicular to flow. This variability is expressed in the range of thickness-to-width dimensions of separate T/TCB sets. For example, in outcrop SC-1 a large-scale (1.2 m thick) set cut perpendicular to flow can be traced 25 m along the outcrop. In this set the crossbeds sweep upwards, gently, away from the axis of the trough at low-angles increasing towards the margins of the set as the set thins and eventually pinches-out. The thickness-to-width ratio of this set is .048. By contrast, outcrop ZA-1 has nested sets of medium-scale trough

Fig. 3.14 Nested sets of medium-scale trough crossbeds.
Photo from outcrop ZA-1.



crossbeds (Fig. 3.14) that curve upwards, away from the trough axis rather abruptly. Here, the thickness-to-width ratio of a typical set is .15, more than three times the thickness-to-width ratio of the set described for outcrop SC-1.

Bounding contacts of T/TCB sets are predominantly erosional. Erosional relief occurs between stacked T/TCB sets or where they overlie other facies. Erosional relief across set boundaries ranges from 3 cm to 40 cm and is easily observed in sets cut parallel or perpendicular to flow. Where T/TCB sets occur at the base of sandy channel-fill sequences, erosional relief may exceed 2 m.

Bounding contacts sometimes show little or no relief. This is most common in small and medium-scale sets. Some medium-scale T/TCB sets cut parallel to flow have sharp, straight contacts, defined by a one or two laminae thick layer of pea-sized quartz pebbles. Upper surfaces of medium and large-scale sets are sometimes capped by small current ripples. These ripples are three-dimensional lunate current ripples forming nested sets usually less than 30 cm thick.

The most abundant facies, the T/TCB facies, is present in all but one of the 15 measured sections. However, the abundance of T/TCB facies from one outcrop to another is highly variable. In some outcrops (e.g. ZA-1 and BA-2) the T/TCB facies comprises more than 90% of the outcrop. In other outcrops (e.g. SL-2 and MC-1) the T/TCB facies is

relatively uncommon comprising less than 10% of the outcrops. A common feature of T/TCB sets is their association with sandy, channel-fill sequences. In outcrops where sand-filled channels are clearly present, medium and large-scale trough/tangential crossbeds dominate the channel-fill.

Interpretation

Thickness variations, internal and external geometry, lateral facies relationships, erosional lower contacts, and close association with channel-form geometries suggest that the T/TCB facies is composed of three-dimensional lunate dunes. These dunes formed in both vertically aggrading and laterally accreting major and minor channels in a braided-fluvial environment.

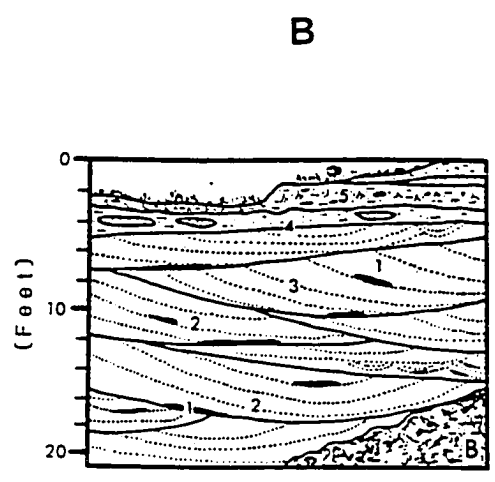
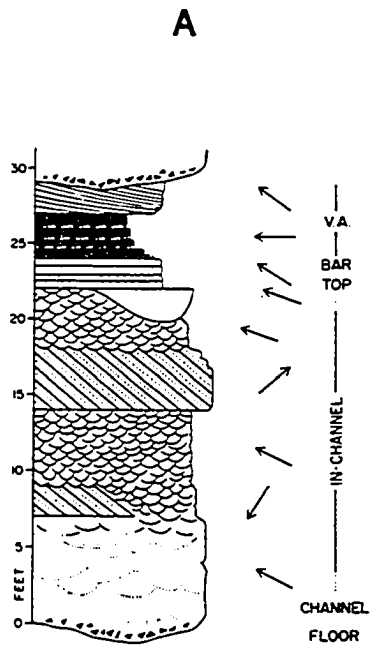
In modern braided rivers, bars can be trenched or cored during low-flow stage to document their internal stratification. However, determining the internal characteristics of channel-fill sediments in modern fluvial environments is more problematic. Coring and trenching are almost impossible in active channels, and observing the types of bedforms flooring the channel is very difficult because of turbidity. However, based on echo soundings in major channels, observations in clear-water channels during low-flow, and trenching of minor channels during extreme

low-flow, a broad consensus exists that the predominant bedform flooring both major and minor channels in braided-fluvial systems are three-dimensional lunate dunes that form trough/tangential cross-stratification (Coleman, 1969; Williams, 1971; Rust, 1972; Miall, 1977; Cant and Walker, 1978; Crowely, 1983; and Collinson, 1986). Figure 3.15 A and B are examples of vertical stratification sequences of channel-fills from both an ancient and modern braided-fluvial setting. In both cases, trough cross-bedding formed from lunate dunes is the dominant sedimentary structure observed.

Echo soundings from active channels reveal that these dunes come in a variety of sizes (Jordan and Pryor, 1992). According to Cant and Walker (1978), large channels contain large dunes. However, Coleman (1969) noted that dunes in the Bramaputra River persisted through depths that ranged from 10 to 90 feet without increasing in size. Coleman also noted the presence of long, low amplitude, lunate and linguoid dunes (his megaripples) with thicknesses of 1 to 5 feet and crestlines that could be traced for more than 1,500 feet. He observed that these long, low-amplitude bedforms appeared most commonly during low-flow and rising-flow stages. The long, low amplitude T/TCB sets observed in some outcrops of the Corbin Sandstone Member may have formed under flow conditions similar to those described by Coleman (1969). Broad low-amplitude trough cross-bedded sets have

Fig. 3.15

Vertical stratification sequences of channel fills from braided river environments. Figure 3.15 A is vertical channel-fill model for the Devonian Battery Pont Sandstone (Cant and Walker, 1992). Figure 3.15 B is a vertical channel-fill sequence from the modern Bramaputra River (Coleman, 1969). In both examples, trough crossbedding is the primary sedimentary structure.



also been observed in ancient deposits by Campbell (1976), who interpreted them as channel-fill sequences formed from braided-fluvial deposition.

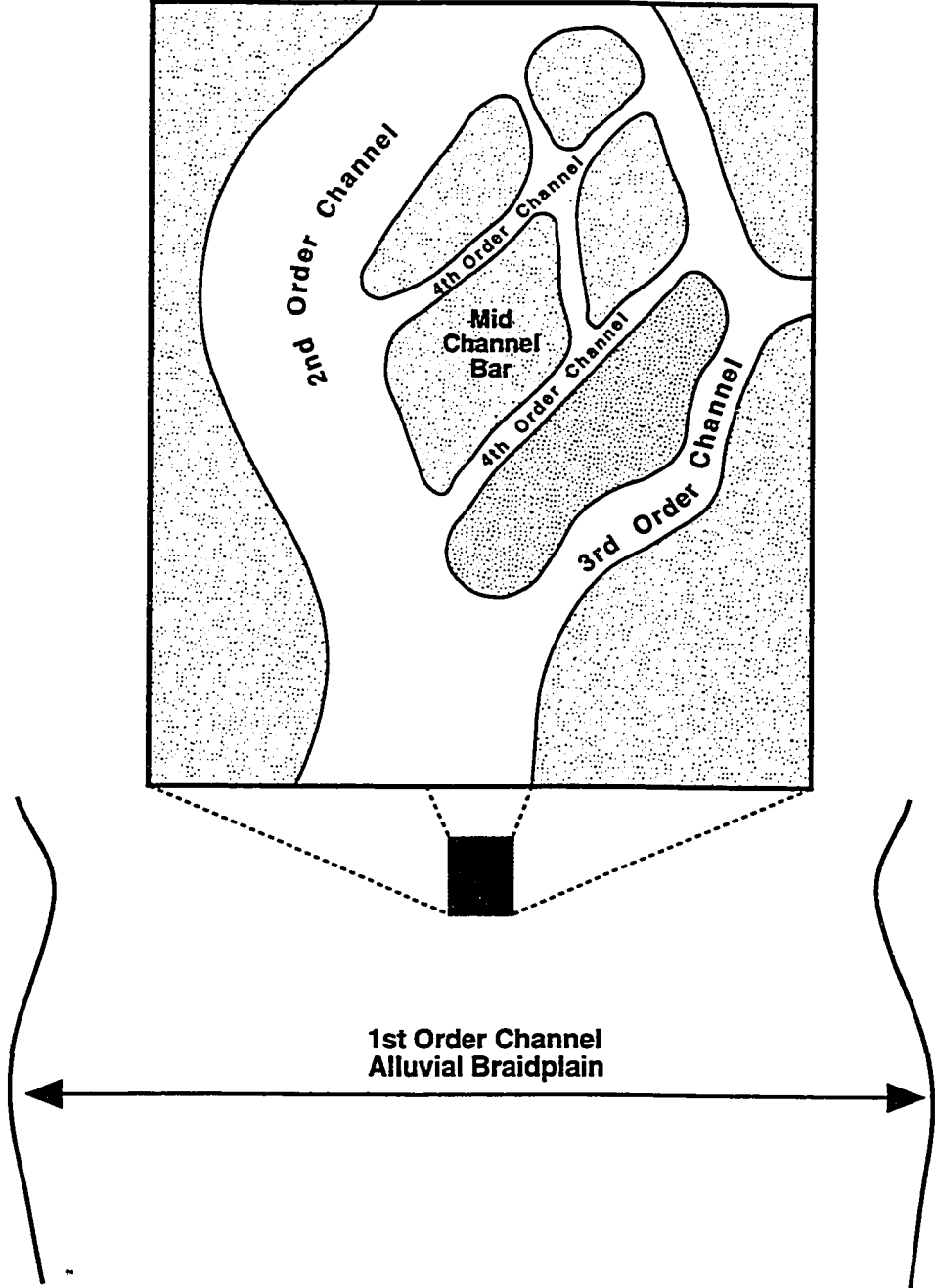
Braided-fluvial systems are multi-channel systems. Researchers working in modern braided-fluvial environments commonly categorize these channels into two broad types: major channels, occupied by water even during low-flow stage, and minor channels occupied during waning-flow stage but inactive during low-flow stage (e.g., Cant and Walker, 1978). This simple classification can be misleading. It implies that braided-fluvial channels are of two distinct sizes, when, in fact, a hierarchy of channel sizes can often be observed (Williams and Rust, 1969; Bristow, 1985).

In the Corbin Sandstone Member, a four order hierarchy of channel sizes can be established, and three distinct orders of channel sizes can be observed at the outcrop level. In all of these channels trough/tangential cross-bedding is the dominant, but not the only, stratification type observed.

Figure 3.16 shows the hierarchy of channels that can be established for the Corbin Sandstone Member. The first order channel is the broad alluvial plain across which braided-fluvial deposition was active, in part or in total, at any given time. This broad valley was unconfined by valley walls, as suggested by the extreme lateral persistence of the Corbin Sandstone Member (Fig. 1.2).

Fig. 3.16

Hierarchy of channels observed in the Corbin Sandstone Member. First order channel is the alluvial braidplain (up to 60 km wide) in which the Corbin Sandstone Member was deposited. Second order channels correspond to major channels active during low-flow conditions. Third order channels may be straight or sinuous and scour bar flanks. Fourth order channels scour bar tops.



However, it was bounded to the west by the Cincinnati Arch and to the east by the nascent Appalachian Mountains which, together, may have restricted its lateral extent.

Second order channels in the Corbin Sandstone Member correspond to major channels that would have been active during low-flow stages. In braided rivers confined by valley walls, there are usually only one or two such channels (e.g., Cant and Walker, 1978; Cant, 1978).

However, in big braided rivers, many large channels may be active during low-flow stage as observed by Coleman (1969) in the Bramaputra River.

Complete second order channels of the Corbin Sandstone Member are beyond outcrop scale. However, the margins of these large channels (comparable to the major channels of Cant and Walker, 1978; and Cant, 1978), can be observed in outcrop. In outcrop BA-2 for example (Fig. 3.17), a second order channel has eroded through a Pennington Formation sandstone and into the Newman Limestone before the basal contact becomes covered. Within the channel, individual sets of large-scale trough/tangential cross-beds up to 1.5 m thick comprise a channel-fill sequence of more than 7 m. Overlying the Pennington Formation, sets of small-scale trough/tangential crossbeds sit above a basal quartz pebble gravel lag.

The extreme erosional relief across the basal contact, the size of the T/TCB sets (amongst the largest observed

Fig. 3.17

Major, second order channel from outcrop BA-2. Channel has eroded through an underlying Pennington Sandstone and into the Newman Limestone. Channel is filled with large-scale T/TCB sets.



anywhere in the Corbin Sandstone Member), and the thickness of the channel-fill, suggest that sediments of outcrop BA-2 were deposited within a large channel that was probably occupied even during low-flow stages. The lack of observable lateral accretion surfaces suggests that the channel was relatively straight, and probably filled by vertical aggradation.

Third order channels are common in the Corbin Sandstone Member and correspond to minor channels that scour bar flanks (Fig. 3.16). They are best observed in outcrops cut perpendicular to flow, where the entire channel-fill sequence is commonly preserved (Figs. 3.18, 3.19, 3.20). Small and medium-scale T/TCB sets dominate the channel-fill. Within the channel-fill, an upward-fining sequence composed of medium-scale T/TCB sets, small-scale T/TCB sets, and ripple bedding can sometimes be observed. Channel dimensions are typically 1 to 3.0 m thick, and up to 20 m wide.

Third order channels sometimes show well-developed lateral accretion surfaces suggesting deposition within a meandering channel (Allen, 1963). For example, outcrop BE-3 contains lateral accretion deposits that can be traced along the outcrop for more than 10 m, directly into a sandy channel-fill sequence (Fig. 3.19). The presence of lateral accretion deposits is not antithetical to a braided-fluvial interpretation. For example, Cant and Walker (1978) noted

Fig. 3.18 Third order channel observed in outcrop
BA-3. Channel-fill contains medium scale
T/TCB sets at bottom that grade upward into
ripples. Lack of lateral accretion surfaces
suggests that the channel was straight and
filled by vertical aggradation. Scale at
bottom of photograph is 1.5 m.

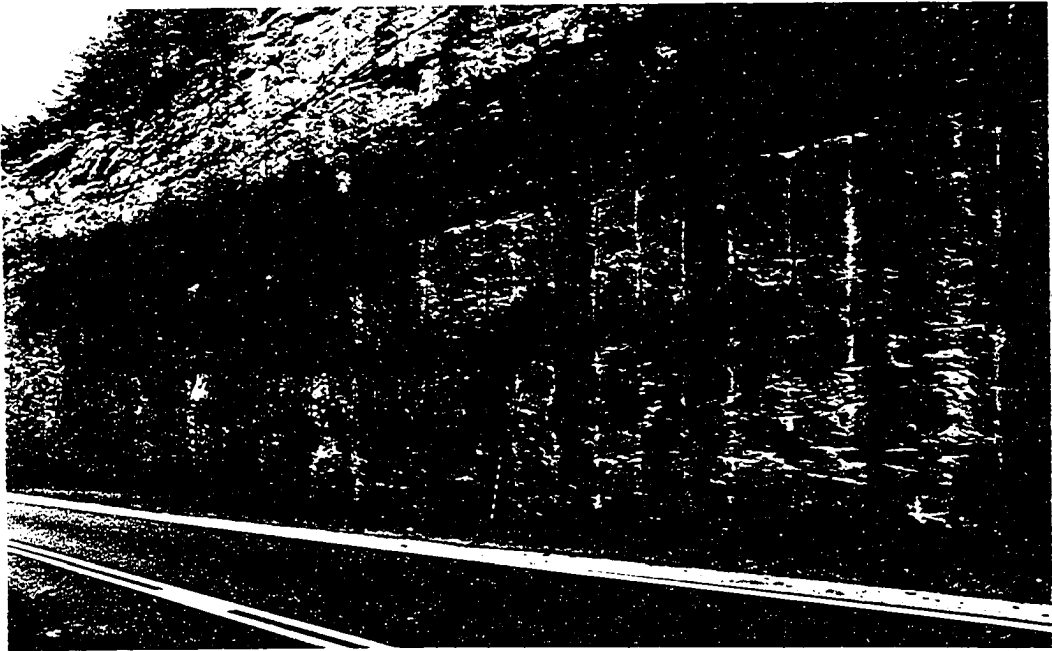
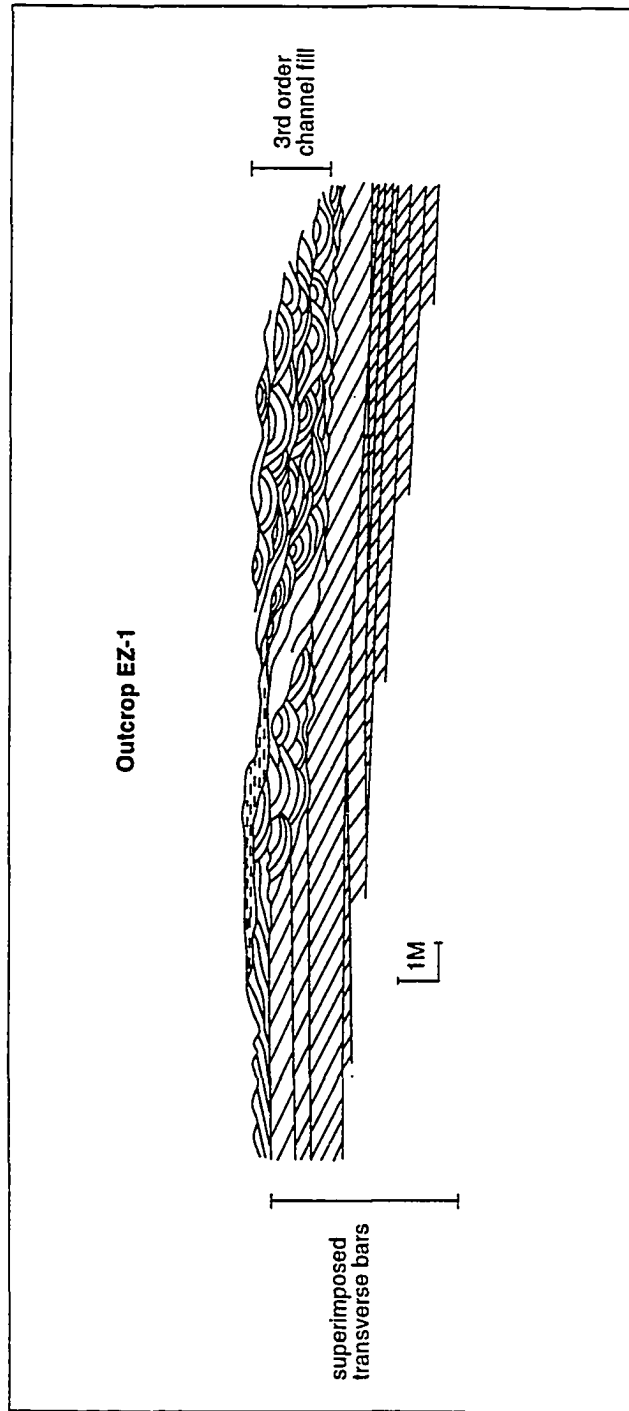


Fig. 3.19

Third order channel from outcrop BE-3.
Well-developed lateral accretion surfaces
(arrows) suggest that this channel had
high sinuosity.



Fig. 3.20 Line drawing from outcrop EZ-1. This drawing shows a small, 3rd order channel that has cut down through two, superimposed transverse bars and into into a third. Medium-scale trough crossbeds dominate the channel-fill.

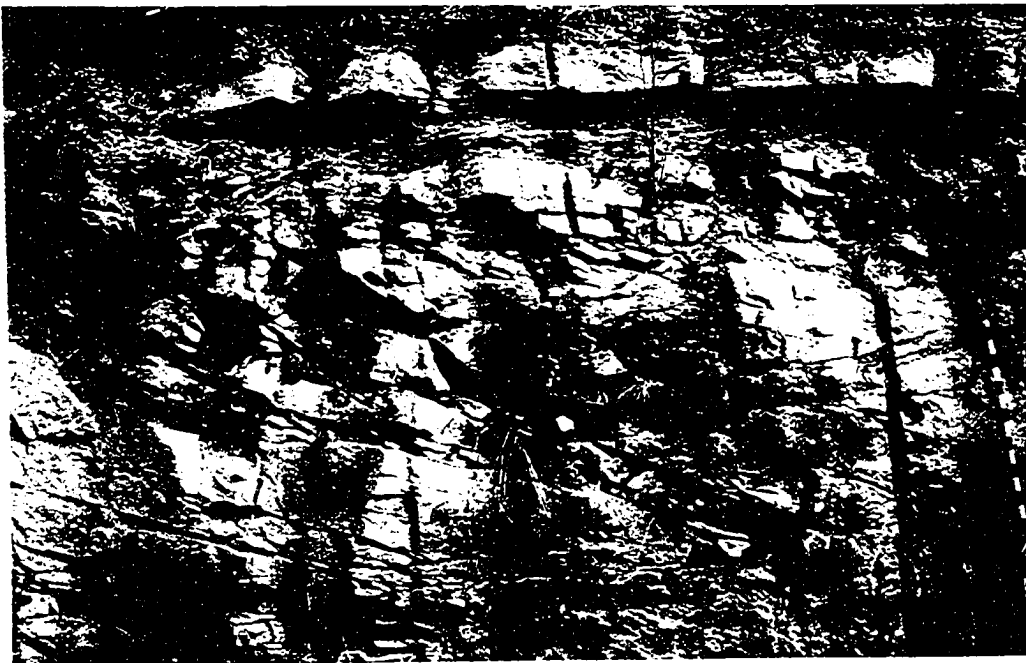


that some channels of the braided South Saskatchewan River were accreting laterally. Also, Allen (1984) noted lateral accretion surfaces in ancient channel-fill sequences which he interpreted as braided-fluvial. Allen further maintains that deposition by lateral accretion is an important depositional mechanism in braided-fluvial systems which has been underemphasized by researchers.

Fourth order channels correspond to minor channels that dissect bar tops during waning-flow stages. These channels are easily observed at the outcrop level and are generally filled by small-scale T/TCB sets. Typically they are less than 1.5 m thick and 8 m wide and can be observed in erosional contact with underlying medium and large-scale PCB sets, representing transverse bar deposition (Fig. 3.21). Fourth order channels show little or no lateral accretion surfaces, suggesting that the channels were straight and filled by vertical aggradation.

In some modern braided rivers, channels are the primary morphological depositional element. Figure 3.22 A is a vertical facies model of the Donjek River. Unlike the Platte River that is dominated by transverse bar deposition, the Donjek River is dominated by major and minor channel-fill sequences (Williams and Rust, 1969). The model shown in Fig. 3.22 A (from Miall, 1977), contains multistory major and minor channel sequences 1 to 20 m thick, with fining-upward textural trends where the dominant sedimentary

Fig. 3.21 Fourth order channel from outcrop EZ-1.
Underlying large scale PCB set represents
a transverse bar into which the channel
has scoured.

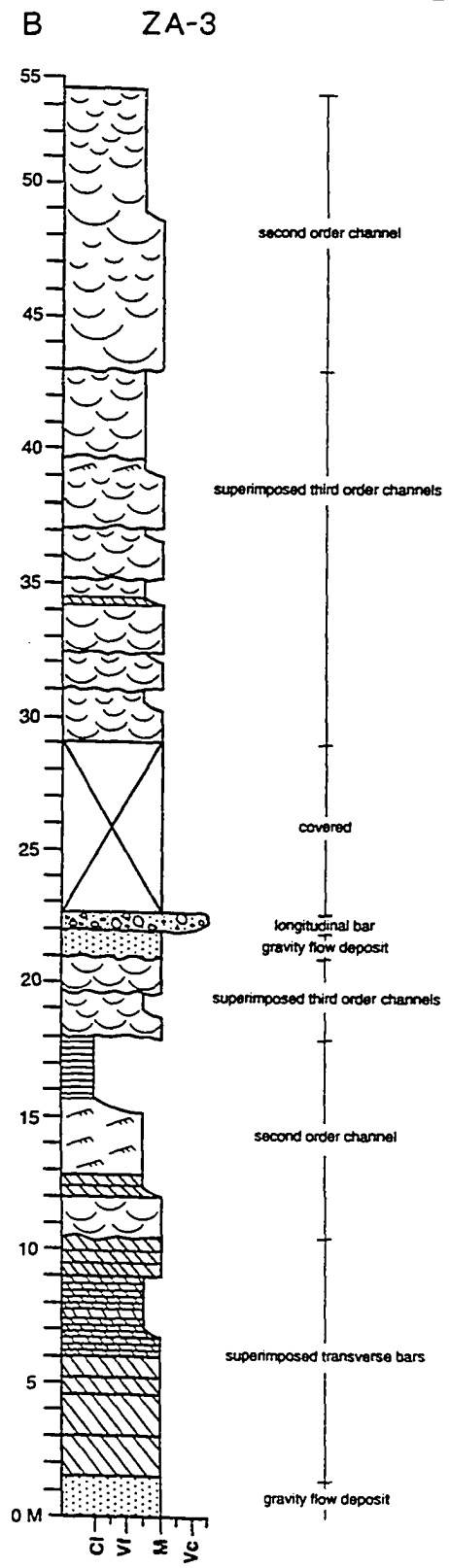
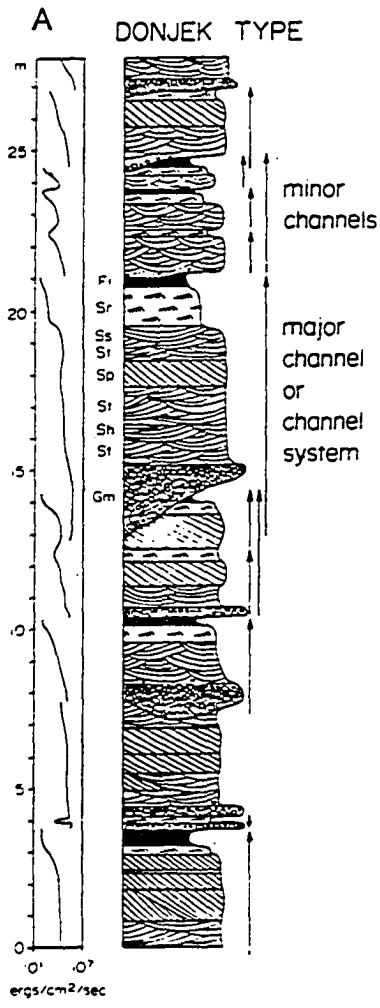


structure is trough crossbedding.

Figure 3.22 B shows the vertical stratification sequence from outcrop ZA-3. This outcrop is dominated by trough crossbedding forming stacked 2nd and 3rd order channel-fill sequences. The vertical stratification sequence from outcrop ZA-3 compares favorably with the model shown in figure 3.22 A and suggests that at the location of outcrop ZA-3, channels are the primary morphological depositional element. Moreover, a comparison of the vertical sequences from outcrops SL-1 with that of ZA-3 (Figs. 3.13 B and 3.22 B) suggests that at places along the ancient Corbin Sandstone river system different depositional elements dominated. Clearly, along some stretches, transverse bars were the primary depositional elements whereas along other stretches channels were the primary depositional elements. This suggests that the facies models proposed for braided fluvial systems are very inadequate. For example, the fact that at certain places within the Corbin Sandstone Member the "Platte Type" model of Fig. 3.13 A fits best with the observed data, whereas at others the "Donjek Type" model of Fig. 3.22 A fits the data best suggests that no single braided river model is adequate for even one system. To suggest that braided river "types" exist that can be represented by individual facies models is not supported by this research.

Fig. 3.22

Figure 3.22 A is a vertical facies model of the Donjek River (Miall, 1977). The primary depositional elements of the Donjek River are major and minor channels that are dominated by lunate dunes that produce trough crossbedding. Outcrop ZA-3 (3.22 B) is interpreted to be dominated by multistory second and third order channel-fill sequences. The vertical sequence from Outcrop ZA-3 compares favorably with the model.



Horizontal-Bedded Sandstone Facies (HBS)

The horizontal-bedded sandstone facies is relatively uncommon in the Corbin Sandstone Member, comprising only 4.2% of the total of all measured sections (Fig. 3.1). It consists of fine to medium-grained, subangular to subrounded, poor to well sorted quartz-rich sand. The mean grain size is lower medium-grained (280 to 350 μ) but grain size among HBS sets is variable, ranging from lower fine-grained (125 to 177 μ) to upper medium-grained (350 to 500 μ).

Sorting in the HBS facies is also variable, ranging from poor to well sorted. Poorly sorted sets often contain rounded to well-rounded quartz pebbles that range from 4 mm to 1 cm in long diameter. Local streaks of coarse to very coarse-grained sand and fine gravel may be observed in some poorly-sorted sets, as well as rounded, 1 cm to 5 cm diameter mudstone clasts. Also, some sets contain mineralized Calamites tree branches up to 10 cm long. In contrast to poorly sorted sets, some HBS sets consist of fine to medium-grained well sorted sand (Fig. 3.23).

HBS sets range in thickness from .8 m to 3.5 m. Generally speaking, well sorted sets tend to be thicker than poorly sorted sets. Individual sets could be traced no more than 20 m before disappearing from view or being truncated by overlying T/TCB sets.

Fig. 3.23 Well-sorted, horizontal-bedded sandstone.
Photo from outcrop SL-2.



Bounding contacts of HBS sets may be straight or erosional. Basal contacts are straight wherever observed, but upper contacts may be erosional where HBS units are overlain by T/TCB sets. In one upper HBS set boundary, an erosional scour was filled by a thin QPC unit.

The HBS facies is present in 8 of the 15 sections measured, but only in outcrops SL-2 and HA-1 does it comprise a significant portion of the section, accounting for 12.8% and 21% of the sections respectively. In all other measured sections the HBS facies accounts for less than 8% of the outcrop.

Interpretation

The horizontal-bedded sandstone facies is interpreted as the product of upper flow-regime plane bed conditions associated with channel-fill, sheet-flood and transverse bar deposition. Although horizontal bedding can form under quiet water conditions, the relatively coarse grain size (fine to medium-grained sand), the presence of scattered quartz pebbles in many units and the association with medium and large-scale trough/tangential crossbedding suggests upper flow-regime conditions.

Upper flow-regime horizontal-bedded sandstone has been documented in modern braided-fluvial deposits, where it occurs in several distinct subenvironments. Smith (1970,

1971) noted that, similar to ripples, horizontal bedding could be observed capping the tops of planar crossbedded transverse bar deposits, where it acts to transport sand to the slipface. Indeed, in the transverse bars that Smith (1970, 1971) examined, trenching of 57 of them revealed that horizontal bedding accounted for 9.4% of the total stratigraphic sequence. Coleman (1969) noted that horizontal bedding was a common stratification type associated with channel-fill sequences in the Bramaputra River. Although Williams (1971), did not commonly observe horizontal bedding, he did note upper flow-regime horizontal bedding at the bottom of some shallow channels. Miall (1977) suggests that horizontal bedding in braided-fluvial deposits is most likely to occur associated with either shallow water flow in channels, or flood conditions.

One of the best documented examples of upper flow-regime horizontal bedding in a modern braided-fluvial setting is that observed by McKee et al., (1967) in flood deposits of the Bijou Creek, Colorado. McKee estimated that horizontal bedding constituted up to 95% of the flood deposits he examined. Individual flood packages up to several thousand feet in width and up to 12 feet thick were observed.

Horizontal bedding has also been documented in ancient braided-fluvial deposits. For example, Dam and Andreason (1990) noted horizontal-bedded units .1 to 3 m thick in

ephemeral stream deposits of Silurian age in Norway. They interpreted these as having formed in wide, shallow, flat-bottomed low-sinuosity channels by high energy ephemeral flows. Godin (1991) examined sandy braided-river deposits of the Jurassic age Morrison Formation in New Mexico and observed that Horizontal bedding comprised some 22.5% of the unit. He interpreted these as the product of upper flow-regime shallow water conditions associated with channel or flood deposition. Fedo and Cooper (1990) noted horizontal bedding in Cambrian age braided-fluvial deposits of the Wood Canyon Formation in California. These deposits occur as single 2 to 3 m thick units of medium to coarse grained arkosic sandstone, that could be traced laterally into trough cross-stratified sets. They interpreted these as the product of upper flow-regime sheet-flood deposition

In the Corbin Sandstone Member, horizontal bedding can be observed associated with all of the subenvironments described above. The most common occurrence of the HBS facies is as discontinuous, tabular, pebbly sandstone units less than 1 m thick that terminate into medium-scale T/TCB sets associated with third order channel-fill sequences. HBS units would have formed in these channels during high-velocity, low-flow conditions, probably during rising or waning-flow stages.

In outcrop SL-2, the HBS facies is not associated with a channel-fill sequence. Instead, the HBS facies forms two

relatively thick units (1.5 m and 3.5 m thick), separated by a covered interval, both of which occur near the top of a section dominated by medium and large-scale PCB sets. The HBS units here are better sorted than those associated with the channel-fill deposits described above. The thickness, overall good sorting, and lack of association with channel-fill deposition suggests these units are the product of upper flow-regime sheet-flood deposition. Thickness intervals are similar to those described by McKee et al., (1967) in modern flood deposits, and by Fedo and Cooper (1990) in ancient ones. Although these units cap a sequence of medium and large-scale PCB sets, they are too thick to have acted as bedforms transporting sand to the slipface of transverse bars, as described by Smith (1970, 1971).

Finally, the HBS facies can be observed capping the top of transverse bar deposits. In the majority of outcrops, medium and large scale PCB units forming compound sets are capped by three dimensional lunate ripples. However, in outcrop EZ-1 for example, a large scale PCB set is capped by a 30 cm thick horizontal-bedded sandstone unit. In this instance the HBS unit acted to transport sand to the slipface of the bar in the manner described by Smith (1970, 1971). However, the association of the HBS facies with transverse bar deposition is uncommon in the Corbin Sandstone Member, it is more commonly associated with sandy channel-fill deposits.

In summary, the HBS facies has three occurrences in the Corbin Sandstone Member: 1) it is found associated with sandy channel-fill sequences along with T/TCB sets, 2) it occurs as relatively thick, overbank, sheet-flood deposits, and 3) it forms thin, capping units on PCB sets. In all cases, it is considered a product of upper flow-regime bedform deposition in a braided-fluvial setting.

Dark Gray Shale Facies (DGS)

The dark gray shale facies is the least abundant of the eight major facies of the Corbin Sandstone Member, accounting for 1.6% of the total of all measured sections. It consists of dark gray to black, micaceous, hackly to platy, clayey to silty, carbonaceous shale. Finely disseminated plant fragments are common along partings. Where clay-rich, the shale is highly fissile with a waxy texture; where silty, it is hackly and sometimes displays a well-developed pencil cleavage. In places, the shale contains continuous beds and/or isolated lenses of fine to medium-grained quartz-rich sandstone. No body or trace fossils were observed in this facies.

The DGS facies is lenticular in its outcrop geometry. Lower bounding contacts are erosional and concave-up, whereas upper contacts are straight. The DGS facies forms isolated lenses within the sandstone, displaying a well

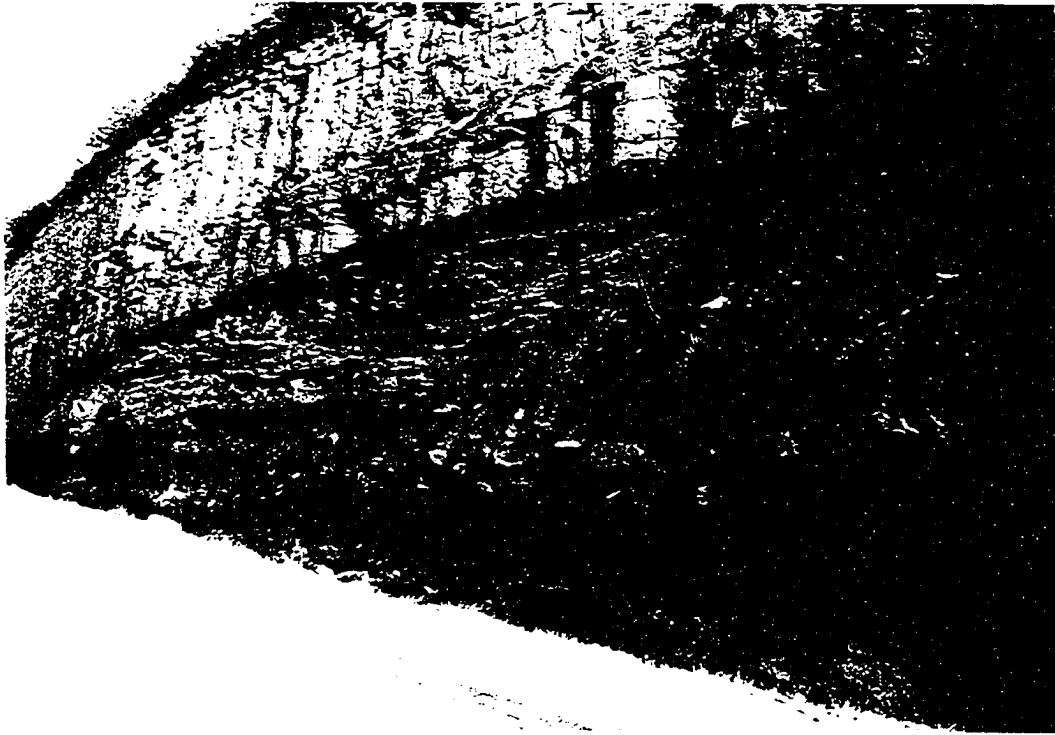
developed channel-form geometry of variable dimensions. For example, one isolated lens measures approximately 2 m thick and can be traced laterally for 12 m before pinching-out into sandstone. A larger, 6 m thick lens (Fig. 3.24), can be traced laterally for approximately 28 m along the outcrop. The DGS facies is present in only 5 of the 15 measured sections and never exceeded 7% in any of the measured sections.

Interpretation

The DGS facies is interpreted as the product of abandoned channel-fill deposition. The erosional and concave-up geometry of the lower bounding surface, the lenticular shape of the DGS units, and the fine-grained nature of the fill suggests deposition in a channel with standing or sluggish water.

In the case of the Corbin Sandstone Member, the size of the shale lenses are comparable with the third order, sandy channel-fill sequences previously described. Channel abandonment may have occurred through either avulsion or meander loop cut off. However, because lateral accretion surfaces are a minor component of the shale-filled channels observed, channels were probably relatively straight. Therefore, abandonment by avulsion is more likely.

Fig. 3.24 Lenticular shale with channel-form
geometry. Photo from outcrop EZ-1.



Interbedded Sandstone and Shale Facies (ISS)

The interbedded sandstone and shale facies comprises 5.2% of the total of all measured sections of the Corbin Sandstone Member (Fig. 3.1). It consists of very-fine to fine-grained, well-sorted, subangular to subrounded, quartz-rich sandstone interbedded with dark gray to black, sandy, silty, micaceous, carbonaceous shale (Fig. 3.25).

Sandstone beds of the ISS facies range in thickness from 5 cm to 1 m and form tabular ledges that can be traced laterally, along with the shale interbeds, the entire length of an outcrop. Overall sorting in the sandstone is very good. Primary sedimentary structures in the sandstone are dominated by current ripples some with clay flasers. A few thin sandstone ledges have round-crested oscillation ripples (Fig. 3.26). Small and medium-scale trough/tangential crossbeds are commonly observed in association with the sandy portion of the ISS facies.

Shale beds are thinner than sandstone beds, ranging from 5 to 30 cm thick. Within the shale beds are numerous, thin (less than 10 cm thick) very fine to fine-grained sandstone beds and lenses that form a variety of small-scale sedimentary bedding features important for paleoenvironmental interpretation. These features include lenticular bedding, wavy and wavy-flaser bedding, and thin (less than 5 mm thick), rhythmically alternating

Fig. 3.25 Interbedded sandstone and shale facies.
Directly above are T/TCB sets within the
ripple-bedded sandstone facies. Photo
from outcrop BA-3.

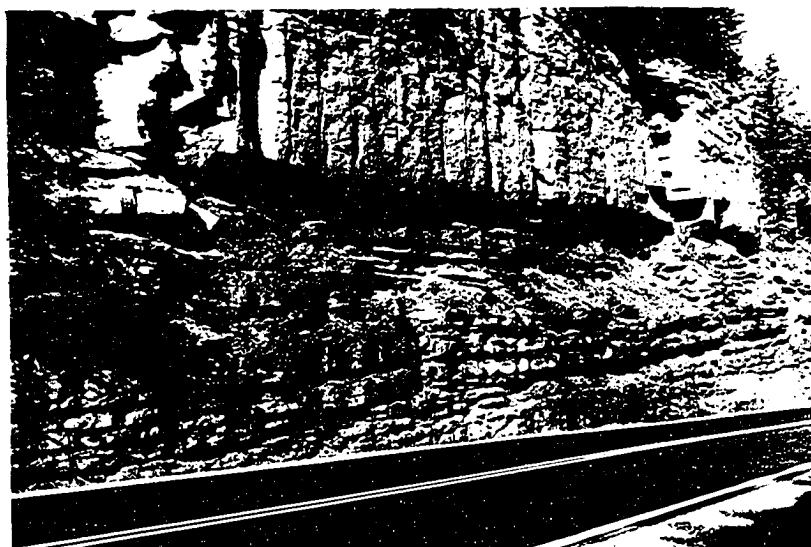
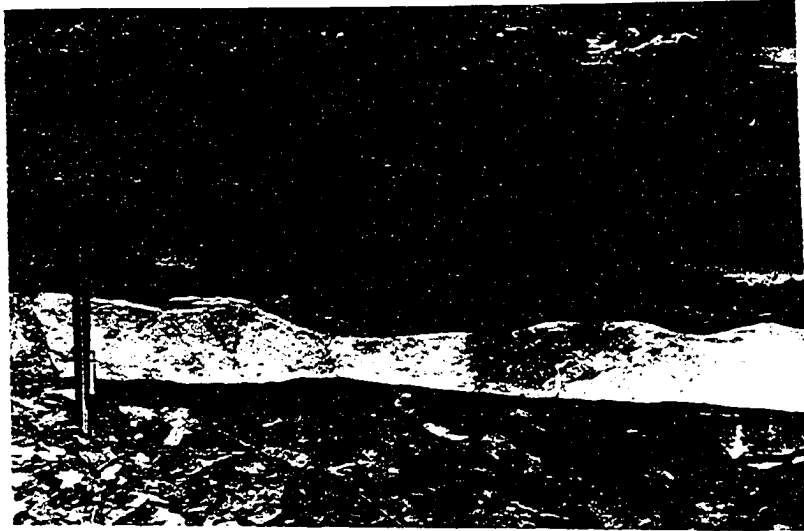


Fig. 3.26 Round-crested oscillation ripples on a sandstone ledge of the ISS facies. Photo from outcrop BA-3.

Fig. 3.27 Isolated "starved" ripples forming lenticular bedding in the ISS facies. Photo from outcrop BA-3.



NO. 1000-100
1000-100
1000-100

Fig. 3.28 Ripple-bedded sandstone encased in wavy and wavy flaser-bedded sandstone in the ISS facies. Photo from outcrop BA-3.

Fig. 3.29 Rhythmically alternating sandstone and shale couplets grading upward into ripple-bedded sandstone in the ISS facies. Note the systematic increase in the sand/shale ratio up-section. Photo from outcrop BA-3.



sandstone\shale couplets (Figs. 3.27 through 3.29).

Rare trace fossils are observed in the ISS facies and occur most commonly on the underside of sandstone ledges. The identification and environmental significance of the traces will be addressed later in this chapter.

Bounding contacts between sandstone and shale units may be sharp or gradational. Sharp contacts are most common, but gradational upper contacts are observed where lenticular-bedded and wavy-bedded shale grade upward into ripple-bedded sandstone

The ISS facies, present in 5 of the 15 outcrops measured, is confined to the upper one third of the section in all cases. This facies, along with the ripple-bedded sandstone facies with which it is often associated, may be underrepresented in outcrops. Erosion has stripped off overlying Breathitt Formation strata and much of the Corbin Sandstone Member in the majority of exposures. However, even where complete sections are preserved, this facies is not always present. For example, outcrop ZA-1 is dominated by the T/TCB facies to the top of the section where Breathitt Formation shale overlies the unit. In this outcrop neither the ISS facies nor the ripple-bedded facies is present.

Interpretation

The interbedded sandstone and shale facies is interpreted as the product of intertidal to shallow subtidal sandflat and mixed flat deposition. The presence of numerous marine indicators in this facies suggests that during the latter stages of Corbin Sandstone deposition, fluvial influence began to wane, and marine influences, particularly tidal, began to exert control on deposition.

Small-scale sedimentary bedding features in this facies are suggestive of tidal influence. For example, flaser bedding, wavy flaser bedding, and lenticular bedding were described by Reineck and Wunderlich (1968), who considered them to be highly indicative, although not diagnostic, of intertidal to subtidal deposits. Since that time, these sedimentary structures have been documented as abundant bedding types on intertidal to subtidal flats by numerous researchers and are therefore still considered an important criteria for recognizing ancient tidal deposits (Middleton, 1991).

Tidal flats in modern environments commonly exhibit a range in textures across the flat from the lower to upper intertidal zone. Whereas sandy tidal flats most commonly occur in the lower intertidal to subtidal environment where flow strengths are consistently higher, mixed flats are more common higher in the intertidal zone (Reineck 1967, 1972; Klein 1970; Tucker 1973; Elliot 1978, etc.). If the tidal flat progrades, a distinct fining upward textural trend will

result. Mixed flats are intermediate between sandflats and mudflats, and they are dominated by flaser bedding, wavy bedding, lenticular bedding and rhythmic bedding (Reineck, 1967, 1972; Dorjes and Howard, 1975; Elliot, 1986).

In addition to the tidal structures described above, bioturbation is also common in the intertidal mixed flat environment. Indeed, the presence of ichnofossils is considered by Terwindt (1988) to be an important attribute of tidal flat sedimentation. Further criteria recognized by Terwindt (1988) include multimodal paleocurrents, rapid and abrupt facies changes, and small-scale vertical sequences on the decimeter to meter scale.

Most of the criteria described above are present in the ISS facies of the Corbin Sandstone Member. Figures 3.27 through 3.28 show the lenticular bedding, wavy bedding and flaser bedding mentioned above. Figure 3.29 is highly suggestive of rhythmic bedding of tidal origin, although a thick enough section is not preserved to demonstrate neap-spring cyclicity. Trace fossils are also observed in this facies, although bioturbation is not.

Combined paleocurrent data for the ISS facies and ripple-bedded facies (discussed in next section) demonstrate a trimodal pattern. Furthermore, the abrupt decimeter to meter scale vertical sequences are clearly demonstrated by the photograph in Fig. 3.25.

No single one of the criteria mentioned above is, in

and of itself, diagnostic of tidal sedimentation. However, the weight and balance of the combined evidence is highly suggestive of the tidal origin of this facies.

Ripple-Bedded Sandstone Facies (RBS)

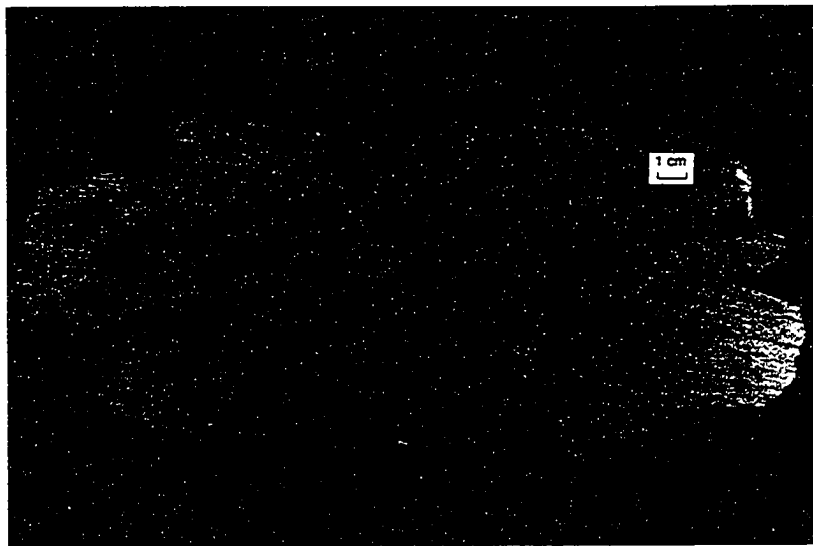
The ripple-bedded sandstone facies is the third most common facies observed, comprising 7.9% of the total of all measured sections (Fig. 3.1). It consists of very-fine to fine grained well-sorted, micaceous, quartz-rich sandstone. Incorporated within the ripple-bedded facies are isolated (occasionally stacked) sets of fine to medium-grained small and medium-scale trough/tangential crossbeds.

Textural variation within the RBS facies is relatively low. Grain size ranges from lower very fine to upper fine-grained (62 to 250 μ), and mean grain size is upper fine-grained (177 to 250 μ). Sorting is very good. Mica is abundant and lines the troughs of small ripples. Ripples are mostly small, lunate, current ripples but discontinuous, straight to sinuous-crested current ripples may be observed in some outcrops. Current ripples with clay flasers can also be observed (Fig. 3.30).

RBS units ranging from 10 cm to 7 m thick, are commonly located at or near the top of outcrops, where they are often associated with the ISS facies (Fig. 3.25).

The medium and small-scale trough/tangential crossbeds

Fig. 3.30 Cut and polished slab showing current ripples
with clay flasers. Photo from the ripple-
bedded sandstone of outcrop LI-2.



incorporated within the RBS facies are similar to those described for the T/TCB facies. However, in several instances where trough/tangential sets are cut parallel to flow, clay drapes with reactivation surfaces can be observed along crossbeds. These were not observed in trough/tangential sets of the T/TCB facies. Rare trace fossils are also present in the RBS facies where they occur on the tops and underside of sandstone ledges.

Interpretation

The ripple-bedded sandstone facies is interpreted as a tidal sandflat deposit. Modern sandy tidal flats are characterized by current ripples showing bimodal or multimodal flow directions, occasional oscillation ripples, and dunes that contain regularly spaced reactivation surfaces with clay drapes (Klein, 1970; Reineck, 1972; Boothroyd and Hubbard, 1975; Terwindt, 1988; Middleton, 1991). In addition, ripples with clay flasers, and wavybedding may be present (Reineck, 1967; Elliot, 1986). Also, infaunal activity is often high, resulting in heavy bioturbation. Most of the characteristics of sandy tidal flats are present in the RBS facies of the Corbin Sandstone Member. Paleocurrent measurements display trimodality for the combined RBS and ISS facies. Bioturbation is rare suggesting that sedimentation rates were high, or salinities

were below normal marine, or both.

Further evidence for tidal influence in this facies is the presence of thick/thin couplets bearing a strong resemblance to a type of vertically-accreting, small-scale, sandy, tidal-rhythmite found in modern tide-dominated environments. Figure 3.31 is an example from the macrotidal (14 m tidal range) Mont St. Michel Estuary on the Normandy Coast of France. According to Tessier (1992), the thick/thin couplets represent distinct ebb/flood events deposited during a single tide. Figure 3.32 is a photograph from the ripple-bedded sandstone facies of outcrop SC-1. Here, distinct thick/thin couplets similar in size and texture to those from the Mont. St. Michel Estuary are observed. Although ebb or flood dominance could not be established for these couplets, the thick/thin coupling is suggestive of tidal deposition.

Additional evidence for tidal influence is the presence of medium-scale trough/tangential crossbedded sets with reactivation surfaces and clay drapes separating sandy intervals. These are highly suggestive of the large-scale tidal bundles first described by Boersma (1969) and documented in modern and ancient tide-dominated environments by numerous researchers (e.g., Terwindt, 1971; Visser, 1980; Boersma and Terwindt, 1981; Allen, 1981; Van Den Berg, 1982, Smith, 1988; de Boer, et al., 1989 etc.). Figure 3.33 is a line drawing of a medium-scale trough/tangential set cut

Fig. 3.31 Photo of modern, vertically-accreting, small-scale sandy tidal-rhythmites from the Mont. St. Michel Estuary, Normandy, France (from Tessier, 1992). According to Tessier (Personal communication) thick/thin couplets represent ebb-flood events (bottom arrow = ebb; top arrow = flood), therefore each couplet represents deposition during a single tide (scale at top in centimeters).

Fig. 3.32 Photo of sandy, vertically-accreting small-scale couplets from the RBS facies of the Corbin Sandstone Member. Thick/thin couplets are almost identical in size and texture to the modern examples shown in the Photo above. Current directions could not be determined therefore ebb or flood dominance could not be ascertained.

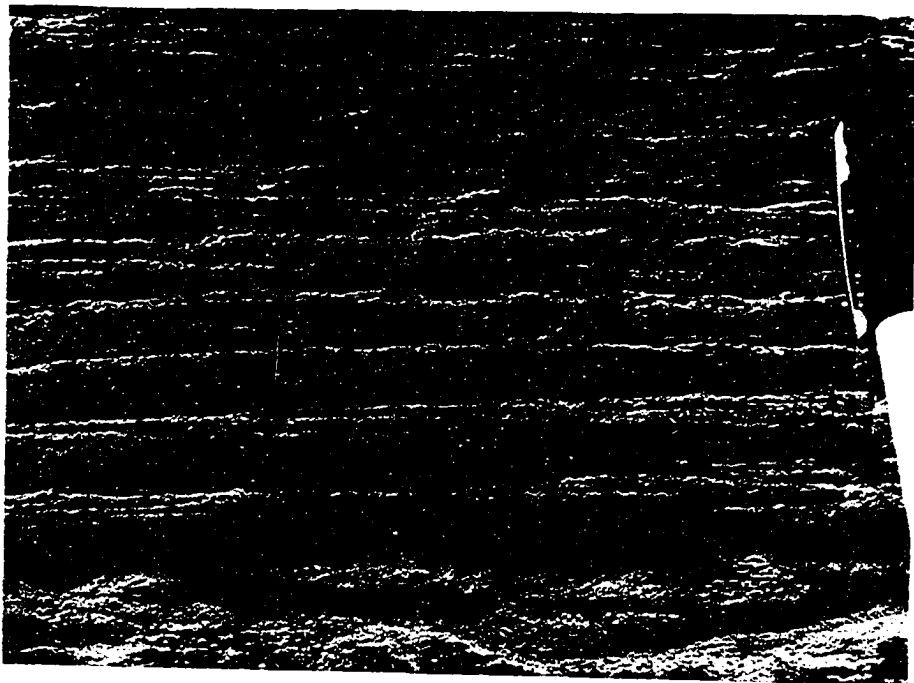
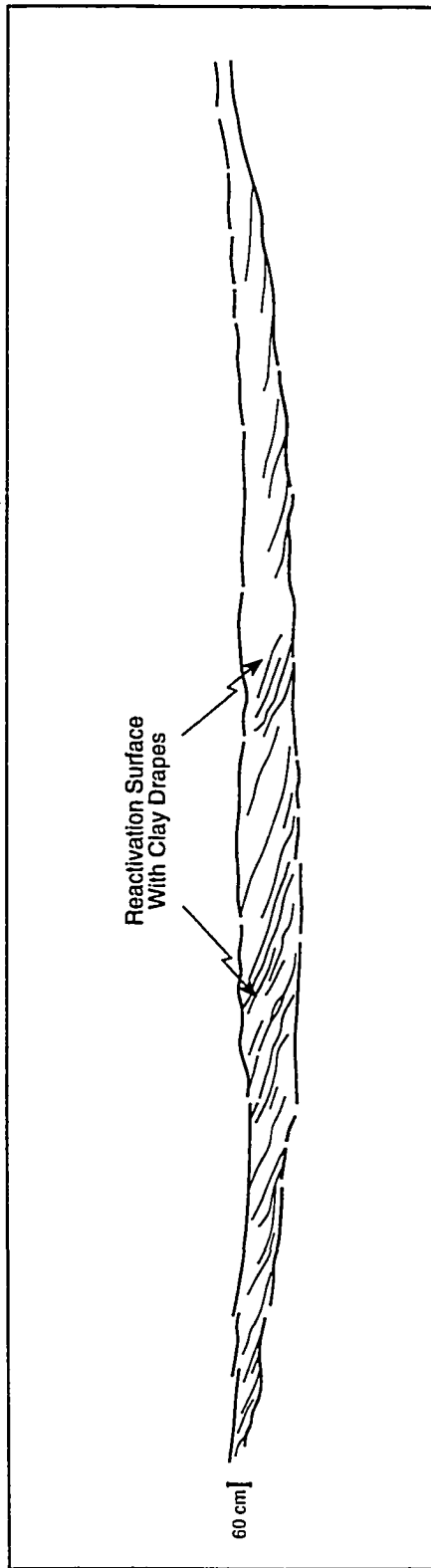


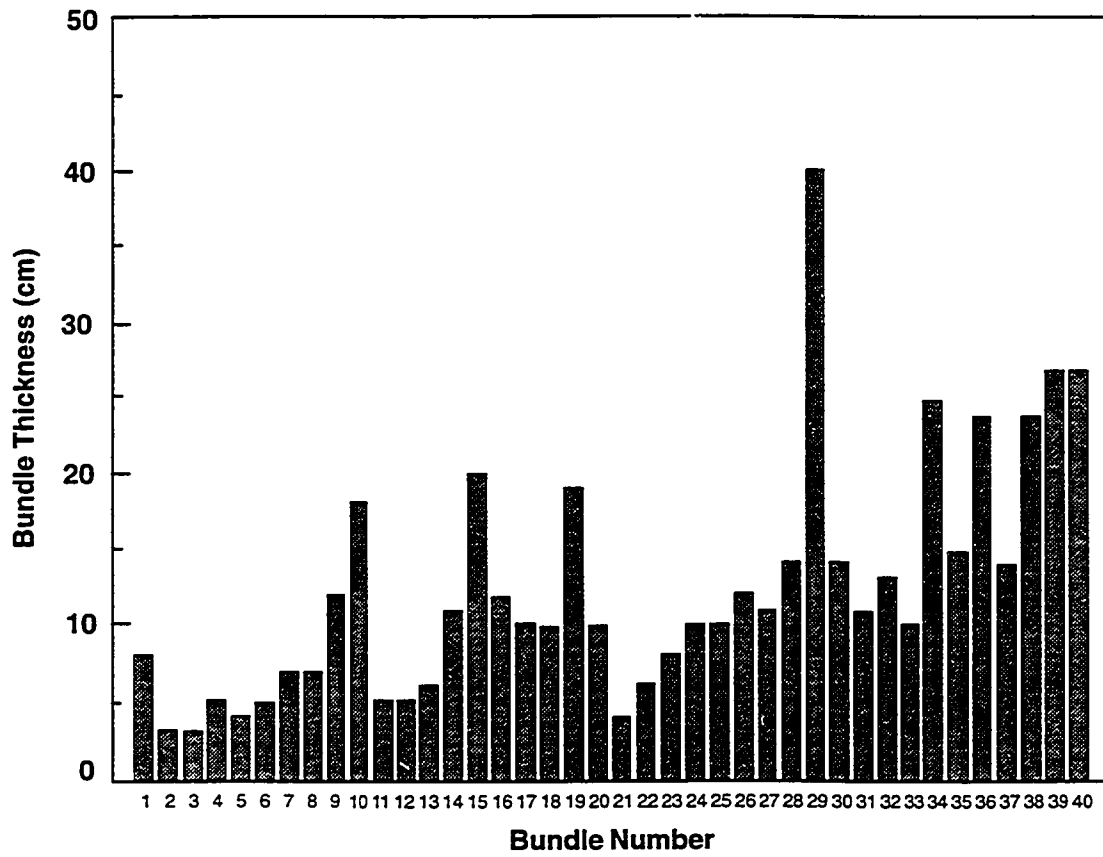
Fig. 3.33 Line drawing from photomosaic showing the location of clay drapes along crossbeds of a medium-scale, trough/tangential crossbed set within the RBS facies.



parallel to flow from the RBS facies of outcrop BA-3. The line drawing shows the location within the crossbed set of reactivation surfaces with clay drapes separating sandy crossbeds (bundles).

Figure 3.34 is a bar graph of bundle number versus bundle thickness. The bar graph shows that the thickest and thinnest bundles occur at intervals of approximately 10. For example, bundle numbers 10, 19, 29 and 39/40 are thick, bundle numbers 2, 10, 21 and 33 are thin. According to ideal tidal theory, maximum (and minimum) bundle thicknesses should occur at intervals of 14 if the system is diurnal, or 28 if it is semidiurnal. However, a complete 14 or 28 day cycle may not be recorded. According to de Boer et al. (1989) and de Boer (1992, personal communication) this is because flow strengths during neap tides are often not strong enough to cause bedform migration, and therefore no bundle is deposited. Tessier (1992, personal communication) observed that in the estuary of Mont St. Michel, vertically accreting, small-scale tidal-rhythmites accumulating in the intertidal zone, often show neap/spring cyclicity with periodicities of approximately 10 because of non-deposition on or near neap-tide. Therefore, the T/TCB set shown in Fig. 3.33, is interpreted as a lunate dune of tidal origin. Although the periodicities do not show a complete 14 day cycle, the presence of regularly spaced clay drapes on crossbed surfaces, the periodic thickening and

Fig. 3.34 Bar graph showing bundle number versus thickness of individual sandy crossbeds (bundles) from the trough/tangential set shown in figure 3.33.



thinning of sandy intervals, and its association with other tidal bedding features, supports a tidal origin.

In brief, the combined data for the ISS and RBS facies show strong evidence for tidal influence. The evidence offered above is based primarily on the interpretation of sedimentary structures. A summary of all the facies, and the significance of their sedimentary structures, textures, and geometries, is outlined in the following section.

Architectural Elements

Table two summarizes the descriptions and interpretations of the major facies discussed above. From this table, the major architectural elements observed in the Corbin Sandstone Member are revealed. The architectural elements of the Corbin Sandstone Member represent the primary, physical, morphological elements present during Corbin Sandstone Deposition, as revealed by the combined textural and physical characteristics of the individual facies.

Nine major depositional features, outlined in table 2, comprise the internal architecture of the Corbin Sandstone Member. These elements include: 1) gravelly longitudinal bars (Fig. 3.6), 2) Simple (Fig. 3.9) and compound transverse bars, 3) erosional-based, thick, laterally persistent gravity-flow deposits (Fig. 3.7), 4) second,

Table 2. Summary of the major architectural elements of the Corbin Sandstone Member including descriptions, geometries, and interpretations.

Table 2

Facies	Description	Geometry	Interpretation
QPC facies	Polymodal, matrix and clast supported, medium, quartz pebble conglomerate. May contain rounded mudstone and claystone clasts, and large (up to 4m) mudstone and shale intraclasts. Fossil tree limbs up to 50cm long at base of some units.	Occurs as basal, erosional, discontinuous lenses 0 to 60cm thick and several meters and long; or, as tabular bedded packages 5cm to 1.1m thick and of undetermined lateral extent; or as irregular, erosional based, units up to 3m thick and 21m long associated with massive bedded sandstone.	Basal channel lags, longitudinal bars and gravity-flow deposits.
MB facies	Medium grained, poor to well sorted, pebbly, micaceous quartz-rich sandstone. Occasional fining upward textural trend. Shale and mudstone intraclasts sometimes present. May intertongue with the QPC facies.	Varies in thickness from 1 to 6.2m, but averages 2m thick. Can be traced laterally for tens of meters. May intertongue with the QPC facies. Erosional basal contacts with up to one meter of relief.	Gravity-flow deposits.
PCS facies	Fine to medium grained, poor to well sorted, pebbly quartz-rich sandstone. Occasional rounded claystone or mudstone rip-up clasts. PCS sets may grade laterally into sigmoidal or compound cross-bed sets. PCS sets commonly capped by 3-d lunate current ripples.	PCS sets range from 7cm to 2.3m thick and may be planar tabular or planar wedge shaped. Planar wedge sets can be traced laterally 30m, planar tabular sets 100m or more. Commonly truncated by third-order channels. Tops scoured by fourth-order channels.	Transverse bars within sandy, braided-fluvial setting.
TCS facies	Fine to medium grained, poor to well sorted, pebbly quartz-rich sandstone. Grain fall and grain flow couplets common. Claystone and mudstone clasts up to 10cm in diameter. Fossilized or mineralized tree limbs at base of some units. Commonly fill second, third and fourth order channels.	TCS sets range from 7cm to 1.8m thick and can be traced laterally (along paleoflow) up to 30m. Thickness-to-width dimensions of troughs highly variable. May be low-amplitude, broad and gently upturned or high-amplitude, tightly nested and sharply upturned.	Three dimensional lunate dunes flooring second, third and fourth-order channels within, sandy, braided-fluvial setting.

Table 2 cont'd

Facies	Description	Geometry	Interpretation
HB facies	subrounded, poor to well sorted quartz-rich sandstone. Rounded mudstone clasts up to 5cm in diameter in some poorly sorted sets. Mineralized tree limbs observed in some sets.	HB sets range from .8 to 3.5m. Sets can be traced laterally up to 20m. Sets are tabular but often truncated by medium and large scale TCS sets.	Sheet-flood overbank deposits, third-order channel-fill deposits, thin capping units on medium and large scale PCS sets.
Shaley facies	Dark gray to black, micaceous, hackly to platy, clayey to silty, carbonaceous shale. Finely disseminated plant fragments common along partings. Well developed pencil cleavage in places. Occasional isolated sandstone lenses.	Lenticular geometry. Erosional basal contacts and sharp upper contacts. Individual lenses up to 6m thick. Can be traced laterally up to 28m.	Third-order abandoned channel fill sequences.
ISS Facies	Very fine to fine grained, well-sorted, subangular to subrounded, quartz-rich sandstone interbedded with dark gray to black, sandy, silty, micaceous carbonaceous shale. Sandstone dominated by current ripples (some with clay flasers), oscillation ripples and small scale TCS sets. Shale intervals contain wavy flaser, flaser and lenticular bedding. Trace fossils common.	Laterally persistent, tabular packages. Sandstone intervals range from 5cm to 1m thick. Shale intervals range from 5cm to 30cm thick. Contacts may be sharp or gradational.	Intertidal to subtidal, mixed sand and mud flats.
RBS Facies	Very fine to fine grained, well sorted, micaceous, quartz rich sandstone. Dominated by small-scale 3-d current ripples and occasional small and medium scale TCS sets. In-situ stygmaria roots observed. Vertically accreting small-scale tidal bundles	Laterally persistent tabular units up to 7m thick. Basal contacts sharp to erosional, upper contacts may be gradational into overlying Breathitt.	Intertidal sand flats.

third and fourth order, vertically aggrading sand filled channels (Figs. 3.17, 3.18, and 3.21); 5) third order laterally accreting sand-filled channels (Figs. 3.19 and 3.20); 6) third order shale-filled abandoned channels (Fig. 3.24); 7) thick, overbank sheet-flood deposits of unknown lateral persistence (Fig. 3.23); 8) tabular, laterally persistent, interbedded shales and sandstones (Fig. 3.25); 9) thick, tabular, laterally persistent ripple-bedded sandstone (Fig. 3.25).

In addition to physical sedimentary structures, their description and interpretation, additional outcrop data will be examined in the following sections. Included are: paleocurrent data, quartz pebble size measurements, trace fossils, and coal palynology. These data provide additional support for the fluvial and tidal origin of the Corbin Sandstone Member. In addition, information regarding source areas, paleoclimates and age constraints on the Corbin Sandstone Member is discussed in the following sections.

Paleocurrents

Paleocurrent measurements of the Corbin Sandstone Member were taken from 16 outcrops along the length of the Pottsville Escarpment. Measurements were taken on planar crossbed sets from the PCB facies, trough/tangential sets from the T/TCB facies, and ripples and trough/tangential

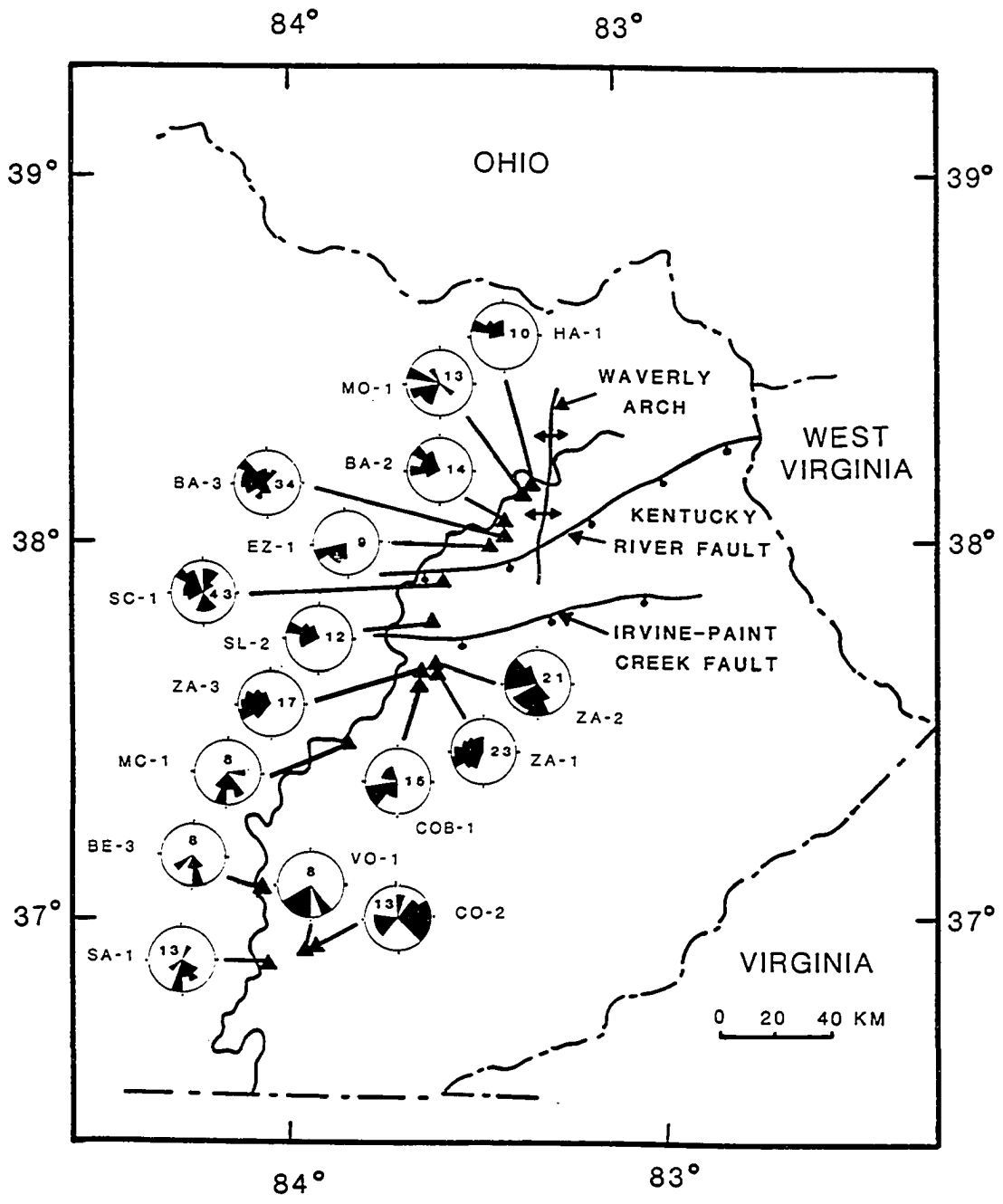
sets from the RBS and ISS facies. A total of 261 measurements were taken. These data reveal two significant points: 1) ancient (Precambrian) structural lineaments (the Kentucky River and Irvine-Paint Creek Fault Systems) strongly influenced paleoflow directions within the Corbin Sandstone Member; and, 2) paleoflow data provide an independent source of support for the interpretation of both fluvial and marine (tidal) facies within the Corbin Sandstone Member.

Figure 3.35 shows paleocurrent rose diagrams for the 16 outcrops from which paleocurrent data were collected. Also included on the figure are the locations of the structural lineaments mentioned above and the location of the Waverly Arch. Generally speaking, paleoflow directions are westerly for those outcrops located near these ancient faults, that is, outcrops north of and including ZA-1, ZA-2 and ZA-3.

Westerly paleoflow directions are not typical for the Lee Formation. The Lee Formation Members form northeast to southwest trending belts (Chestnut, 1988), and this geometry is reflected by paleocurrent directions which are generally south to southwest (e.g., Schlee, 1963; Bement, 1976, etc.). The westerly paleoflows observed in the Corbin Sandstone Member in the northern portion of the outcrop belt appear to be related to the presence of the Kentucky River and Irvine-Paint Creek Fault Systems as mentioned above. These data suggest that the south to southwest flowing river systems

Fig. 3.35

Paleocurrent rose diagrams of data from 16 outcrops of the Corbin Sandstone Member. Note the westerly paleoflows for locations near the Kentucky River and Irvine-Paint Creek Faults and the more southerly paleoflows for outcrops south of the faults.



responsible for deposition of the Lee Formation were deflected westward by these ancient fault systems during deposition of the Corbin Sandstone Member. This is further supported by subsurface isopach data, which will be discussed fully in the next chapter.

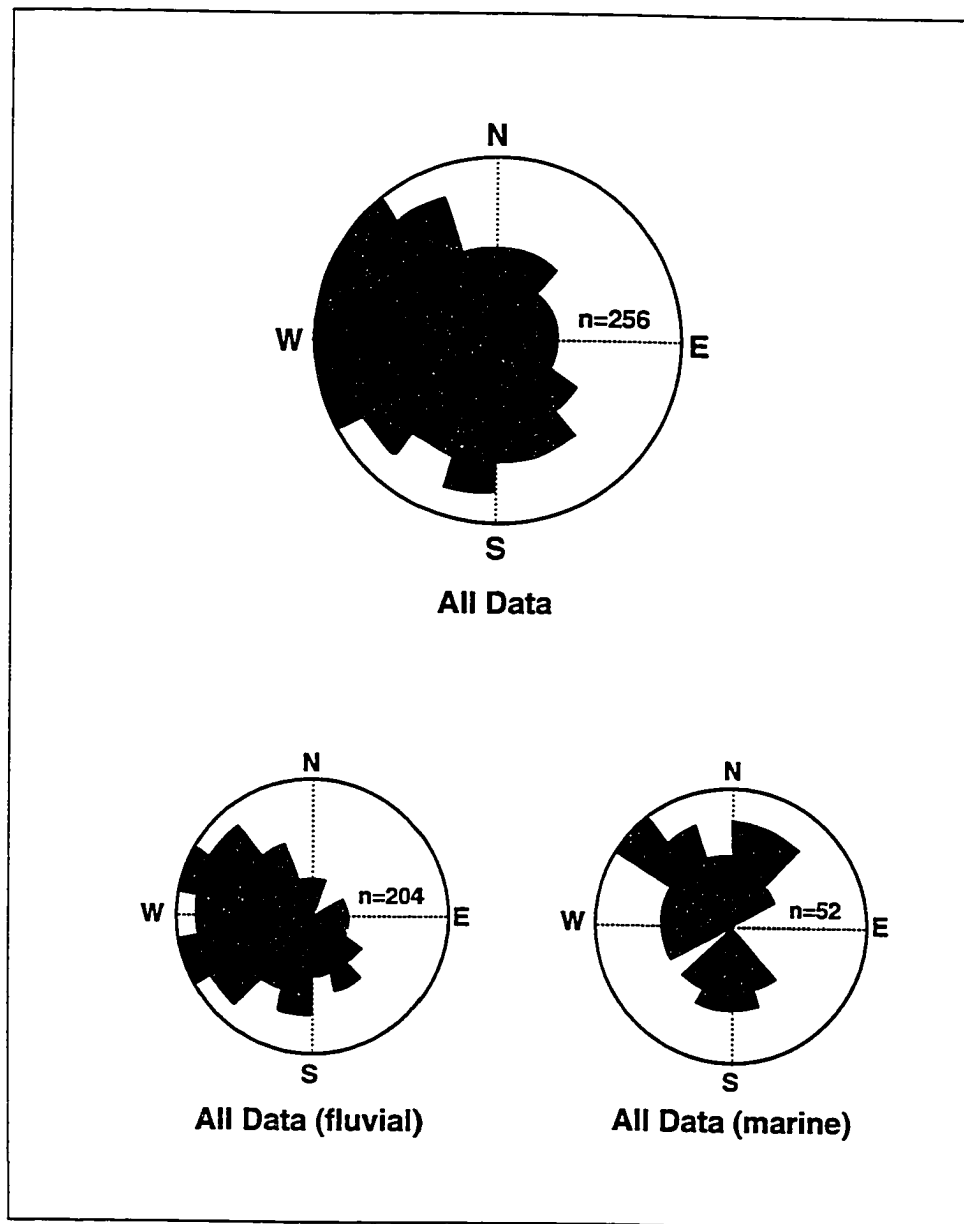
Once south of the influence of the fault systems, paleoflows for the Corbin Sandstone Member show some evidence of returning to the more southerly directions typical of the Lee Sandstone Formation. For example, outcrops BE-3, MC-1, VO-1 and SA-1 (Fig. 3.35) all show southerly paleoflows.

Paleocurrent data support the interpretation for both fluvial and marine (tidal) facies within the Corbin Sandstone Member. Figure 3.36 shows three paleocurrent rose diagrams. The diagram at the top, the paleocurrent rose for all measurements, reveals an overall westerly to southwesterly paleoflow. However, when paleocurrent measurements are grouped by facies, two separate and distinct paleocurrent patterns emerge. The diagram at the bottom left is the paleocurrent rose for the combined PCB and T/TCB facies, which, based on criteria other than paleocurrent patterns, are interpreted as braided-fluvial facies. This paleocurrent rose shows a more unidirectional pattern, than either of the other two paleocurrent roses, and is consistent with a fluvial interpretation.

The diagram at the bottom right is the paleocurrent

Fig. 3.36

Paleocurrent rose diagrams for the Corbin Sandstone Member. At top is the current rose pattern for the combined data. At bottom left is the current rose pattern for those facies which, based on sedimentary structures, are considered to be fluvial (the PCB and T/TCB facies), at bottom right is the current rose pattern for those facies which, based on sedimentary structures, are considered to be tidally influenced (the ISS and RBS facies).

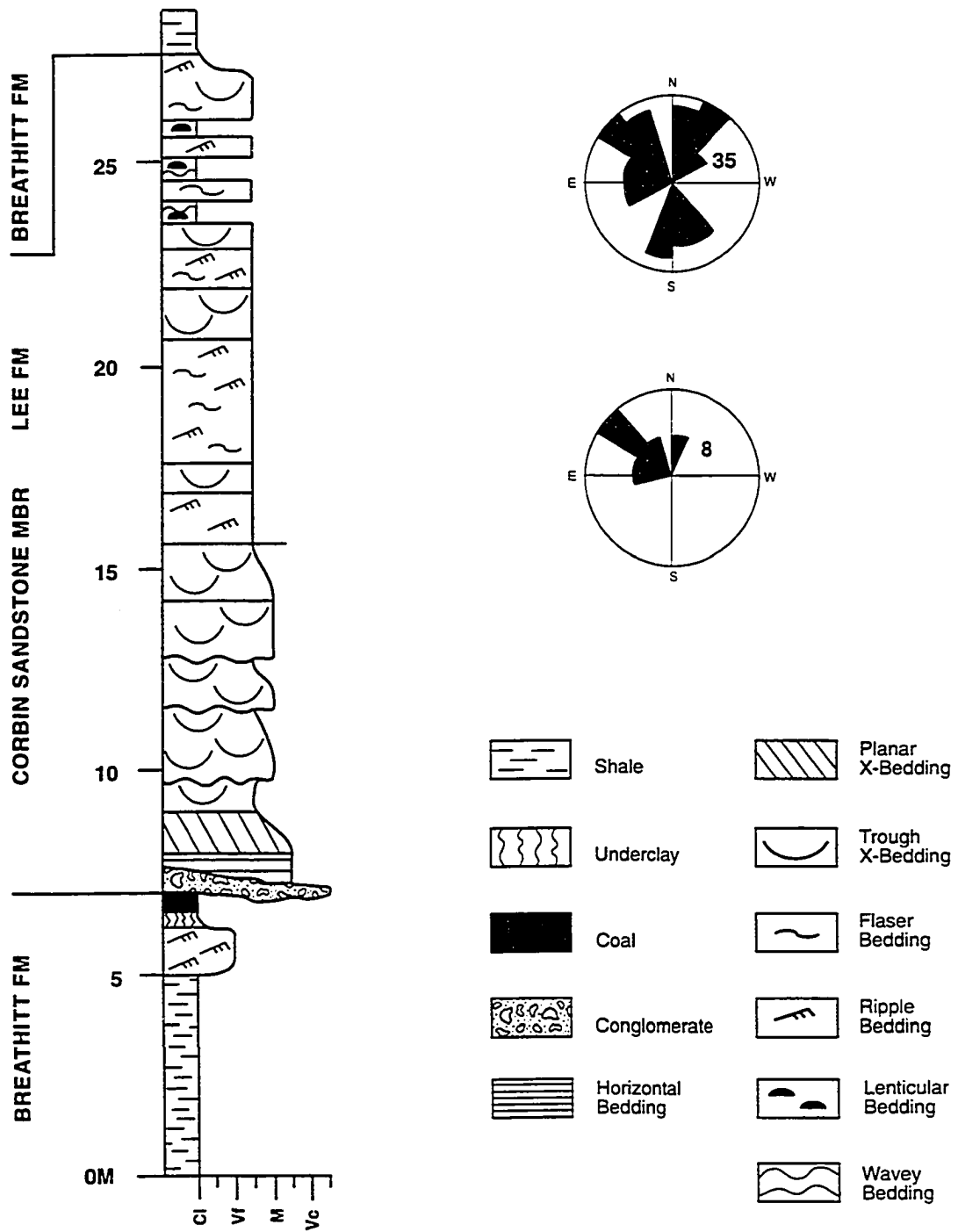


rose diagram for the combined ISS and RBS facies. These facies are interpreted as mixed flats and sandflats respectively. The trimodal paleocurrent pattern supports the tidal interpretation for these two facies. Multimodal paleocurrent patterns are a characteristic of tidal environments (e.g. Reineck and Wunderlich, 1968; Klein, 1970; Clifton, 1982; Terwindt, 1988 etc.) Therefore, the trimodal paleocurrent pattern shown in Fig. 3.36 supports the tidal interpretation for these two facies. Paleocurrent data provides further support for the presence of tidal influence during the later stages of deposition of the Corbin Sandstone Member.

Paleocurrent measurements provide evidence for a fluvial to marine (tidal) transition for the Corbin Sandstone Member. Figure 3.37 is a vertical columnar profile of outcrop SC-1 (see Fig. 3.35 for location). This outcrop contains both braided-fluvial and marine (tidal) facies. The lower portion of the outcrop is dominated by medium and large-scale T/TCB sets resulting from braided-fluvial channel deposition. Above this facies is a thick (more than 12 m) section dominated by the RBS and ISS facies. Paleocurrent measurements for the lower, braided-fluvial portion are unidirectional to the northwest. However, paleocurrent measurements of the upper, tidal portion are trimodal, as shown. This section clearly demonstrates the fluvial to tidal transition that can be

Fig. 3.37

Vertical columnar profile of outcrop SC-1. Paleocurrent pattern of braided-fluvial part of section is unidirectional to the northwest. Paleocurrent pattern of tidally-influenced part of the section is trimodal. Paleocurrent data support the paleoenvironmental interpretations for the Corbin Sandstone Member.



observed is some outcrops of the Corbin Sandstone Member.

When the tidal facies are present in the Corbin Sandstone Member, they occur above the braided-fluvial facies in all the cases observed. However, outcrop SC-1 (Fig. 3.37) is somewhat atypical of the Corbin Sandstone because of the extreme thickness of the tidal sandflat and mixed flat facies. It should be emphasized here that in the majority of outcrops the ISS and RBS facies are absent because of erosion or nondeposition, and that the ISS and RBS facies observed in outcrop SC-1 are the thickest of the three measured sections that contain these facies.

In summary, paleocurrent data suggest that the ancient Kentucky River and Irvine-Paint Creek Fault Systems exerted strong influence on paleocurrents by directing paleoflows in a westerly direction, along the axes of the ancient fault systems. In addition, paleocurrent rose diagram patterns show a distinct difference between those facies interpreted to be marine (tidally-influenced) and those facies interpreted to be fluvial (braided-river). Tidally-influenced facies show a trimodal paleocurrent rose pattern, whereas the fluvial facies show a unimodal pattern. The paleocurrent data, therefore, offers further support for both a fluvial and marine component for the Corbin Sandstone Member.

Finally, paleocurrent data generally suggest an overall northern to northeastern source for the Corbin Sandstone

Member. A northern source is further supported by quartz pebble size trends, discussed in the following section.

Quartz Pebble Size Measurements

Quartz pebble size measurements were taken from the 10 outcrops of the Corbin Sandstone Member containing conglomerates. The majority of these outcrops are located in the northern half of the field area; in the southern half, very few outcrops examined contain conglomerates.

The long diameter of the ten largest observed quartz pebbles was measured, and a replicate set of an additional ten measurements was taken from a separate location within the conglomerate, using the method described in the first chapter. The purpose of these measurements was to determine if a measurable decrease in diameter of quartz pebbles exist along the length of the outcrop belt.

According to Ferm et al., 1971, the primary sediment source for the Lee Formation was the Appalachian Mountains that were building to the east and southeast at this time. If this is true, it is unlikely that a significant difference in quartz pebble size would exist along the Corbin Sandstone Member outcrop belt. If the Ferm et al. (1971) model is correct, sediment would have entered the basin at many locations by west-flowing rivers carrying sediment from the nascent Appalachian Mountains. In this

case, no systematic change in quartz pebble size would be expected along the northeast to southwest trending outcrop belt. If anything, a northeastern decrease in quartz pebble size would be expected because of the closer proximity of the southern part of Corbin Sandstone Member to the nascent Appalachian Mountains, as indicated by a southward thickening in the Pennsylvanian section (see Fig. 2.3).

Figure 3.38 shows the size relationship of quartz pebble measurements from 10 outcrops containing the QPC facies. The figure shows a general southward decrease in quartz pebble size along the length of the outcrop belt.

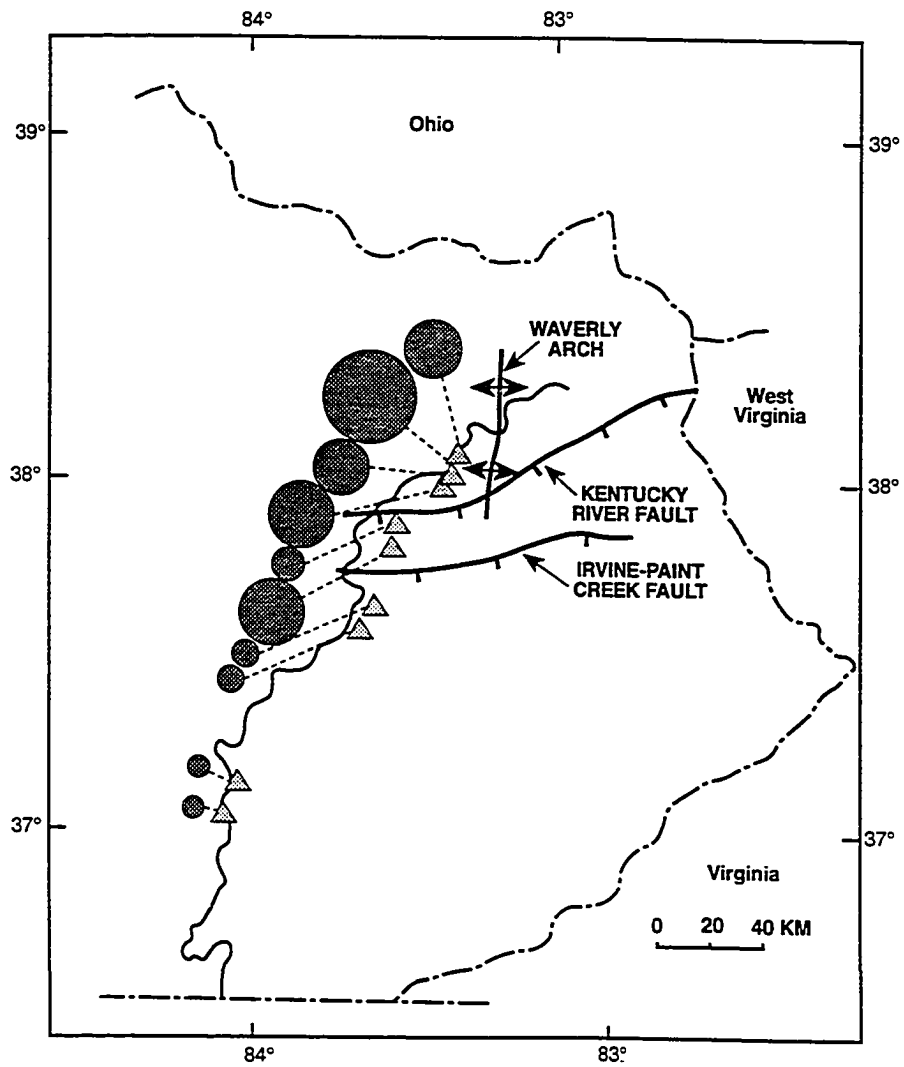
Figure 3.38 suggests that the primary source area for Corbin Sandstone was to the north, not the nascent Appalachians building to the east and southeast, although they may have been a secondary source as suggested by Chesnut (1988). A southward decrease in quartz pebble size measurements agrees with the overall southern paleoflow directions for the Lee Formation as indicated by Schlee (1963), and Bement (1976), and is consistent with the overall decrease in quartz pebble size observed by Bement (1976), in the Lower Lee Formation along the Cumberland Thrust Sheet.

Trace Fossils

Trace fossils are rare in the Corbin Sandstone Member.

Fig. 3.38

Quartz pebble size distribution for the Corbin Sandstone Member. Overall southerly decrease in quartz pebble size suggests that the source area was to the north.



Their distribution is best characterized as monospecific. Only one trace fossil is common and consistently identifiable, and in all cases it was confined to the ISS and RBS facies. No trace fossils were observed in any of the facies interpreted to be braided-fluvial.

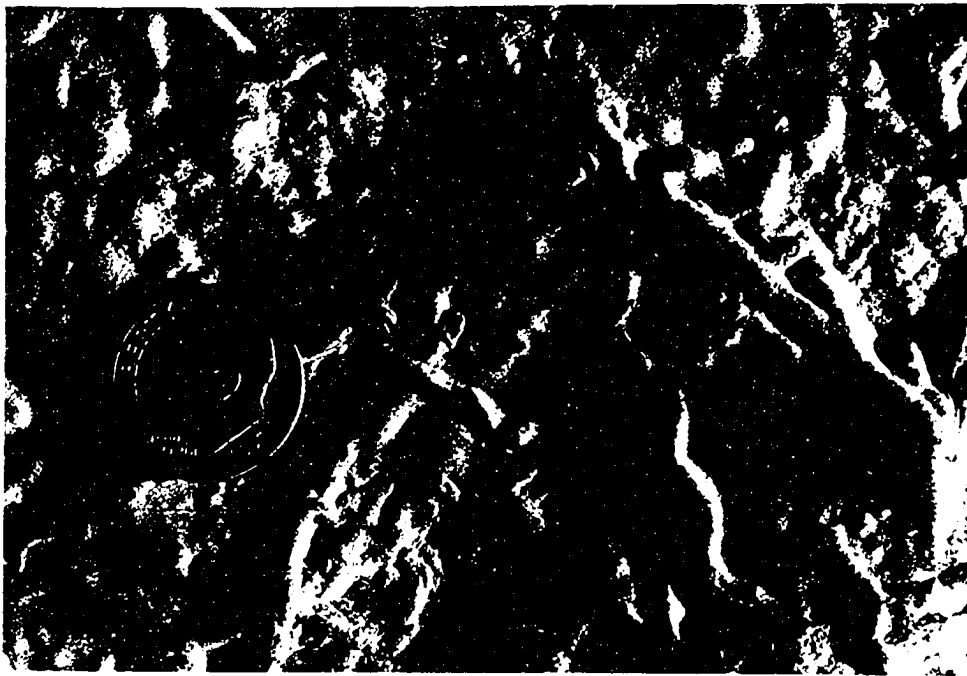
Figure 3.39 is a photograph of the trace fossil Cochlichnus. It is a wave-like trail that, according to Devera (1989), probably formed from the sediment excretion of a worm-like, infaunal detritus feeder. Moussa (1970), suggested that this wave-like trace is a nematode trail. However, in the examples shown by Moussa the wave-like traces show concave upper relief, whereas those observed in the Corbin Sandstone Member are in full relief. Therefore the interpretation offered by Devera (1989) is more consistent with the preservational form of the traces observed.

The environmental range of Cochlichnus is not well constrained, therefore the presence of Cochlichnus in the Corbin Sandstone Member is of little help regarding environmental interpretation. For example, Ekdale et. al. (1984), noted that Cochlichnus has been found in glacial lake deposits. In contrast, Devera (1989), noted the presence of Cochlichnus in early Pennsylvanian age rocks in the Illinois Basin interpreted to be brackish water, tidally-influenced deposits.

In addition to Cochlichnus, there are other forms that

Fig. 3.39

Photograph of the trace fossil Cochlichnus (arrow). Cochlichnus is the only identifiable trace fossil observed in the Corbin Sandstone Member. It was observed in the RBS and ISS facies only.



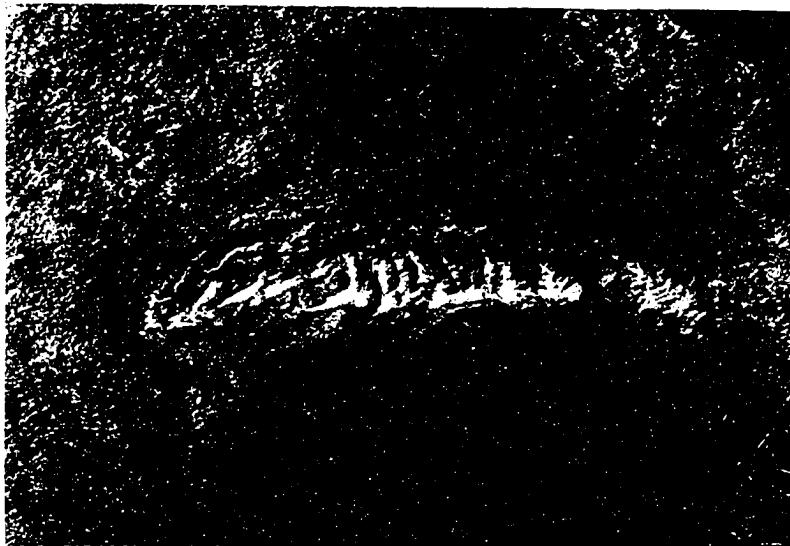
bear a resemblance to known trace fossils, but none could be absolutely identified. For example, Chondrites-like traces and Planolites-like traces were observed in the ISS and RBS facies. However, the poor preservation quality prohibited positive identification.

A large (approximately 45 cm long) enigmatic trace fossil was found on a bedding plane exposure from the RBS facies of outcrop SC-1. Figure 3.40 is a photograph of this unusual trace. The trace fossil was found in a very fine-grained sandstone of the RBS facies interpreted to be a tidal sandflat deposit. Bedding plane exposures above and below the trace show current ripples with south directed paleoflows, and the trace fossil itself is elongated north-south. The bottom of the impression has a ribbed or furrowed aspect, and the sandstone around the margins of the trace has been raised to form a lip approximately 1 cm high. According to Devera (personal communication) and Archer (personal communication), this trace is most likely a vertebrate death trace of some kind, possibly from a fish or an amphibian.

The lack of body fossils and meager trace fossil assemblage in the Corbin Sandstone Member suggest a stressed environment for the paleofauna. However, palynological analyses discussed in the next section suggest a rich paleofloral assemblage.

Fig. 3.40

Large, enigmatic trace fossil from the RBS facies of outcrop SC-1. The origin of this trace fossil is unknown, but it may represent a vertebrate death trace, possibly from a fish or an amphibian.



Coal Palynology

Three outcrops of the Corbin Sandstone Member examined for this study have associated coal seams. Outcrops SC-1 and ZA-1 have coals at the base of the Corbin Sandstone Member, whereas outcrop EZ-1 has two coals, one at the base, and one in the middle of the sandstone. Samples from all four coals were collected and the palynomorphs were identified by Cortland Ebel (Kentucky Geological Survey). Palynology was performed in order to determine the paleoclimatic conditions that existed during Corbin Sandstone Member deposition, and to ascertain the age of the Corbin Sandstone, as it is not presently well-constrained.

Table three is a list of the dominant floral taxa observed in the four coals. By far the most abundant taxa observed are from Lycopsid trees, which account for 93.0%, 49.2%, 86.8% and 97.6%, respectively, of the taxa from the four coals listed in the table. Lycopsid trees, with the exception of Sigillaria, could tolerate very wet environmental conditions. According to Ebel (in press), Lycopsid trees could tolerate standing water, as well as supersaturated peat-forming mires. In fact, Lycospora pellucida and Lycospora granulata had developed reproductive mechanisms designed for water dispersal (Ebel, in press). The dominance of water tolerant plants during Corbin Sandstone Member deposition suggests that a very-wet climate

Table Three

TAXA	EZ-1(B)	EZ-1(M)	ZA-1	SC-1
LYCOPSID TREES				
<i>Lycospora pullucida</i>	62.0%	30.8%	33.2%	27.2%
<i>Lycospora Pusilla</i>	16.4	12.4	1.6	15.6
<i>Lycospora granulata</i>	2.0	1.6	16.4	40.4
<i>Lycospora orbicula</i>	0.4	0.4	14.0	
<i>Lycospora micropapillata</i>			12.0	
<i>Lycospora spp.</i>	13.0	4.0	9.6	14.0
<i>Granasporites medius</i>				0.4
SMALL LYCOPSIDS				
<i>Denosporites sphaerotriangularis</i>	0.4		0.4	
<i>Denosporites annulatus</i>		0.8	0.4	
<i>Endosporites globiformis</i>		15.2		
SEED FERNS				
<i>Schulzospora rara</i>	2.4			
TREE FERNS				
<i>Punctatisporites minutus</i>		1.6	5.2	0.8
SMALL FERNS				
<i>Granulatisporites parvus</i>	2.0	0.8	0.4	
<i>Granulatisporites piroformis</i>		0.4		
<i>Granulatisporites granulatus</i>		1.6		
<i>Lophotriletes microsaetosus</i>		0.4		
<i>Lophotriletes commissuralis</i>		0.8		
<i>Lophotriletes granoornatus</i>		0.8		
<i>Cyclogranisporites breviornatus</i>		0.8		
<i>Camptotriletes bucculentus</i>		0.4		
<i>Apiculatasporites spinulistratus</i>			0.4	

Table Three Cont'd

TAXA	EZ-1(B)	EZ-1(M)	ZA-1	SC-1
CALAMITES				
Calamospora breviradiata	0.4%	5.2%	0.8%	1.2%
Calamospora hartungiana		3.6	0.4	
Laevigatosporites minor		7.2	4.0	0.4
Laevigatosporites vulgaris		3.6	0.8	
CORDAITES				
Florinites florini		1.6		
Florinites mediapudens		1.2		
Florinites similis		3.6		
Florinites volans		0.4		
UNKNOWN AFFINITY				
Dictyotriletes bireticulatus			0.4	

existed at that time.

According to Ebel, (Personal communication) the palynofloral assemblage observed in the coals suggests that the Corbin Sandstone Member is early Middle Morrowan in age (early Westphalian B). Paleoclimatic reconstructions reveal that in the eastern United States a tropical/rainy climate existed during early middle Morrowan time (e.g., Cecil, 1990). Therefore the palynology of the coals associated with the Corbin Sandstone Member supports previous Paleoclimatic interpretations.

In summary, outcrop analyses reveal that the Corbin Sandstone Member represents a braided-fluvial to marine (tidally-influenced) transition. The source area to the north and northeast provided sediment to a multichannel system the major channels of which were locally diverted to the west by the Kentucky River and Irvine-Paint Creek Fault Systems. Sedimentary structures reveal that marine (tidal) influence began to exert control during the late stages of Corbin Sandstone deposition. The lack of body fossils and paucity of trace fossils suggests a stressed environment. Finally, paleopalynology suggests a rainy tropical climate during Corbin Sandstone deposition, and dates the unit as early Middle Morrowan in age.

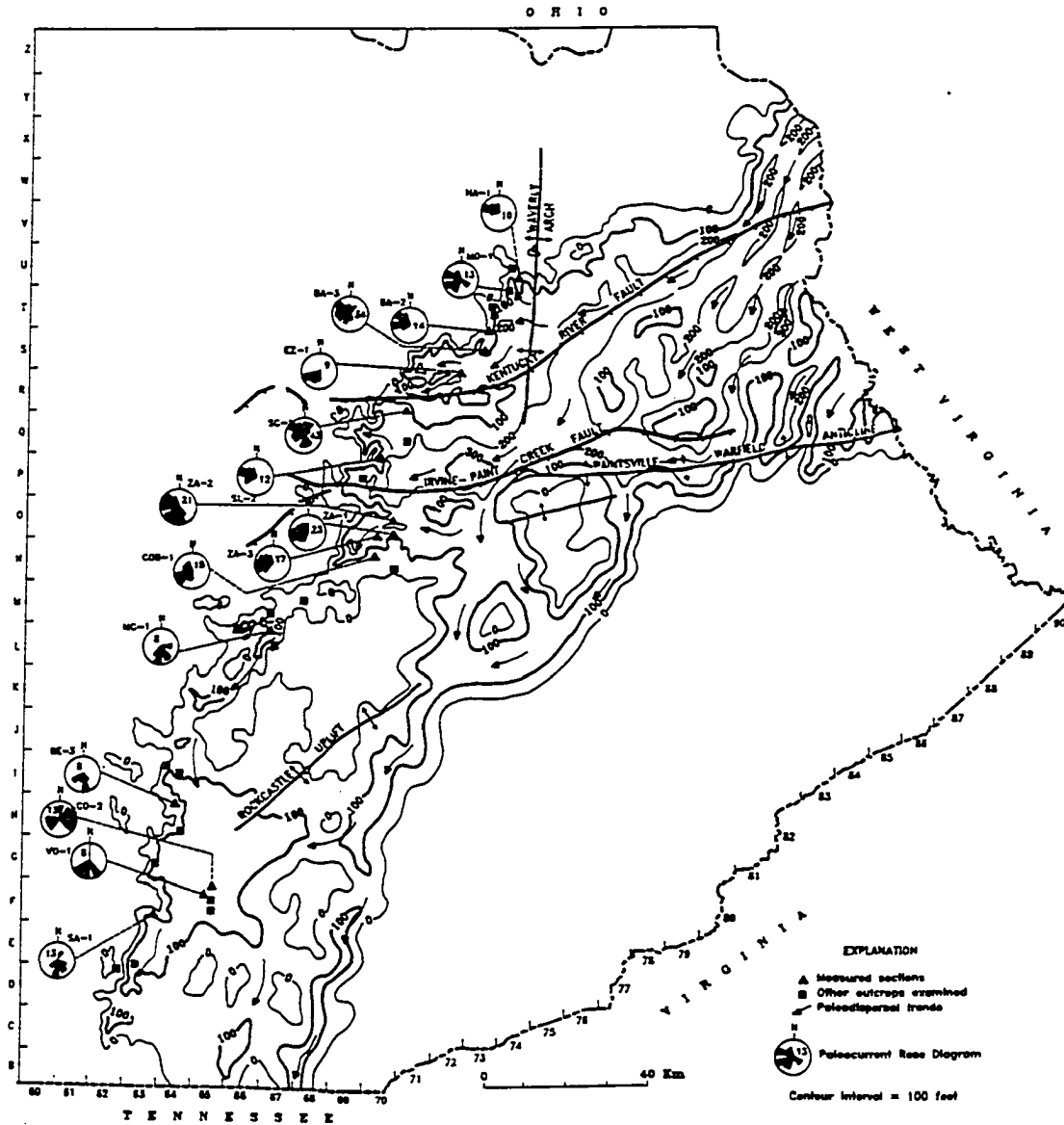
SUBSURFACE ANALYSIS

Intrabasinal Tectonic Controls on the Three Dimensional
Geometry of the Corbin Sandstone Member

In the Appalachian Plateau area of eastern Kentucky, several large, intrabasinal, structural features existed prior to Corbin Sandstone deposition. These features include the Waverly Arch, the Paintsville Anticline, the Rockcastle Uplift, the Kentucky River Fault and the Irvine-Paint Creek Fault (see plate 1 and Fig. 4.1). The history of the intrabasinal structures mentioned above suggests that these features were active throughout much of the Paleozoic, and therefore they may have exerted influence on the 3-D architecture of the Corbin Sandstone.

The Waverly Arch was recognized and named by Woodward (1961), based on depositional thinning of early Paleozoic strata in the northeastern Kentucky and southeastern Ohio area. Renewed uplift apparently occurred during the late Paleozoic, as indicated by a westward shift in the axis of the arch, and thinning of Mississippian strata across it (Ettensohn, 1975; Dever et al., 1977). Depositional thinning of Mississippian rocks across the axes of the Paintsville-Warfield Anticline and the Rockcastle uplift (Dohm, 1963; Maynor, 1984) suggests that these structural features were also positive during Mississippian time.

Fig. 4.1 Isopach map of the Corbin Sandstone Member.
Note the influence of the Irvine-Paint
Creek Fault and the Kentucky River Fault
on the sediment thickness pattern,
paleodispersal trends, and the paleocurrent
directions in the Corbin Sandstone member



(plate 1 and Fig. 4.1) are part of the westward extension of the Rome Trough, a Precambrian basement lineament that extends from eastern Kentucky to Pennsylvania (McDowell, 1986). Although the faults are ancient structures, they were actively subsiding during the early Paleozoic and were periodically active during the late Paleozoic as well (Cable and Beardsley, 1984; Rice et al., 1979).

Tectonics and subsidence influence the three dimensional distribution of fluvial deposits. According to Alexander and Leeder (1987), one of the most important ways in which this influence is exerted is in the detailed surface topography of the alluvial plain across which the fluvial system was active. In spite of the extended research that has been done on the Lee Formation sandstones, little is known about the influence of preexisting intrabasinal tectonic features on the three dimensional geometry of these sandstone bodies.

The Corbin Sandstone Member lends itself to recognizing this influence for three reasons: 1) it is a sheet sandstone that covers hundreds of square kilometers, therefore the influence of relatively large-scale structural features can be revealed by isopach mapping; 2) there are a number of well-documented tectonic features beneath the Pennsylvanian section in eastern Kentucky that were periodically active throughout the Paleozoic, which may have influenced the three dimensional geometry of the Corbin Sandstone Member;

and, 3) the subsurface lithostratigraphic relationship of the Corbin Sandstone Member to the intertonguing Breathitt Formation is not complex, making subsurface correlations relatively easy. Plate 1 (and Fig. 4.1) is an isopach map of the Corbin Sandstone Member. Located on the map are the major intrabasinal tectonic features of the Appalachian Plateau area of eastern Kentucky previously described. The isopach map reveals that all of the intrabasinal tectonic features mentioned above affected the three dimensional geometry of the Corbin Sandstone Member.

The major positive features affected the thickness distribution patterns and paleodispersal trends by blocking and diverting flow of fluvial channel systems as they moved down-flow within the alluvial plain. For example, the axis of the Paintsville-Warfield Anticline runs east-west as shown on Plate 1 and Fig. 4.1. To the north of the anticline, along its eastern extension, southwest oriented isopachous thicks and thins suggest major channels and associated interfluves. However, on the southern flank of the anticline the Corbin Sandstone thins and abruptly pinches-out. This suggests that here, southwest-flowing fluvial channels were blocked by the Paintville-Warfield Anticline. Farther west, near the middle of the anticline, a large south-directed channel (the 200 foot contour) is diverted sharply to the west-northwest, along the northern flank of the Paintsville-Warfield Anticline.

The isopach data shown on Plate 1 and Fig. 4.1 strongly suggest that the Paintsville-Warfield Anticline exerted strong intrabasinal tectonic control on local paleodispersal trends and thickness distribution patterns within the Corbin Sandstone Member. The anticline blocked the flow of major southwest-flowing channels along its eastern extension; along its western extension, a major channel system was diverted from a south-southwesterly flow to a westerly flow.

The Rockcastle Uplift may have also exerted local control on the three dimensional distribution of the Corbin Sandstone Member by blocking and diverting flow of southwest-directed dispersal channels around the flanks of the uplift. The axis of the Rockcastle Uplift trends north-northeast to south-southwest, as shown on plate 1 and Fig. 4.1. The absence of the Corbin Sandstone northwest of the axis of the uplift is shown by the large area outlined by the zero contour line.

Although the zero isopach contour is located northwest of the axis of the Rockcastle Uplift, it seems likely that it is related to its existence. This is possible if the axis of the Rockcastle Uplift shifted northwestward after Mississippian time but prior to Corbin Sandstone deposition. Thrust loading was occurring in the southern Appalachians during early Pennsylvanian time (Beaumont et al., 1987). This may have resulted in a northwestward shift of the axis of the Rockcastle Uplift during early Pennsylvanian time

prior to Corbin Sandstone deposition.

The Kentucky River and Irvine-Paint Creek Faults are down-to-the-basin, normal faults that exerted strong, local, intrabasinal tectonic control on the three-dimensional distribution of the Corbin Sandstone Member. For example, plate 1 and Fig. 4.1 show a northeast-to-southwest trending isopachous thick with a channel-form geometry that follows the axis of the northeastern arm of the Kentucky River Fault. The 200 foot contour line tracks the fault until, near the southern end of the Waverly Arch, the channel trends southward. This suggests that the Kentucky River Fault was controlling the trend of this major dispersal system until the Waverly Arch effectively blocked its flow and diverted it to the south, away from the axis of the fault.

South of the Waverly Arch, the isopachous thick is once again oriented west-southwest. Here however, the Irvine-Paint Creek Fault is the primary structural feature controlling the paleodispersal trend. Isopach contours are elongate parallel to the Irvine-Paint Creek Fault all along its western extension until the Corbin Sandstone comes to outcrop. Moreover, the Corbin Sandstone reaches thicknesses of more than 300 feet along the northern side of the Irvine-Paint Creek Fault but thins abruptly, to 150 feet or less, just south of the fault.

These data clearly suggest that the Kentucky River and

Irvine-Paint Creek Faults exerted strong, local, intrabasinal tectonic control on paleodispersal trends and sediment thickness distribution patterns within the Corbin Sandstone Member. Influence was exerted by capturing major south-to-southwest directed dispersal channels and diverting them westerly, along the axes of the faults.

The relationship of paleocurrent data to the major structural features described above has been discussed in chapter three. Paleocurrent rose diagrams are included on plate one because they demonstrate the relationship between paleodispersal trends, largely defined by subsurface isopach mapping, and paleocurrent directions observed at the outcrop. The westerly paleoflows observed along the outcrop belt in the northern part of the field area are a direct result of the diversion of major dispersal centers to the west, along the Kentucky River and Irvine-Paint Creek Faults.

The role of tectonics in controlling the flow and geometry of fluvial sandstone bodies is becoming increasingly well-documented. Researchers have recognized that modern fluvial channels respond very quickly to even very subtle tectonic influences. For example, Burnett and Schumm (1983) noted changes in channel pattern and sinuosity in several small rivers in Louisiana and Mississippi in response to subtle neotectonic deformation. Butler (1984) demonstrated that the Amargosa River followed a major graben

along the Death Valley fault zone in California for several kilometers before being diverted by preexisting terraces.

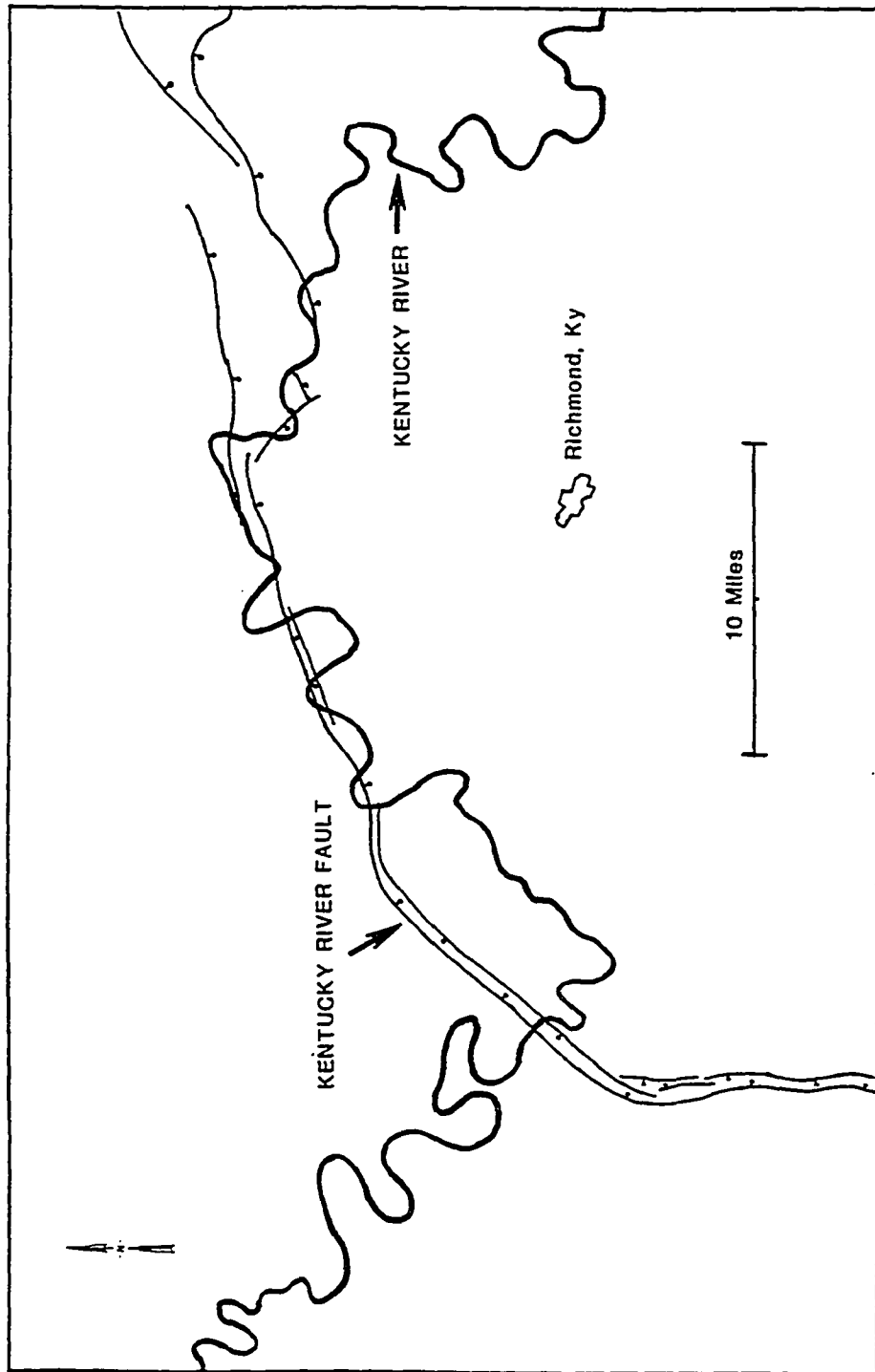
A more obvious example is the influence of the Kentucky River Fault on the present day Kentucky River. Figure 4.2 shows a stretch of the Kentucky River south of Lexington, Kentucky. This figure shows that the Kentucky River is being diverted to the west, along the axis of the Kentucky River Fault, for more than 20 miles before returning to its northwesterly course. Here, the Kentucky River Fault is diverting the flow of an active river, just as it did the Corbin Sandstone Member during Pennsylvanian time.

Isopach mapping clearly demonstrates that the preexisting uplifts and faults of eastern Kentucky influenced the three dimensional geometry of the Corbin Sandstone Member over large areas of its distribution. The significance of these findings is that they provide powerful corroborating evidence for the predominantly fluvial nature of the Corbin Sandstone Member and for the role intrabasinal tectonics play in influencing the architecture of fluvial sandstone bodies.

Subsurface Stratigraphy of the Corbin Sandstone Member and Associated Rocks

The Corbin Sandstone Member can be mapped in the subsurface because of its continuity and its lithologic distinction from Breathitt Formation Sandstones. The Corbin

Fig. 4.2 Map showing the influence of the Kentucky River Fault on a stretch of the Kentucky River south of Lexington, Kentucky. The Kentucky River Fault has diverted the northwest-flowing Kentucky River to the west-southwest along a 20 mile portion of the fault.



Sandstone is sheetlike and present in the majority of the wells that penetrate the the eastern and western limits of the belt in which it is contained. More importantly, it is texturally and compositionally more mature than Breathitt Formation sandstones, making its gamma-ray well-log signature distinct from Breathitt Formation Sandstones.

Figure 4.3 shows the location of three subsurface cross-sections. Figures 4.4, 4.5, and 4.6 are the cross-sections themselves. Included are two northwest-to-southeast trending dip-sections (Figs 4.4 and 4.5) and a northeast-to-southwest trending strike section (Fig. 4.6). Thicknesses of the Lee Formation sandstones and the Breathitt Formation were determined from correlated gamma-ray well-logs. All cross-sections are hung from the same stratigraphic datum, a relatively continuous Breathitt shale beneath the Corbin Sandstone Member.

Directly above the Newman Limestone is the Pennington Formation, a thin (sometimes absent) unit which consists predominantly of interbedded sandstone, shale, and limestone. Because of their lithologic similarity, it is very difficult to distinguish the Pennington Formation from the Breathitt Formation based on gamma-ray log signatures alone. Therefore, the interval located directly above the Newman Limestone is designated Breathitt/Pennington on the cross-sections.

Cross-section A-A' (Fig. 4.4) reveals the stratigraphy

Fig. 4.3 Location map of three subsurface cross-sections, A-A', B-B', and C-C'.

Fig. 4.4 Subsurface cross-section A-A'. This cross-section shows the stratigraphic relationship of the Corbin Sandstone Member to the Breathitt Formation, and the underlying Rockcastle Sandstone Member.

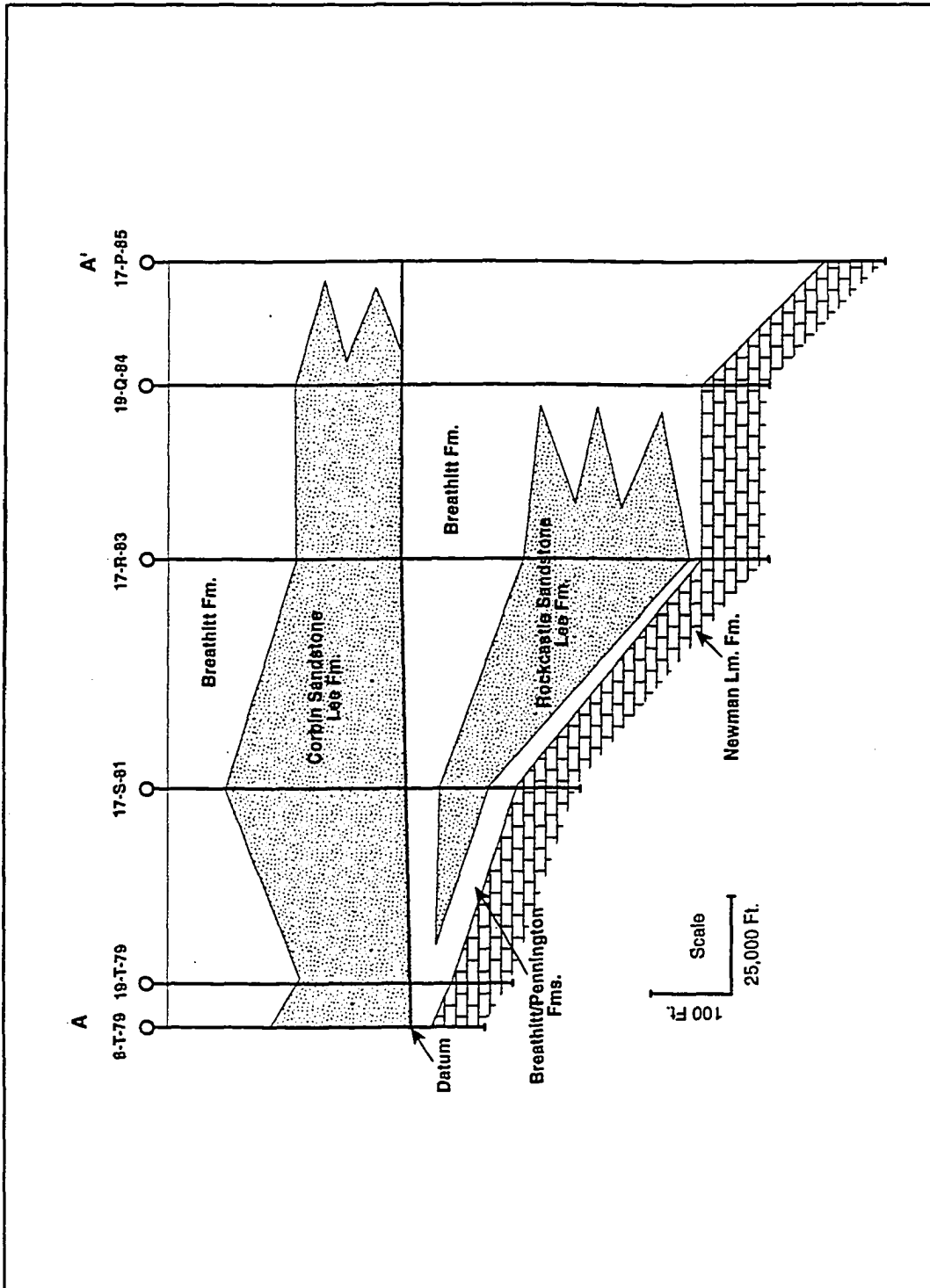


Fig. 4.5 Subsurface cross-section B-B'. This cross-section shows the stacked en-echelon arrangement of the Lee Formation Sandstone Members in the northern part of the study area.

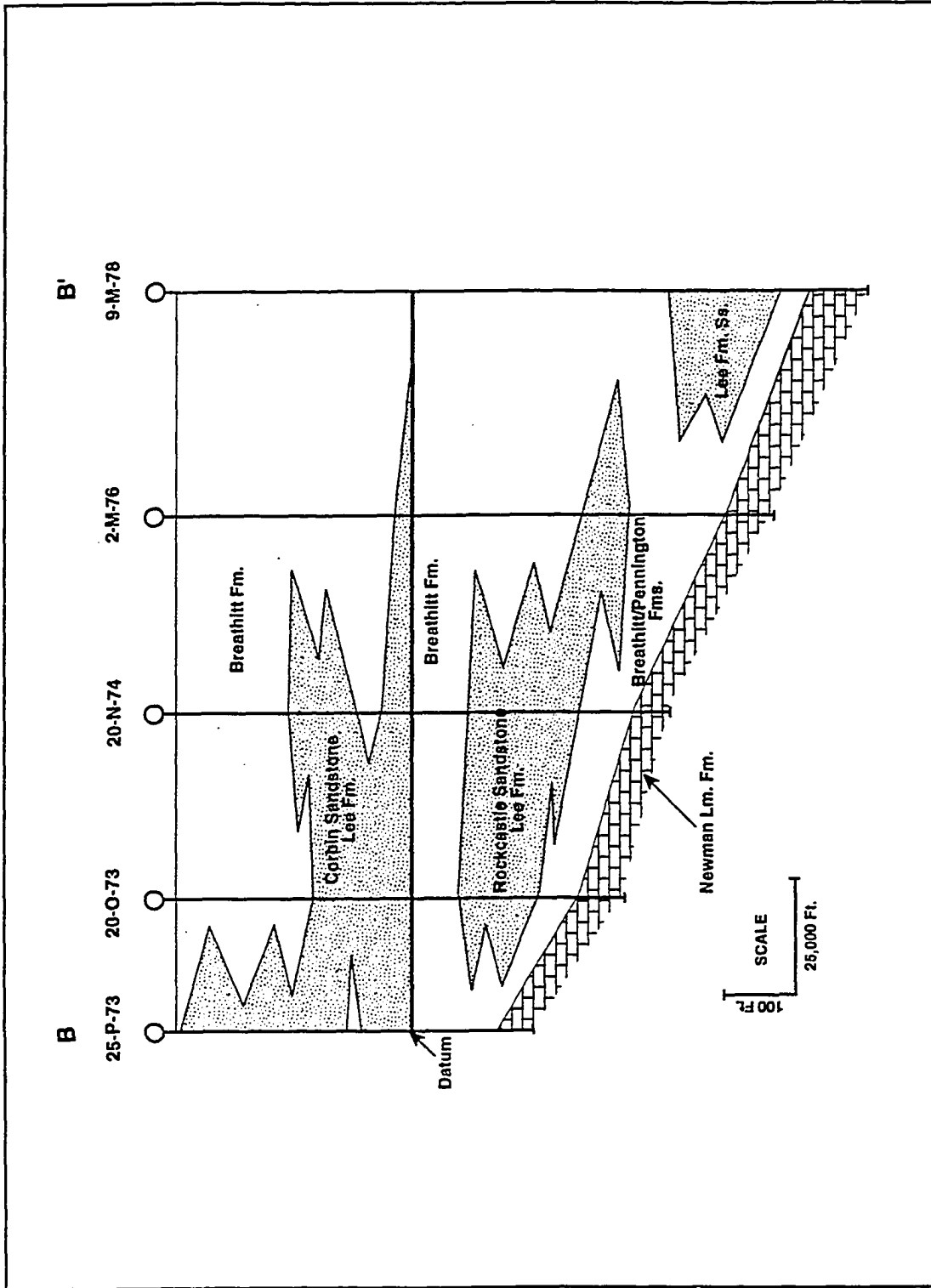
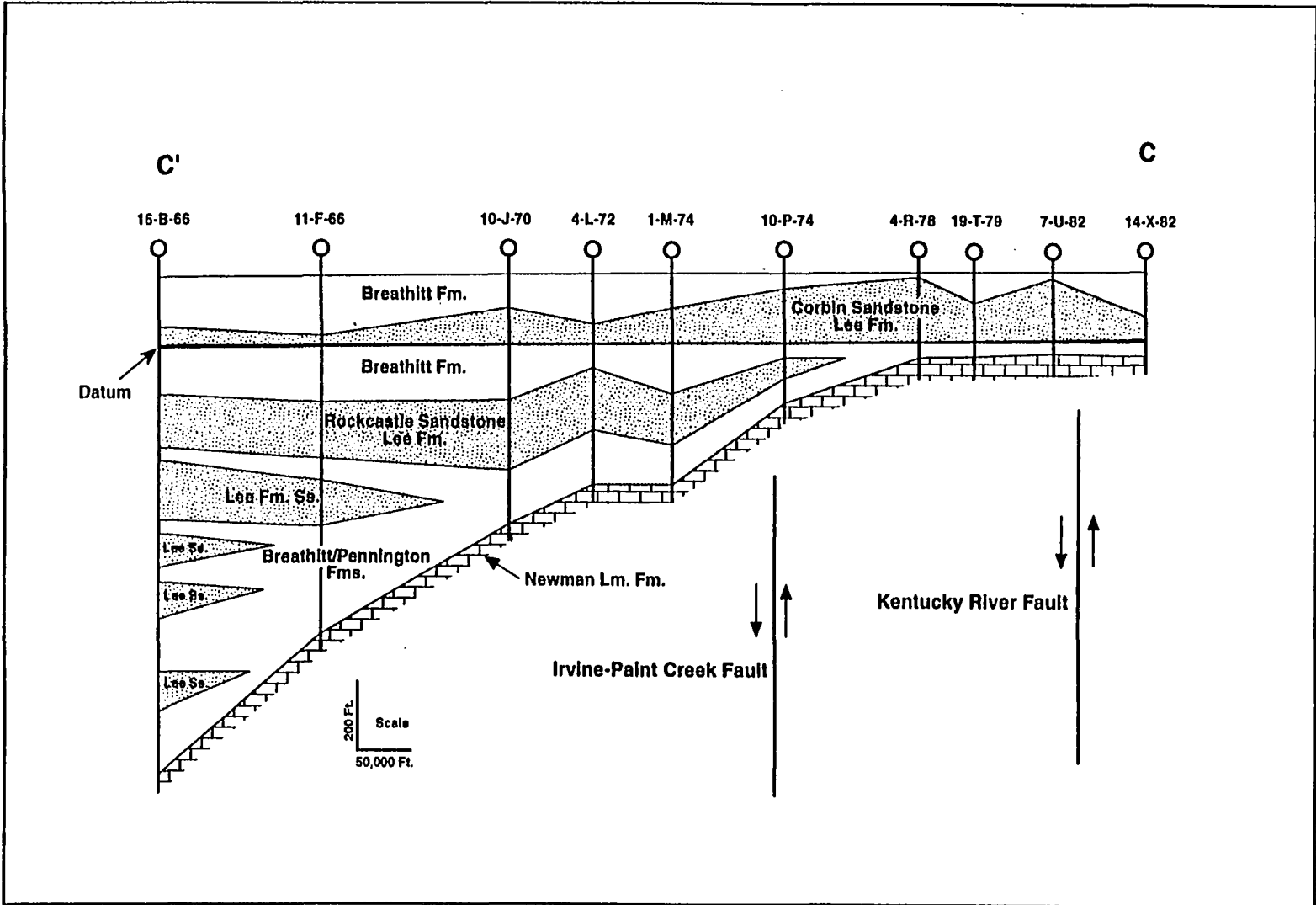


Fig. 4.6

Cross-section C-C'. This cross-section shows the southward thickening of the Pennsylvanian section, and the thinning of the Corbin Sandstone Member. Note the abrupt thickening in the Pennsylvanian section on the downthrown side of the Irvine-Paint Creek Fault.



of the Pennsylvanian section in the northern-most part of the study area. From northwest-to-southeast the cross-section shows considerable thickening in the Pennsylvanian section. In the northwestern part of the cross-section, the Pennsylvanian section is thin, and the Corbin Sandstone rests on a thin Breathitt/Pennington interval (see 8-T-79 and 19-T-79). To the southeast, the Rockcastle Sandstone thickens, and a Breathitt tongue develops between the Corbin and Rockcastle Sandstones. Eventually, both sandstones pinch-out into a thick Breathitt Formation section.

Cross-section B-B' (Fig. 4.5) is also a dip section but is located farther south than cross-section A-A'. Cross-section B-B' reveals the stacked en-echelon arrangement of the Lee Sandstone Members. The Corbin Sandstone is thickest in section 25-P-73, but thins to the southeast. The Rockcastle Sandstone is absent in section 25-P-73, and reaches its maximum thickness farther to the southeast, in section 20-N-74. Here, the overlying Corbin Sandstone Member begins to thin, intertonguing with the Breathitt Formation. The Corbin and Rockcastle Sandstones both pinch-out between sections 2-M-76 and 9-N-78. In section 9-N-78 another Lee Formation Sandstone is encountered. This sandstone is probably the Sewanee Sandstone Member (see Chesnut, 1988). However, without correlations farther into the basin its origin is uncertain.

Cross-section C-C' (Fig. 4.6) is a regional strike

section. This cross-section shows the southward thickening in the Pennsylvanian section and the southward thinning in the Corbin Sandstone Member. The northeast part of the cross-section shows a thick Corbin Sandstone resting directly on a thin Breathitt/Pennington interval.

The Kentucky River Fault is located between 7-U-82 and 14-X-82, and, while this fault exerted local influence on thickness patterns in the Corbin Sandstone Member, no significant thickening in the overall Pennsylvanian section is observed on either side of the fault. This suggests that the fault was relatively inactive during Pennsylvanian sedimentation.

South of 4-R-78 the Pennsylvanian section begins to thicken and the Rockcastle Sandstone develops. South of section 10-P-74 the Pennsylvanian section thickens abruptly, but remains unchanged between 1-M-74 and 4-L-72. This suggests that, unlike the Kentucky River Fault, the Irvine-Paint Creek Fault was active during Pennsylvanian sedimentation and possibly during Corbin Sandstone deposition. Once south of section 4-L-72, the Pennsylvanian section thickens continuously until the end of the cross-section. Beginning with well in 11-F-66 additional Lee Sandstone Members are encountered.

Subsurface cross-sections reveal the continuous, sheet-like nature of the Corbin Sandstone Member. They further demonstrate the stacked en-echelon arrangement of the Lee

Sandstone Members as well as the southward thickening of the Pennsylvanian section observed in outcrop.

Gamma-Ray Well-Log Signatures and Interpretations

Gamma-ray well-logs are commonly used to interpret depositional environments in the subsurface. This is possible because many depositional environments show consistency in gamma-ray well-log signatures. As a result, certain signatures have become generally accepted as characteristic of specific depositional environments (Fig. 1.6). However, considerable variation may exist in gamma-ray log signatures within a given depositional setting. These variations reflect the complexities in the spatial and temporal distribution of clay, sand, and gravel within any given depositional system.

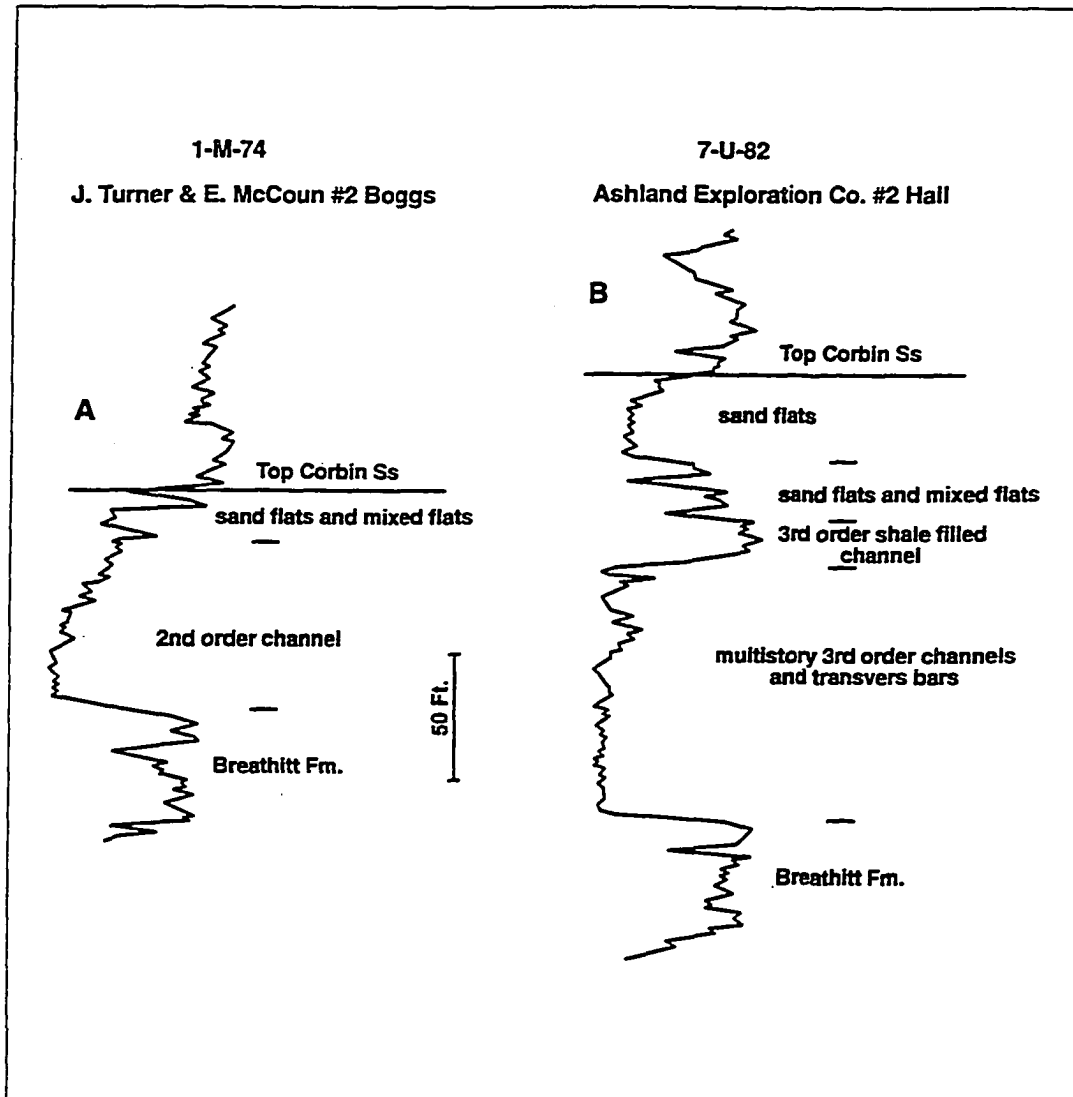
In subsurface analysis, the interpretation of gamma-ray well-log profiles is often limited by the lack of core or outcrops that can provide insight into the complexities of the depositional environment. However, extensive outcrop work on the Corbin Sandstone Member (described in chapter three) allows for a more comprehensive understanding of what the range in gamma-ray well-log signatures represents in a braided river environment.

Examination of more than 500 gamma-ray well-logs in the Corbin Sandstone Member reveal two common profiles: fining

upward and blocky (see bell-shaped and cylindrical, Fig. 1.6). However, within these two broad classifications, considerable variation exists. Figures 4.7 A and 4.7 B, and Fig. 4.8 A represent three examples of fining upward gamma-ray well-log profiles. Figure 4.7 A shows a relatively simple fining upward profile. The abrupt basal contact is characteristic of almost all the gamma-ray logs examined and reflects the generally erosional nature of the Corbin Sandstone basal contact. The gamma-ray log shows a relatively continuous fining upward trend until, at the upper 20 feet or so, the log shows abrupt deflections suggesting sudden changes in lithology.

This profile is interpreted as a single, large (second order) channel, capped by the tidal sandflat and mixed flat facies. The sharp basal contact and fining upward (bell-shaped) profile is characteristic of sinuous channels. The abrupt deflections at the top suggest rapidly changing sand and shale dominated intervals, indicative of the alternating tidal sandflats and mixed flats observed in outcrop. Moreover, positioned at the top of the Corbin Sandstone, they are consistent with the location of the tidal facies observed in outcrop. The bell-shaped character of some gamma-ray logs, such as the one shown in Fig. 4.7 A, suggests that second order channels were not completely straight but exhibited some degree of sinuosity. The gamma-ray log in Fig. 4.7 A compares well with outcrop BA-2,

Fig. 4.7 Gamma-ray well-log signatures of the
Corbin Sandstone Member. Both A and B
show fining-upward profiles but represent
different facies arrangements.



interpreted as a second order channel-fill sequence (Appendix A). However, this outcrop lacks the tidal facies.

Figure 4.7 B displays a more complex fining upward profile than Fig. 4.7 A. The bottom 100 feet is a sandstone with a blocky to slightly fining upward profile. This sandstone is overlain by a 40 foot shaley interval, which is then capped by a 30 foot sandstone that shows a higher gamma count than the lower sandstone.

The basal sandstone is interpreted as consisting of multistory third order channels and transverse bars. The generally blocky character is consistent with outcrop observations wherein fining upward textural trends are observed within third order channels, but stacking of the channels results in a vertical textural profile that does not display a continuous fining upward trend. Moreover, in outcrop, stacked transverse bars do not show fining upward trends at all. However, it is possible that all or part of this blocky sandstone interval may represent a second order, vertically aggrading, sand-filled channel. Unlike laterally accreting channels, vertically aggrading channels are less likely than to show distinct fining-upward textural trends.

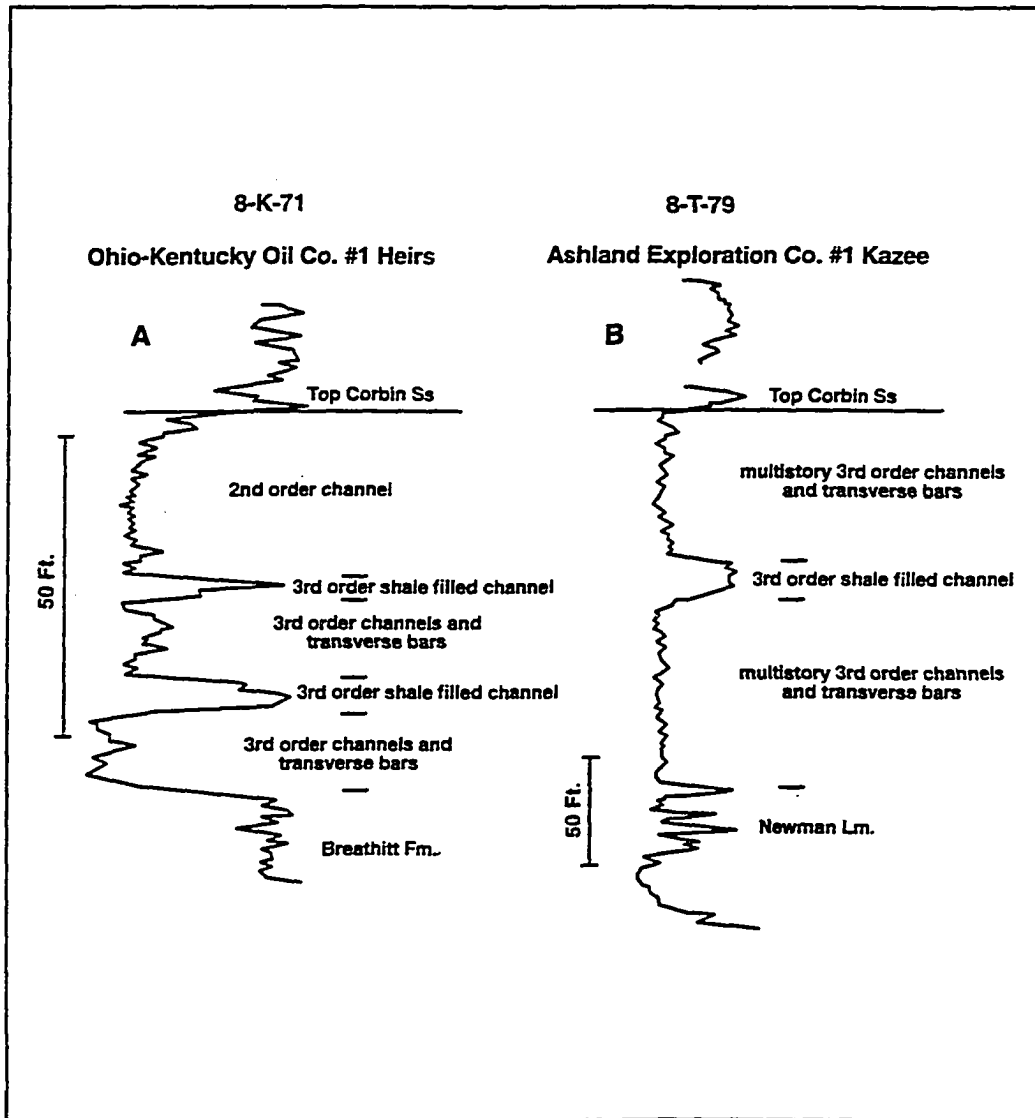
The 15 to 20 foot thick shale directly above the thick basal sandstone in Fig. 4.7 B is interpreted as a third order, abandoned, shale-filled channel. It is possible, considering its position near the top of the unit, that it represents a tidal mudflat facies. However, no true

mudflats this thick were observed in outcrop. Above this shale is a 20 foot thick alternating shaley and sandy interval, interpreted as interbedded mixed flats and sandflats, showing similar gamma-ray log characteristics to the mixed flat and sandflat interval of Fig. 4.7 A. Capping the sequence is a 35 foot sandstone interval. This interval is interpreted as the tidal sandflat facies. In the field, the tidal sandflat facies can be observed directly above the alternating sandflat and mixed flat facies. The gamma-ray log profile shown in Fig. 4.7 B compares well with vertical textural profiles and facies arrangements from several outcrops (see BA-3, CO-2 and EZ-1, Appendix A).

Figure 4.8 A is another example of a complex fining upward gamma-ray log profile. The basal 35 feet is best interpreted as sandstone dominated by stacked transverse bars and third order sand-filled channels with associated third order shale-filled channels. The sandstones are too thin and lack consistent fining upward trends to be second order channels. Moreover, the thicknesses of the shale intervals are compatible with third order shale-filled channels observed in outcrop.

The upper 28 feet in Fig. 4.8 A shows a continuous, gradual, fining upward trend interpreted as a small, second order channel-fill sequence. The less distinct fining upward trend of this second order channel compared to the larger second order channel shown in Fig. 4.7 A, suggests

Fig. 4.8 Gamma-ray well-log signatures of the Corbin Sandstone Member. Well-log A is another example of an fining-upward profile. Well-log B shows a blocky profile.



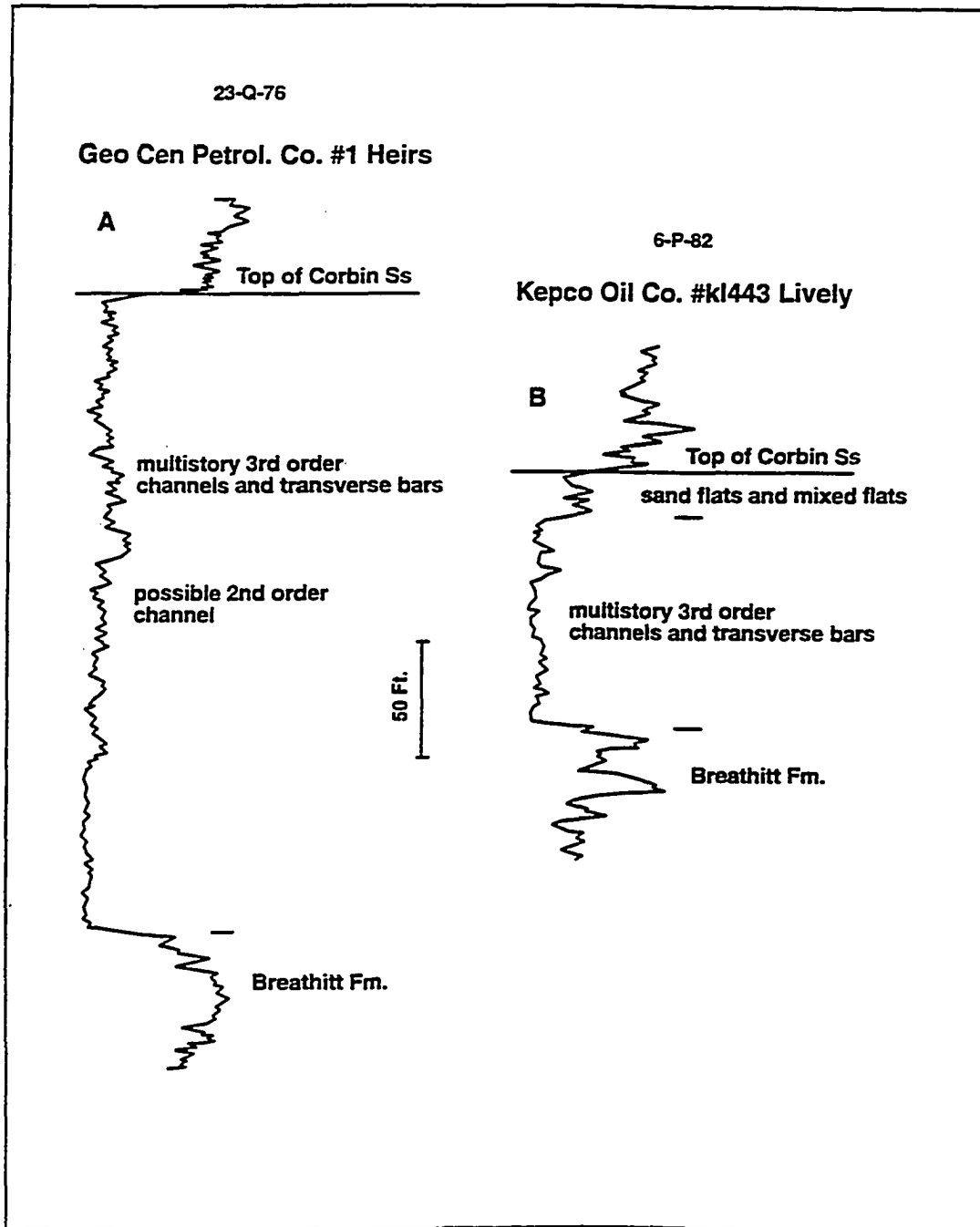
that this channel displayed less sinuosity. The gamma-ray well-log profile of Fig. 4.8 A shows characteristics interpreted to reflect a vertical facies arrangement similar to that shown in outcrop ZA-3 (appendix A).

Figures 4.8 B and Figs. 4.9 A and B display blocky (cylindrical) profiles (Fig. 1.6). The majority of logs examined in the Corbin Sandstone Member display this blocky gamma-ray well-log profile, which is considered characteristic of braided river deposits (Cant, 1984; Busch and Link, 1985). Architectural and textural analysis from outcrops suggests that the gamma-ray well-logs shown in Figs. 4.8 B, and Figs. 4.9 A and 4.9 B represent multistory sandstone bodies, consisting predominantly of stacked third order sand- filled channels and transverse bars.

Figure 4.8 B shows a blocky gamma-ray well-log profile with a single, 15 to 20 foot thick shale near the middle. Shales of similar thickness were observed in outcrop and are interpreted as abandoned third order channel-fill sequences. (Note that this gamma-ray log apparently lacks the tidal facies near the top). Figure 4.8 B compares favorably with outcrop BA-3 (appendix A). Figures 4.9 A and 4.9 B are also interpreted to be dominated by transverse bars and third order channels. However, Fig. 4.9 B contains the sandflat and mixed-flat facies.

In addition to second order channels, third order channels, transverse bars, tidal sandflats and mixed flats,

Fig. 4.9 Gamma-ray well-log signatures of the Corbin Sandstone Member. Profiles A and B both show blocky profiles. Blocky gamma-ray well-log profiles are the most common type observed in the Corbin Sandstone Member.



other architectural elements are almost certainly reflected in the gamma-ray well-log profiles shown in the figures. For example, basal conglomerates, massive-bedded gravity-flow deposits, and horizontal-bedded sheet-flood deposits are probably present. However, these facies are much less common than planar crossbeds and trough/tangential crossbeds associated with transverse bars and channel-fill sequences in the braided-fluvial portion of the Corbin Sandstone Member. Therefore, without additional subsurface information in the form of core to further refine the gamma-ray log signature interpretations, their existence is difficult to recognize.

In summary, subsurface analysis has provided valuable evidence of the predominantly fluvial origin of the Corbin Sandstone Member. Modern river systems are very sensitive to tectonic influences. Subsurface isopach mapping has demonstrated the powerful influence intrabasinal tectonic features had in controlling the 3-D architecture of the Corbin Sandstone Member by blocking and diverting the flow of the major fluvial dispersal channels associated with Corbin Sandstone deposition.

Subsurface cross-sections demonstrate the sheet-like nature of the Corbin Sandstone Member, and dip sections show its stacked en-echelon stratigraphic relationship to other Lee Sandstone Members. Cross-section A-A' suggests activity along the Irvine-Paint Creek Fault during early

Pennsylvanian time, and shows an actively subsiding basin to the southeast prior to Corbin Sandstone deposition.

Gamma-ray well-log profiles reflect the vertical facies and textural arrangement observed in outcrops of the Corbin Sandstone Member. Fining upward and blocky gamma-ray well-log profiles are observed. These profiles generally reflect a multistory braided fluvial system dominated by channels and transverse bars. Moreover, gamma-ray well-logs of the Corbin Sandstone are dominated by blocky (cylindrical) profiles that are generally accepted as typical of braided fluvial environments (Fig. 1.6). Gamma-ray well-log profiles also record the presence of the tidal facies observed in outcrop, and both the interbedded mixed flat/sandflat (ISS) facies, and the sandflat (RBS) facies can be recognized.

The combined outcrop and subsurface data demonstrate that in the Appalachian Basin, during Corbin Sandstone deposition, braided fluvial processes dominated, but marine (tidal) processes were operating during the later stages of Corbin Sandstone deposition. Moreover, the recent work of Greb and Chesnut (1992) and Martino and Sanderson (1993), suggests that tidal processes were an important component of Breathitt Formation sedimentation as well.

In the eastern part of the Illinois Basin, Kvale and Archer (1990), Archer and Kvale (1989), and Kvale et al. (1989), have documented vertically-accreting, small-scale

tidal rhythmites in lower Pennsylvanian rocks previously interpreted as fluvio-deltaic. The availability of abundant core at the Naval Surface Warfare Center located at Crane, Indiana, has permitted a detailed investigation into the processes and environments operating in the eastern part of the Illinois Basin during Morrowan/Atokan time. This has allowed for a reexamination of the fluvio-deltaic interpretation for the Mansfield Formation, in light of the recent discovery of significant tidal deposits within this unit. The following chapter, then, concerns the origins of the Mansfield Formation which is the secondary focus of this research. A comparison of the Corbin Sandstone Member to the Mansfield Formation will be the subject of chapter six.

SEDIMENTOLOGY OF THE MANSFIELD FORMATION OF INDIANA

Introduction

Rocks of the Morrowan/Atokan age Mansfield Formation of southwestern Indiana, were examined to determine their sedimentological characteristics. The investigation was conducted as part of the Department of the Navy's ongoing Installation Restoration Program at the Naval Surface Warfare Center (NSWC) located at Crane, Indiana. The purpose of the investigation was to provide a detailed geological study of the Pennsylvanian age rocks located on the center. This information is used by hydrologists with the U.S. Army Corps of Engineers in groundwater remediation efforts that are presently being conducted at the NSWC.

Examination of the lower Pennsylvanian rocks at the NSWC has provided an opportunity to compare the geology of the Corbin Sandstone Member of the Central Appalachian Basin, with that of the Mansfield Formation of the Illinois Basin. These rocks are of the same or similar age (Morrowan/Atokan). However, the origin of the Mansfield Formation of the Illinois Basin is substantially different from that of the Corbin Sandstone Member of the Appalachian Basin. Comparing the sedimentology of these similar aged units should provide insight into the physical depositional processes that were operating in separate basins during

General Geology and Methods of Investigation

The Illinois Basin (Fig. 5.1) is a large, spoon-shaped cratonic basin that began forming in Cambrian time (Klein and Hsu, 1987). It is bounded to the east by the Cincinnati Arch, to the northeast by the Kankakee Arch and to the west by the Ozark Uplift. The youngest Paleozoic rocks in the Illinois Basin are Pennsylvanian in age and reach a maximum thickness of more than 750 m in southern Illinois (Wanless, 1955). Across southwestern Indiana, the Pennsylvanian section thins and eventually pinches-out.

The Mansfield Formation was studied at the 110 square km area of the NSWC which is located at the eastern margin of Pennsylvanian age rocks (Fig. 5.2). Here, the Pennsylvanian section is comprised exclusively of the Mansfield Formation which ranges from 0 to 300 feet thick, and consists of interbedded sandstones, siltstones, shales, coals and underclays (Barnhill, 1992). Figure 5.3 is a columnar profile showing the Carboniferous stratigraphy at the NSWC and surrounding area.

For this study, more than 1,550 m of core from 63 coreholes drilled at the NSWC were described. Figure 5.4 is a map of the NSWC, and the 3 principle locations where the core were taken. More than half of the total core is from the Rockeye site where 35 closely spaced coreholes (150 m spacing) provided 855 m of core. The Dye Burial Ground (DBG)

Fig. 5.1 Map showing the location of the Illinois Basin.

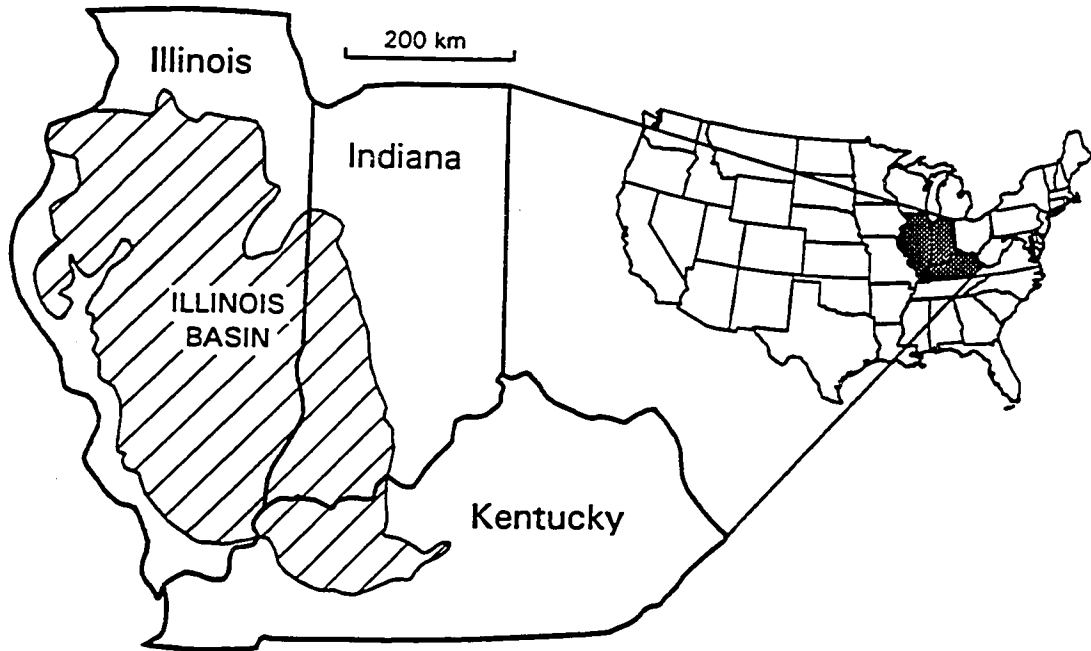


Fig. 5.2 Map showing the distribution of Pennsylvanian
age rocks in Indiana. The NSWC is located
along the eastern edge of Pennsylvanian age
rocks as shown on this map.

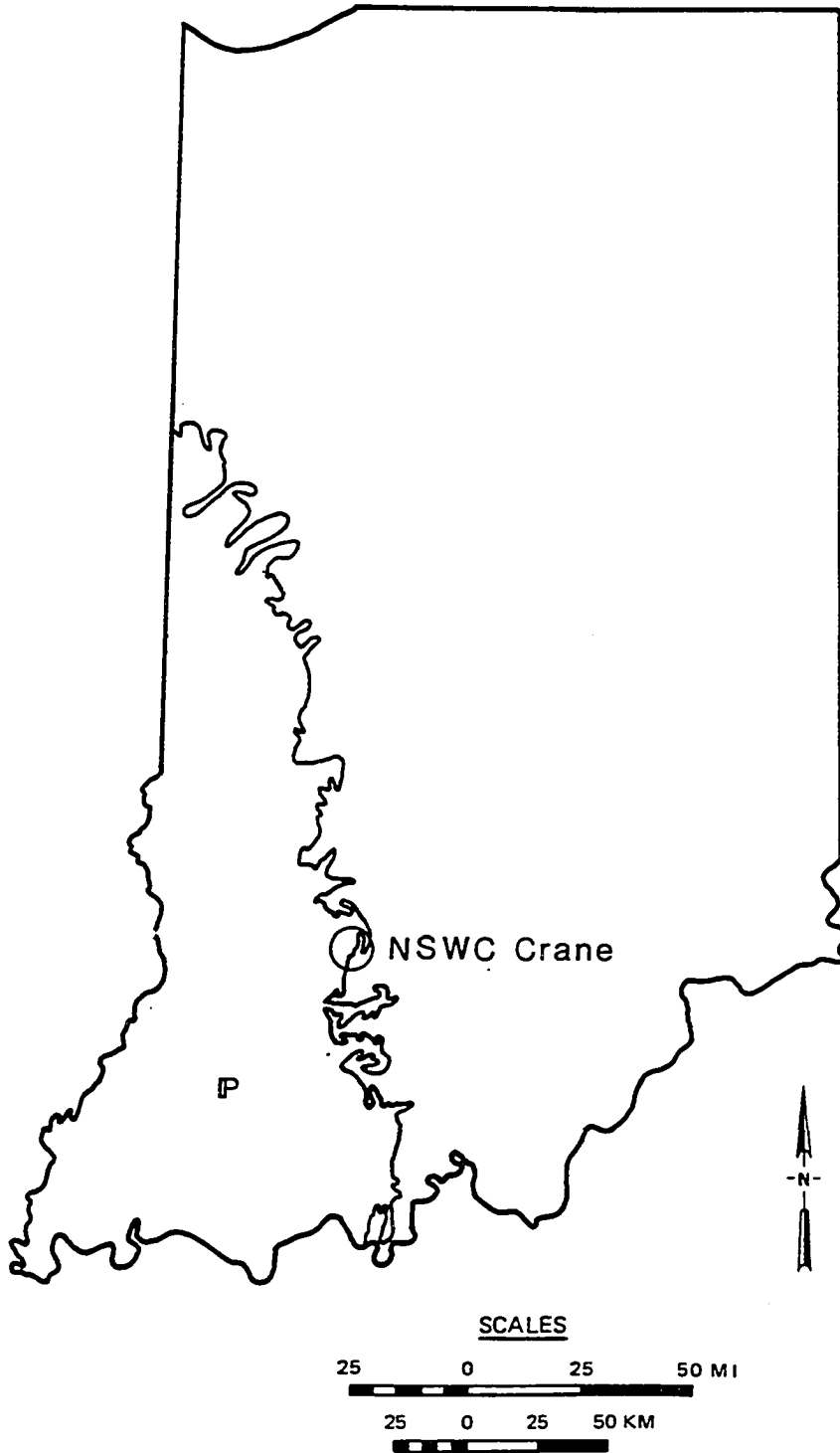
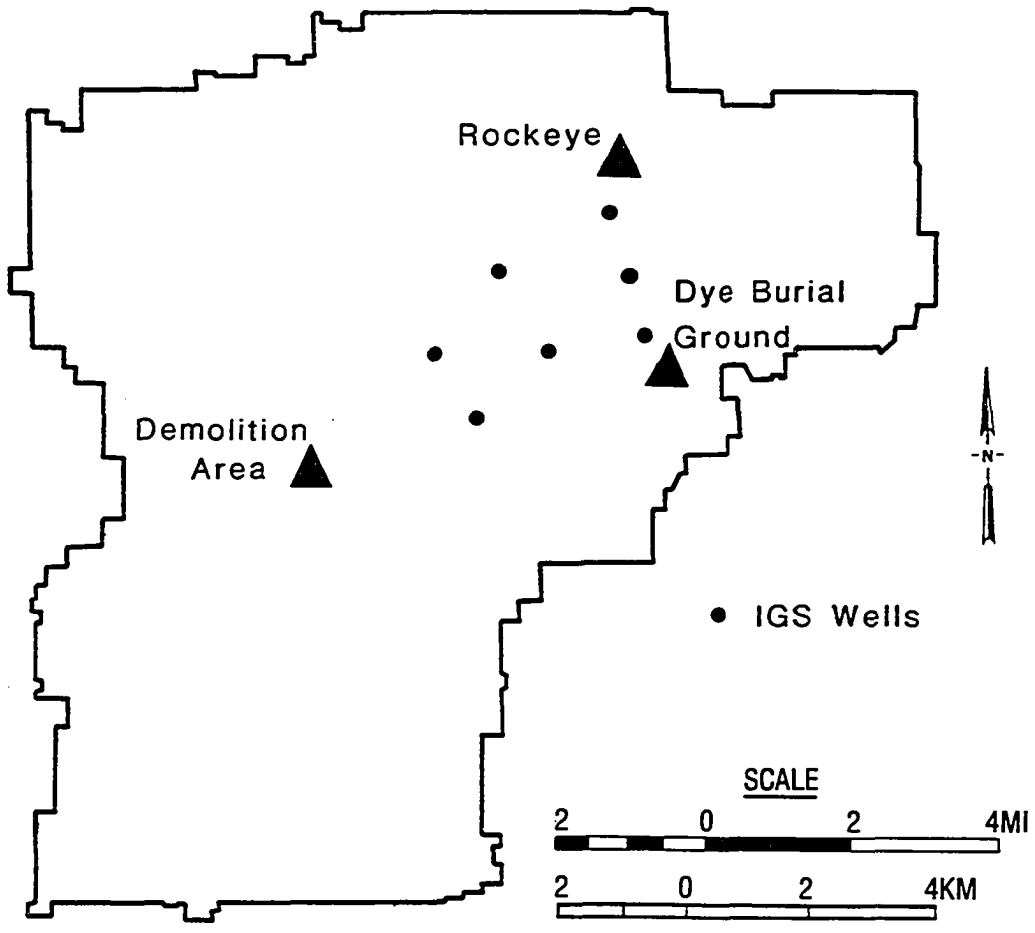


Fig. 5.3 Stratigraphic column of Carboniferous rocks
at the Naval Surface Warfare Center, Crane,
Indiana and the surrounding area.

TIME UNIT		ROCK UNIT		LITHOLOGY
PERIOD	EPOCH	GROUP	FORMATION	
PENNSYLVANIAN	MORROWAN	Raccoon Creek	Brazil Fm.	
	ATOKAN		Mansfield Fm.	
MISSISSIPPIAN	CHESTERIAN	Buffalo Wallow	Tar Springs Fm.	
			Stephensport	
		Hardinsburg Fm.		
		Haney Ls.		
		Big Clifty Fm.		
		Beech Creek Ls.		
		West Baden	Elwren Fm.	
			Reelsville Ls.	
			Sample Fm.	
			Beaver Bend Ls.	
		Blue River	Bethel Fm.	
			Paoli Ls.	
VAL.			Ste. Genevieve Ls.	

Fig. 5.4 Map of the NSWC showing the location of the major coring sites. In addition to dense coring at the Rockeye, Dye Burial Ground and Demolition Area sites, seven additional coreholes linking these sites were drilled. These are the IGS (Indiana Geological Survey) coreholes shown as black dots on the map.



Naval Surface Warfare Center (NSWC)
Crane, Indiana

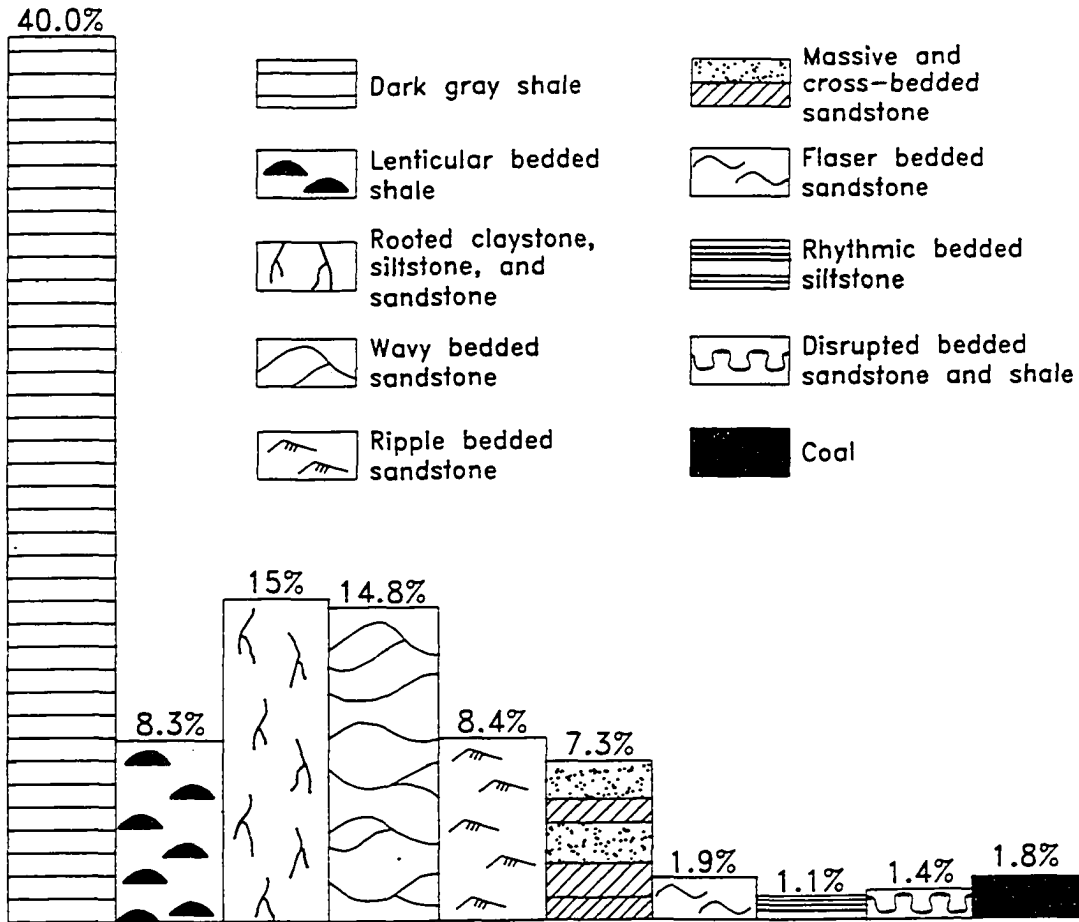
provided 246 m of core from 17 coreholes, while the demolition area (DEMO) provided 120 m of core from 4 coreholes. In addition, the 7 Indiana Geological Survey (IGS) coreholes provided an additional 342 m of core, and allowed a stratigraphic link to be made among the three sites.

Core were described in detail, and a network of cross-sections were constructed at the Rockeye and Dye Burial Ground sites (see Barnhill, 1992). In addition, "regional" cross-sections linking the three sites were constructed. Cross-sections were constructed to determine lithostratigraphic facies relationships, and to ascertain the continuity of the facies. Isopach maps of sandstone units were constructed to determine sandstone body geometries. Finally, block diagrams were constructed at the Rockeye site to demonstrate the three-dimensional relationship of the facies at this geologically complex area.

Facies Descriptions and Interpretations

Rocks of the Mansfield Formation were divided into ten major facies (Fig. 5.5), and the relative abundance of each was calculated from the 15 coreholes that contain a complete Mansfield Formation section. Coreholes that did not penetrate the entire Mansfield Formation were excluded from

Fig. 5.5 Bar graph showing the relative percent of the major facies of the Mansfield Formation at the NSWC.



the relative percentage calculations. Facies subdivisions were based on a combination of sedimentary bedding features and textures that were interpreted to represent specific depositional environments. The description and interpretation of these facies are given below, and photographs are provided in Fig. 5.6.

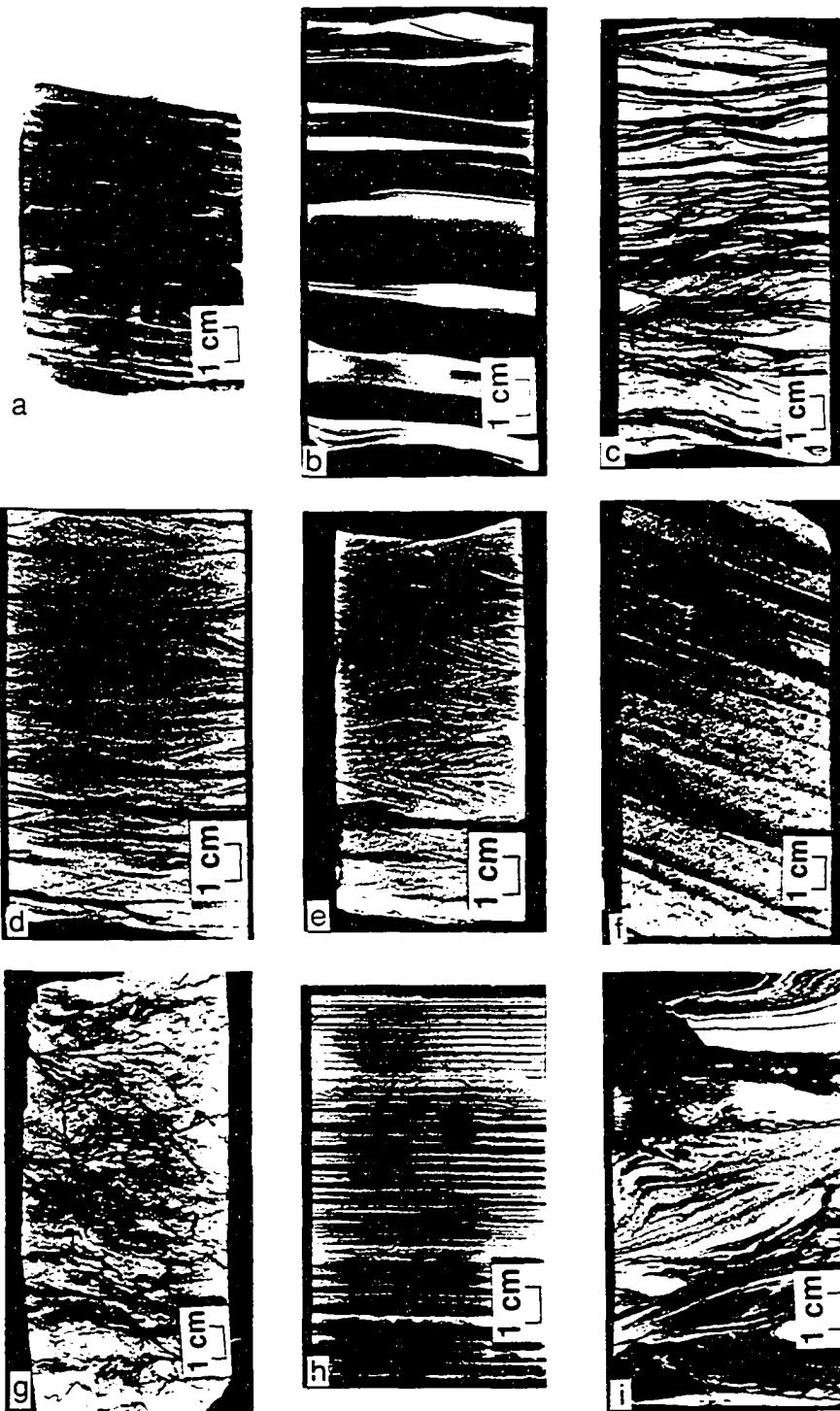
Dark Gray Shale Facies (DGS)

The DGS facies consists of waxy, platy, occasionally silty and micaceous, dark gray shale (fig. 5.6 a). Finely disseminated plant material is common along parting planes. Body fossils are usually absent, but rare neospiriferid brachiopods are sometimes observed. In addition, conodonts and foraminifera are present in this facies. Chondrites traces are sometimes present in silty intervals. Siderite beds and/or nodules 40 cm or more thick are common. Thicknesses range from 1 to 18 m. The DGS facies is the most common facies observed, accounting for more than 40% of the total volume of the Mansfield Formation (Fig. 5.5).

The DGS facies has three occurrences in the Mansfield Formation: 1) it occurs as incised valley-fill deposits within paleovalleys that are 30 m or more deep, and 1.6 km wide; 2) it occurs as a relatively widespread, regionally correlatable .5 to 10 m thick, marine transgressive unit directly above coals or subaerial exposure surfaces; and, 3)

Fig. 5.6

Core photographs of the major facies of the Mansfield Formation. Facies include: a) dark gray shale (DGS), b) lenticular shale (LS), c) wavy-bedded sandstone (WFBS), d) flaser-bedded sandstone (WFBS), e) ripple-bedded sandstone (RBS) with herringbone crossbedding, f) crossbedded sandstone (MCBS), g) rooted sandstone (RMSS), h) rhythmic-bedded siltstone and mudstone (RBSM) showing well-developed spring-neap cyclicity (S and N on photograph), i) disrupted-bedded sandstone and mudstone (DBSM) forming load-casted ripples.



it occurs as thin (.5 to 2 m thick), laterally discontinuous units associated with coals, rooted horizons, and coarser-grained facies with tidal structures. This occurrence is interpreted as the product of tidal mudflat deposition. Based on the presence of marine body fossils and microfossils, a marine origin is interpreted for all three occurrences.

Lenticular Shale Facies (LS)

This facies consists of dark gray, silty, micaceous, carbonaceous shale with isolated lenses of silty, very-fine grained, quartz-rich sandstone (Fig. 5.6 b). The sandstone lenses represent isolated or "starved" current ripples that vary from 3 mm to 1 cm in thickness. Trace fossils are common and usually consist of Planolites, and Teichichnus, and bioturbation may be heavy. The LS facies can often be observed grading vertically and/or laterally into dark gray shale (DGS facies), wavy-bedded sandstone (WFBS facies), and rooted underclays (RMSS facies). The LS facies ranges in thickness from 1 to 4 m.

The LS facies is interpreted as the product of intertidal to subtidal mixed-flat deposition. Lenticular bedding is considered characteristic of tidal environments (Reineck and Wunderlich, 1968), although it has been documented in other environments as well. However, its

occurrence with other tidal structures such as wavy bedding and small-scale tidal rhythmites supports a tidal interpretation. Its association with rooted underclays suggests that locally the LS facies formed in the intertidal zone (Clifton, 1983).

Rooted Mudstone, Siltstone and Sandstone Facies (RMSS)

The RMSS facies consists of rooted, greenish gray structureless mudstone to light gray, clayey, siltstone and very fine-grained sandstone (Fig. 5.6 g). In most cases rooting has disrupted primary bedding features. However, in some cases lenticular bedding, wavy bedding, ripple bedding, rhythmic bedding and small-scale crossbedding is preserved. In almost all cases the RMSS facies is overlain by a coal, or shows evidence of subaerial exposure. Often, the RMSS facies is underlain by lenticular shale or wavy-bedded sandstone. The RMSS facies ranges from 10 cm to 5 m in thickness, and accounts for 15% of the Mansfield Formation (Fig. 5.5).

The presence of rooting and associated tidal bedding features, suggests that this facies formed in an intertidal to supratidal marsh environment. The location of the rooted intervals directly beneath coals and above lenticular-bedded shale and wavy-bedded sandstone suggests that the marsh was located between intertidal/subtidal flats, and supratidal

coal-forming peat mires. Modern sediments very similar to those described above are found in salt marsh and mangrove swamp deposits of modern tide-influenced settings (e.g., Clifton, 1983; Tucker, 1973).

Wavy and Flaser-Bedded Sandstone Facies (WFBS)

Wavy and flaser bedding are described together because they are usually interbedded, and represent the product of the same depositional environment. Wavy and flaser bedding, together, account for more than 16% of the Mansfield Formation section (Fig. 5.5). The WFBS facies consists of light gray, well-sorted, quartz-rich, current-rippled sandstone interlaminated with medium to dark gray, carbonaceous, micaceous shale. Shale may form continuous laminae 1 mm to 1 cm thick (wavy bedding, Fig. 5.6 c), or it may form thinner, 1 to 2 mm thick discontinuous laminae confined to ripple troughs (flaser bedding, Fig. 5.6 d). The WFBS facies can be observed grading upward into rooted intervals (RMSS facies). Bioturbation is sometimes observed, and in some cases it has almost completely destroyed primary bedding features.

The WFBS facies is interpreted to be the product of intertidal to subtidal mixed-flat deposition. Although documented in environments other than tidal, wavy and flaser bedding are highly characteristic of tidal environments

(Reineck and Wunderlich, 1968; Terwindt, 1971; Clifton, 1982; Frey and Howard, 1986; Martini, 1991; Amos, et al., 1991, etc.). Moreover, their association with other facies such as ripple-bedded sandstone with herringbone crossbedding, and rhythmic-bedded siltstone showing spring-neap cyclicity, is consistent with a tidal interpretation.

Ripple-Bedded Sandstone Facies (RBS)

The RBS facies consists of very fine to fine-grained, well sorted, micaceous, quartz-rich sandstone. Clay laminae can sometimes be observed separating rippled intervals 10 to 20 cm thick. The RBS facies sometimes shows herringbone crossbedding (Fig. 5.6 e). Thin (50 cm to 1 m thick), very fine to fine-grained, crossbedded sandstone units encased within the RBS facies are sometimes observed within sheet-like sandstones. The RBS facies has two common occurrences in the Mansfield Formation: 1) it occurs as 2 to 9 m thick sheet-like sandstones that can be correlated laterally more than 3000 m, and 2) it occurs as part of small (250 m diameter), pod-shaped, fining-upward channel-fill sequences. Here, the RBS facies occurs above crossbedded sandstones but beneath rooted zones (RMSS facies), wavy-bedded and flaser-bedded zones (WFBS facies) and lenticular shale (LS facies).

The RBS facies is interpreted to be the product of intertidal to subtidal sandflat deposition, and tidal-

fluvial point bar deposition. The presence of ripple-bedded sandstone with herringbone crossbedding supports a tidal origin for this facies. Differences in the geometries of this facies reflect differences in environmental settings. Sheet-like RBS units are interpreted as outer estuarine and coastal sandflat deposits, whereas discontinuous RBS units associated with crossbedded sandstones forming pod-shaped bodies, are interpreted as the product of tidal-fluvial point bar deposition.

Massive and Crossbedded Sandstone Facies (MCBS)

The MCBS facies consists of light gray to tan, very fine to fine-grained, well-sorted, micaceous, quartz-rich sand. Small to medium-scale (7 to 40 cm thick) crossbed sets (Fig. 5.6 f) dominate, and are interbedded with massive-bedded sandstone. Outcrops reveal that crossbedded units form trough crossbedding. One to 5 cm diameter claystone rip-up clasts are common at the base of crossbedded units. Basal contacts are usually erosional, whereas upper contacts are often gradational into overlying ripple-bedded or wavy-bedded sandstone. Reactivation surfaces with reverse oriented ripples and clay drapes are observed on some crossbed sets. Sandstones of the MCBS facies range from 7 cm to 13 m in thickness.

The MCBS facies formed as 3-d lunate dunes that floored

active bed-load dominated channels. The presence of crossbed sets with reactivation surfaces and clay drapes, suggests tidal influence (Boersma, 1969; Terwindt, 1988; Smith, 1988; de Boer et al., 1989, etc). Gradational upper contacts with overlying ripple-bedded sandstone containing herringbone crossbedding supports a tidal interpretation. In some instances, tidal indicators were not observed in this facies. This suggests that, in addition to tidal influences, a fluvial component may be present in these channels.

Rhythmic-Bedded Siltstone and Mudstone Facies (RBSM)

The RBSM facies consists of light to dark gray, siltstone and mudstone. Grain sizes are segregated into thin, vertically accreting couplets with well-developed spring-neap cyclicity (Fig. 5.6 h). Thicknesses range from 10 cm to 10 m. Occasionally, raindrop impressions and arthropod tracks are observed on parting planes in this facies.

The RBSM facies is interpreted as the product of intertidal mixed-flat deposition. The well-developed rhythmicity corresponding to 14 day spring-neap cycles is highly suggestive of tidal deposition (Kvale et al., 1989; Archer and Kvale; 1989; Kvale and Archer, 1990). The presence of raindrop impressions and arthropod trackways

observed in the RBSM facies, suggests an intertidal setting.

Disrupted-Bedded Sandstone and Mudstone Facies (DBSM)

Disrupted bedding is relatively uncommon. It comprises only 1.4% of the Mansfield Formation (Fig. 5.5). Types of disrupted bedding observed include contorted bedding, microfaulting, and load-casted ripples (Fig. 5.6 i). In almost all cases, the DBSM facies occurs associated with lenticular shale (LS facies) and wavy-bedded sandstone (WFBS facies). Disrupted-bedded intervals rarely exceed 2 m in thickness.

The DBSM facies is interpreted as soft-sediment gravity-flow deposition associated with the intertidal to subtidal channels. In many cases where the DBSM facies is present, it can be correlated directly into tidal-channel deposits.

"Regional" Subsurface Geology

The facies described above are associated with two distinct environmental settings within the Mansfield Formation. These include a time-transgressive, tide-dominated, estuarine valley-fill sequence, followed by a progradational, tide-influenced deltaic sequence. Separating the two, is a transgressive shale of the DGS

facies.

Figure 5.7 is a cross-section going from the Rockeye site to the demolition (DEMO) site showing both sequences (Fig. 5.8 for location). The cross-section datum is the base of the transgressive shale of the DGS. Below this datum, rocks of the Mansfield Formation comprise an estuarine-fill sequence within two incised-valleys on the Mississippian unconformity. Dominant facies of the valley-fill include dark gray shale (DGS facies), rhythmic bedded siltstones (RBSM facies), and wavy and flaser bedded sandstones (WFBS facies) as shown in Fig. 5.7. Overlying these are crossbedded sandstones (MCBS facies), ripple-bedded sandstones (RBS facies), and wavy-bedded sandstones (WFBS facies). These sandstones are the product of intertidal/subtidal sandflat and tidal channel deposition.

The valley-fill sequences are interpreted as central-basin estuarine deposits (Reinson, 1992; Dalrymple, 1992) that are overlain by outer estuarine shoal deposits. The presence of conodonts such as Adetognathus suggest brackish water to normal marine salinities during deposition of the valley-fill sediments (Carl Rexroad pers. communication, 1993). Deposition occurred in a tide-dominated estuarine setting as part of a time-transgressive depositional continuum.

Estuarine-fill sequences occupy narrow (1 to 1.5 km wide), north/south trending incised-valleys up to 30 m or

Fig. 5.7 Cross-section A-A' going from the Rockeye site to the Demolition site. Cross-section A-A' shows an estuarine-fill sequence, and a tide-influenced deltaic sequence separated by a transgressive marine shale.

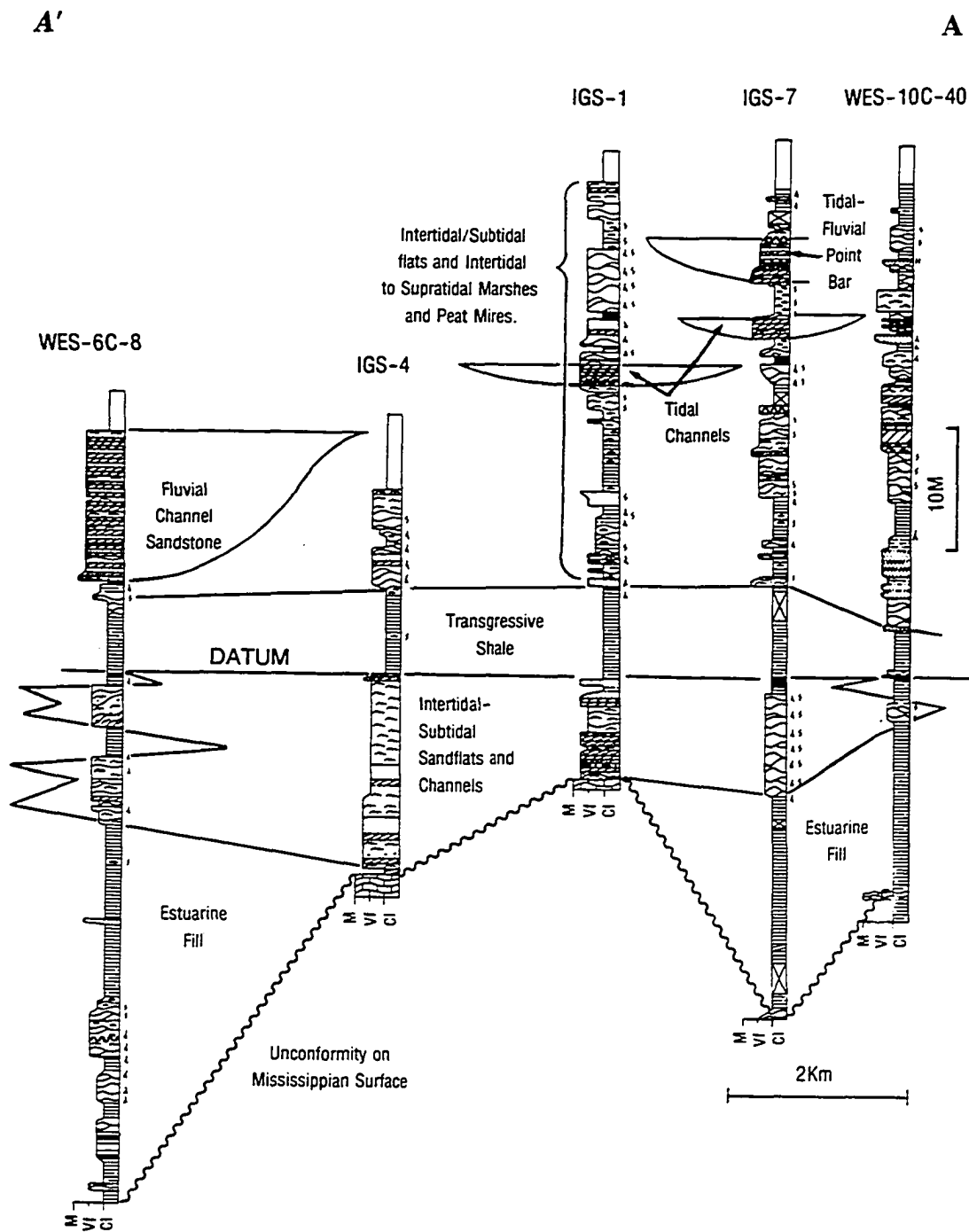
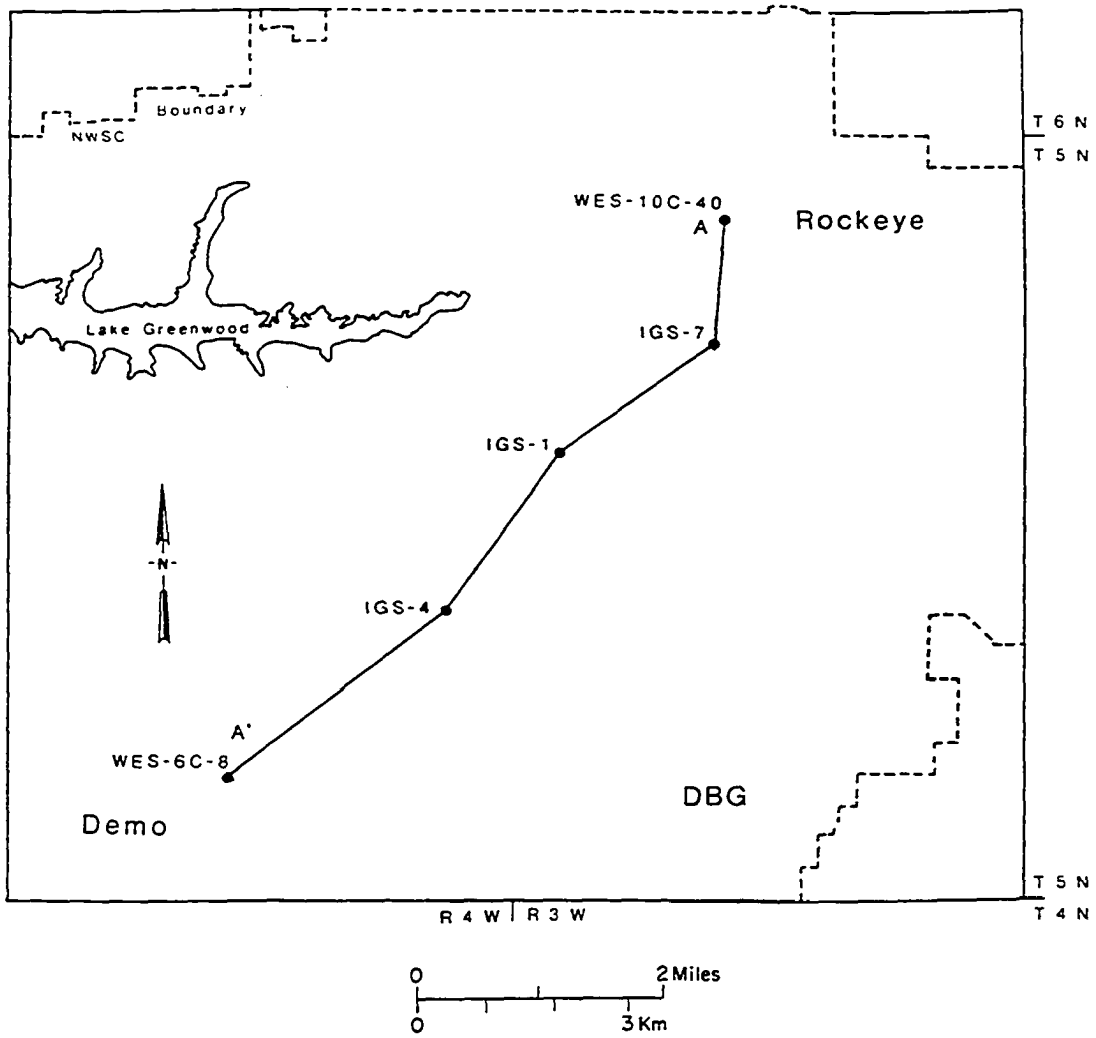


Fig. 5.8 Map showing the location of cross-section
A-A' at the NSWC.



more deep. Valleys can be traced in the subsurface for more than 7 km. Intertidal/subtidal sandflats and channels range from 1 to 15 m thick, and can be traced over a 15 sq. km area. Their geometry is sheet-like (Barnhill, 1992).

After deposition of the estuarine-fill, a relative sea-level drop is recorded. This is represented by the presence of coals and subaerial exposure surfaces at the position of the datum in Fig. 5.7. Above the datum is a transgressive shale of the DGS facies, that can be correlated over most of the NSWC (110 sq. km). Whether this shale is the result of a regional, eustatic sea-level rise or local subsidence is uncertain.

The transgressive shale is overlain by a lithologically complex progradational sequence. This progradational sequence consists predominately of intertidal/subtidal mudflats, and mixed flats (DGS, LS, and WFBS facies), and intertidal/supratidal salt marshes and peat mires (RMSS facies and coal) as shown in Fig. 5.7. In addition, tidal channels, tidal-fluvial point bars, and fluvial-channels are present (MCBS and RBS facies). The lithofacies relationships, sandstone body geometries and depositional environments of this complex sequence are revealed by the dense coring at the Rockeye site.

Subsurface Geology of the Rockeye Site

A total of 33 closely spaced coreholes were drilled at the Rockeye site. These coreholes average 30 m in depth, and penetrate most of the progradational sequence shown in Fig. 5.7. Figure 5.9 shows the corehole locations, and the position of an east-west (C-C') and north-south (G-G') cross-section through the site. Cross-section C-C' and G-G' (Figs. 5.10 and 5.11) show three channel sandstones labeled "A", "B" and "C" in ascending order.

The geometry of sandstone "A" is pod-shaped as shown in Fig. 5.12. Its pod-shaped geometry, erosional basal contacts, presence of rip-up clasts, and fining-upward textural trends shown in the columnar profiles of Figs. 5.10 and 5.11, suggest point-bar deposition within a high sinuosity channel (Walker and Cant, 1984; Busch and Link, 1985). Outcrop and core analyses reveal the presence of reverse oriented ripples and clay drapes on crossbed sets, and herringbone crossbedding within ripple bed sets suggesting that the channels were tide-influenced. Although point bars are small (.5 sq. km), individual channels can be traced in the subsurface for several kilometers (Barnhill, 1992).

Figure 5.13 is a block diagram showing a paleogeographic reconstruction of the Rockeye site during maximum lateral accretion of sandstone "A". Four environments are observed: 1) a tide-influenced point-bar dominated by massive-bedded and crossbedded sandstone

Fig. 5.9 Corehole locations, and locations of
cross-sections C-C', and G-G' at the
Rockeye site.

Rockeye Corehole Locations

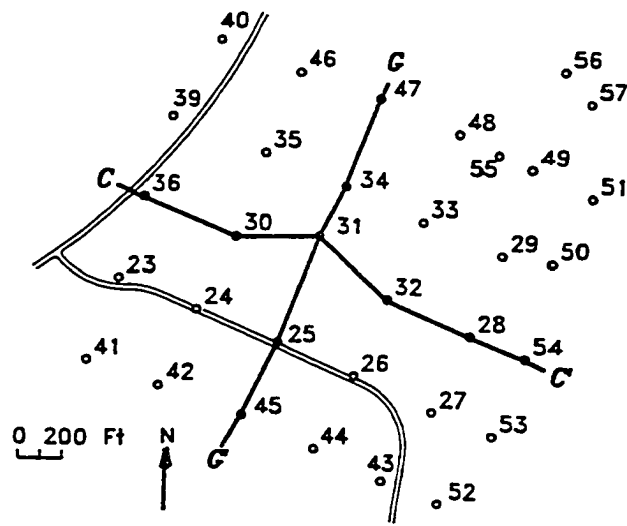


Fig. 5.10 Cross-section C-C' of the Rockeye site.
Cross-section C-C' reveals the presence of
three channel sandstones. Sandstones "A"
and "B" are tide-influenced, sandstone "C"
is a fluvial sandstone.

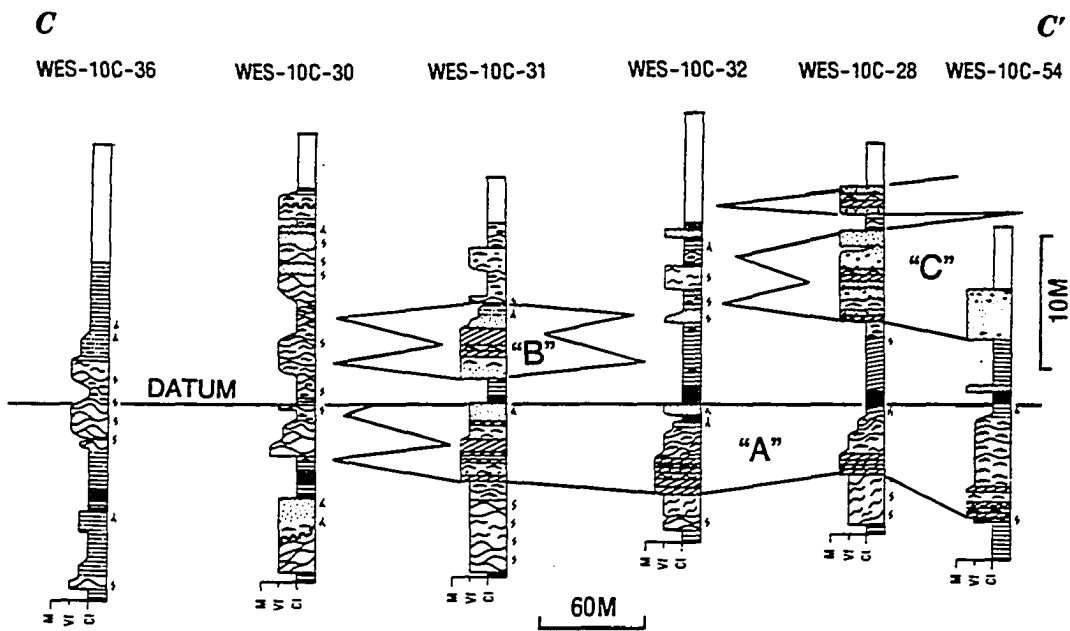


Fig. 5.11 Cross-section G-G' of the Rockeye site. Sandstone "B" grades laterally into the DGS, LS, and WFBS facies. Sandstone "A" grades laterally into coal and the RMSS facies.

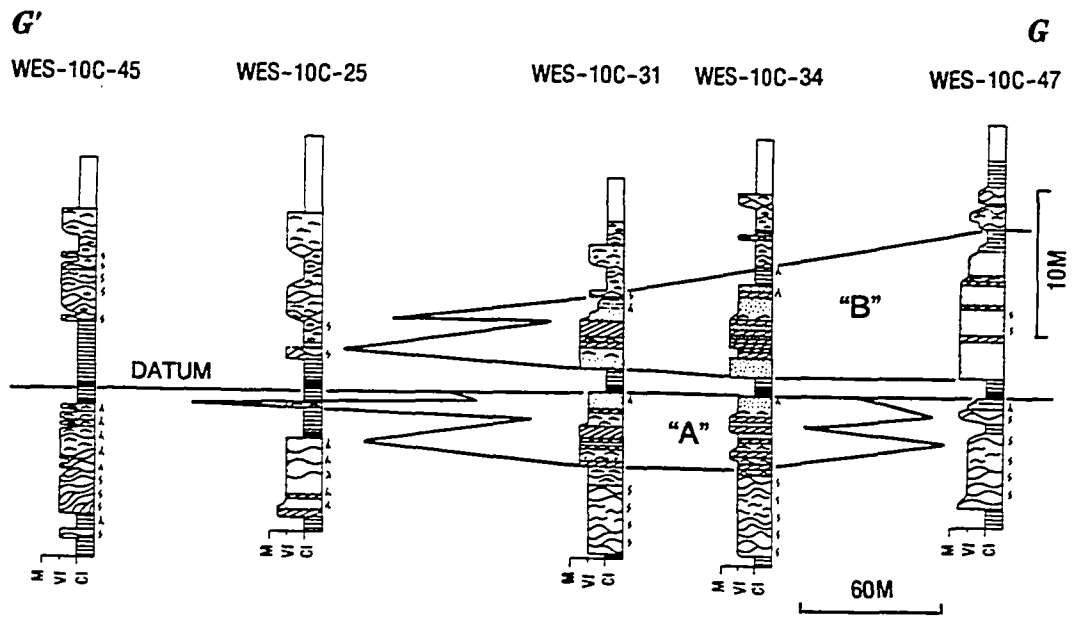


Fig. 5.12 Isopach map of sandstone "A" of the
Rockeye site. The pod-like geometry
of this sandstone is highly suggestive
of point-bar deposition.

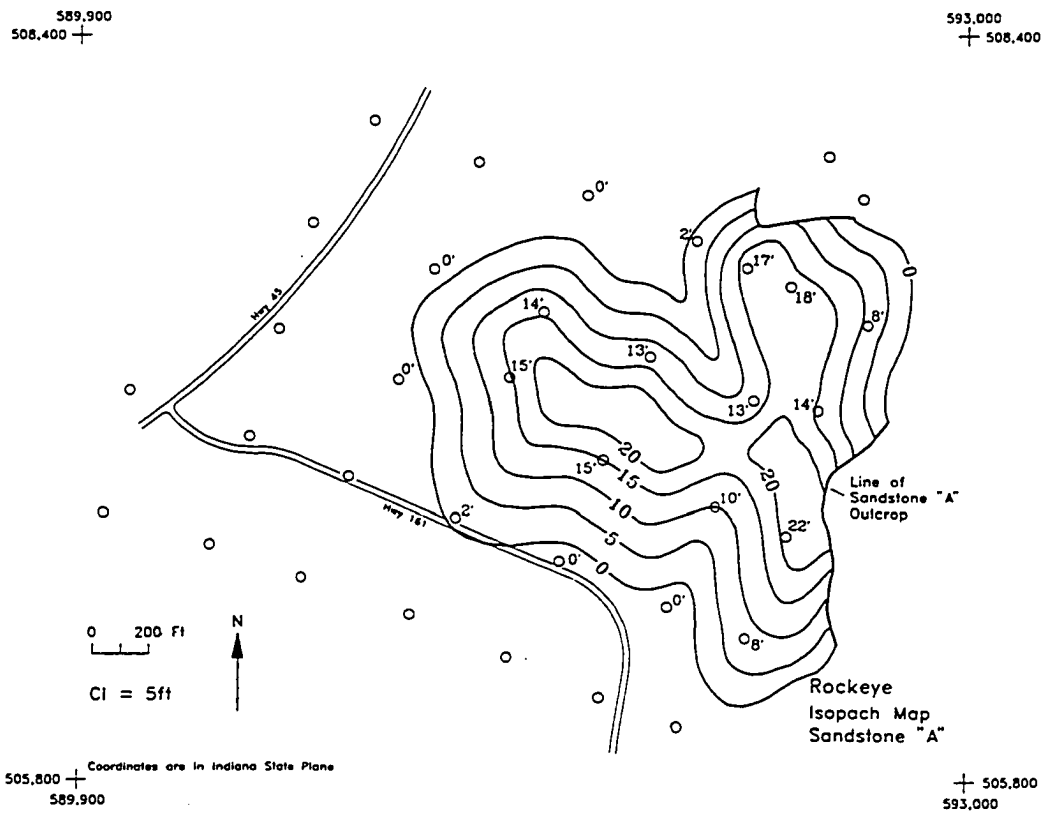
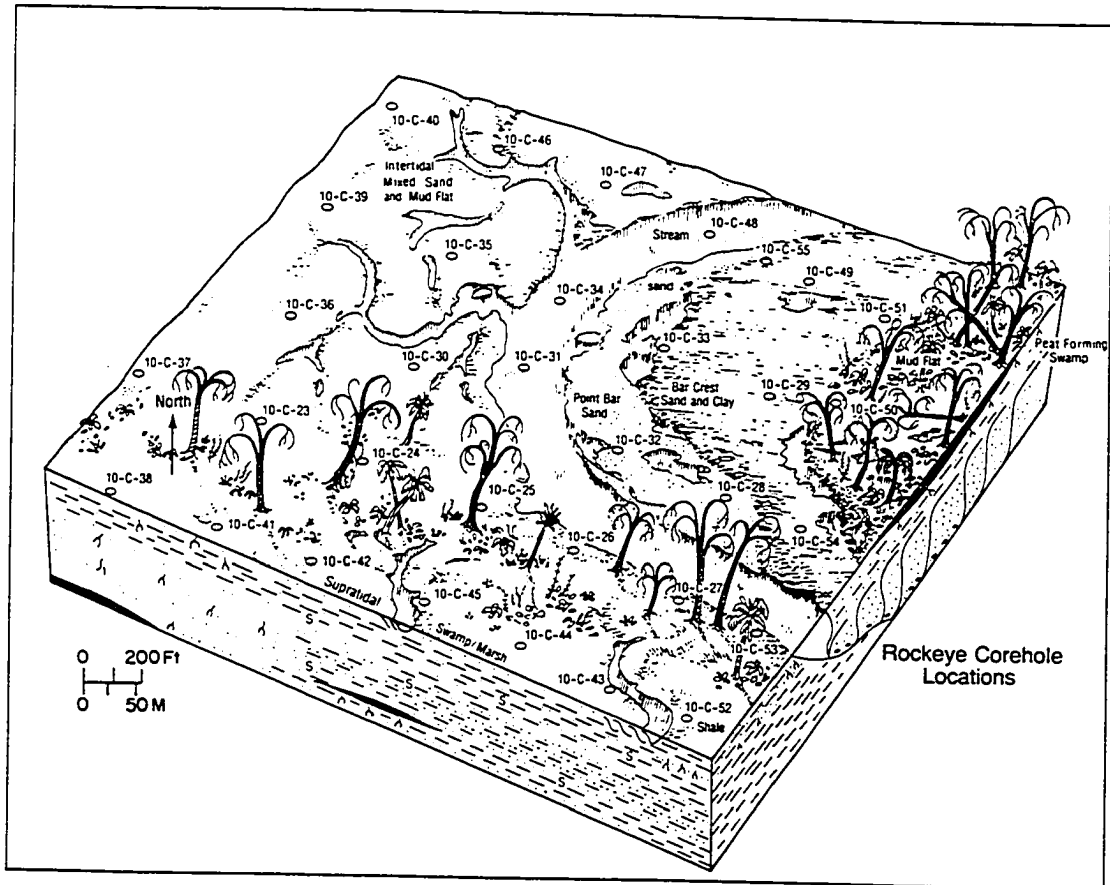


Fig. 5.13 Block diagram showing a paleogeographic reconstruction of the Rockeye site during maximum lateral accretion of sandstone "A". Diagram shows a tide-influenced point bar with intertidal mixed flats, intertidal/supratidal swamp, a sand dominated tidal-fluvial point bar, and a supratidal peat-forming mire.



(MCBS), and ripple-bedded sandstone (RBS), 2) a backswamp peat-forming mire evidenced by the coal capping the point bar, 3) intertidal/subtidal flats consisting of wavy and flaser bedding (WFBS), lenticular shale (LS, and dark gray shale (DGS), and 4) intertidal/supratidal marsh deposits represented by rooted horizons (RMSS). The complex vertical and lateral lithostratigraphy observed in the progradational sequence at the Rockeye site is the result of the rapid change, both temporally and spatially, of these four environments.

Isopach mapping of sandstone "B" shows a pod-shaped geometry identical to sandstone "A" (Barnhill, 1992). Except for the absence of coal above sandstone "B", lateral facies relationships of the channel-fill sequence are virtually the same for the two sandstones. The environments described above are best interpreted as part of a prograding, tide-influenced deltaic sequence. Today, tide-dominated deltas of rainy, tropical climates appear to be the best modern analogs. For example, environments and facies observed in the Klang/Langat Delta by Coleman et al. (1970), and the Mahakham Delta by Allen et al. (1979), are very similar to the progradational sequence described above.

Within tide-dominated deltas, extensive tidal flats and associated tidal channels of the interdistributary area and abandoned delta-plain comprise the bulk of the sediments (Coleman, 1970; Meckel, 1975; Allen, 1979; Dalrymple, 1992).

Prograding tidal flats consist of sand and clay that are often bioturbated (Coleman, 1970; Meckel, 1975). Highly sinuous tidal channels drain the tidal flats. Tidal channels may have a fluvial component and serve as small distributaries like those of the Klang/Langat (Coleman et al., 1970), or be completely tidal such as those of the Mahakham Delta (Allen et al., 1979).

In the Klang/Langat Delta, fining-upward, sandy, subtidal to intertidal flats and channel deposits are capped by rooted deposits of the intertidal Mangrove swamp. After channel abandonment, freshwater supratidal peat mires may migrate over mangrove swamp deposits. A typical, progradational sequence consists of fining-upward sandy deposits of the tidal flats and channels, followed by rooted underclays of the mangrove swamp, capped by freshwater peat deposits (Coleman et al., 1970).

The facies and vertical sequences described above are observed at the Rockeye site. Bioturbated, wavy and flaser bedding (WFBS) occurring below sandstone "A" in Figs. 5.10 and 5.11, represent prograding tidal flats. Vertical sequences consisting of bioturbated wavy and flaser-bedded sandstone (WFBS), fining-upward point bar deposits, followed by rooted horizons (RMSS) and coals (e.g., sandstone "A", Figs. 5.10 and 5.11) are very similar to those described by Coleman et al. (1970), for the Klang/Langat Delta, and Allen et al. (1979) for the Mahakham Delta.

The Mansfield Formation also contains fluvial sandstones. A fluvial sandstone occurs at the top of Corehole WES-6C-8 (Fig. 5.7), and at the Rockeye site (Fig. 5.10, sandstone "C"). Sandstones interpreted as fluvial lack tidal or other marine indicators, are less compositionally and texturally mature than tidal-channel sandstones, and show no fining-upward textural trends. Isopach mapping indicates a more linear geometry for these sandstones (Barnhill, 1992). Sandstones of the Mansfield Formation interpreted as fluvial may represent deposits of the alluvial plain that prograded across, and downcut into underlying deltaic deposits. More likely, however, is the possibility that they represent deposition in the upper reaches of fluvial-dominated distributary channels, beyond recognizable tidal influences.

In modern tide-dominated deltas, tidal sand ridges occur at the mouths of active distributaries, and seaward of the abandoned delta plain (Dalrymple, 1992). Distributaries and delta-plain tidal flats commonly prograde over tidal sand ridges. At the Rockeye site, the sandstone unit directly above the transgressive shale in corehole WES-10C-40 (Fig. 5.7) has characteristics of tidal sand ridge deposits. The unit has a scoured basal contact and coarsens upward from very fine to fine-grained sandstone. The bottom one third of the unit is dominated by wavy bedding which changes up-section into horizontal and low-angle bedding

that contain clay laminae. This sequence is very similar in textures, sedimentary structures and thicknesses, to tidal sand bars described by Meckel (1975) from the Colorado River Delta.

Tidal sand ridge deposits were observed in this one corehole only. Therefore if tidal sand ridge deposits are present, they cannot be considered abundant or even common. This may indicate a lack of significant sand sized material available for tidal sand ridge development, or it may suggest that the area studied lacked significant enough tidal currents to support tidal sand ridge development. This would most likely occur if the tidal range were microtidal to mesotidal (Dalrymple, 1992).

The presence of fluvial sandstones, and the lack of significant tidal sand ridge development suggests that the deltaic sequence, although strongly tide-influenced, was probably not tide-dominated.

Until recently, significant tidal deposits were thought by some to be incompatible with sedimentation in ancient epeiric seas. The significance of this research is that it provides further evidence of tide-influenced deposits in Pennsylvanian age rocks of the Illinois Basin, a true cratonic basin. More importantly, it provides details of the facies, geometries, vertical sequences and paleogeographic settings of specific tide-influenced environments within a cratonic basin setting. This is

significant not just for the Illinois Basin, but other basins as well. Very few tide-influenced deltaic sequences have been recognized in the rock record. The recent recognition of tide-influenced deposits in the Illinois Basin suggest that these deposits may be much more common in cratonic basins than previously thought.

In the Illinois Basin, for many decades, the presence of abundant plant material, the lack of marine body fossils, the paucity of trace fossils, and the presence of abundant rooted horizons and coals in lower Pennsylvanian rocks was considered evidence of their non-marine origin. Recent work, including that presented here, provides evidence that the traditional non-marine indicators mentioned above can be found in tide-influenced marginal marine environments.

COMPARISON OF THE CORBIN SANDSTONE MEMBER OF EASTERN
TO THE MANSFIELD FORMATION OF INDIANA

Comparison of Depositional Facies

The depositional facies of the Corbin Sandstone Member and Mansfield Formation are strongly contrasting. Figures 3.1 and 5.5 show the facies abundances for the Corbin Sandstone Member and Mansfield Formations respectively. The bar graphs reveal two significant differences: 1) the Corbin Sandstone Member (and the Lee Formation in general) is dominated by sandstone, whereas the Mansfield Formation is dominated by shale, and, 2) the Corbin Sandstone consists primarily of fluvial facies consisting of trough and planar crossbedding, whereas the Mansfield Formation consists primarily of marginal marine facies of tidal origin dominated by structureless shale, wavy-bedded sandstone, lenticular-bedded shale, and rooted intervals.

The facies distribution shown in Figs. 3.1 and 5.5, and discussed in chapters three, four, and five suggests that marine (tidal) processes were dominant in the eastern part of the Illinois Basin whereas nonmarine (fluvial) processes were dominant in the central Appalachian Basin during Morrowan/Atokan time. However, it is unreasonable to draw such a conclusion solely on the basis of the data provided in this study. The Morrowan/Atokan section is thick and persistent over large areas of both basins and a more

comprehensive study, beyond the scope of the present one, would be needed to draw such a conclusion. It is, however, generally supported by the data presented here in combination with a review of the recent literature.

In the central Appalachian Basin, the Morrowan/Atokan section is dominated by the Lee and Breathitt Formations in eastern Kentucky and their equivalent units in other parts of the basin (table 1). Although the depositional environment of the Lee Formation is controversial, recent work, including that presented here, has supported a predominantly fluvial origin (Rice, 1985; Rice, 1988; Chesnut, 1988; Wizevich, 1992). The Breathitt Formation has been interpreted as fluvio-deltaic by numerous researchers (Englund and Thomas 1990; Donaldson et al., 1985; Horne et al., 1978; Flores, 1978; Gardner, 1977, etc.).

Generally speaking, then, the overall data suggests that the Morrowan/Atokan section in the central Appalachian Basin is dominated by fluvial and fluvio-deltaic deposits. Tidal deposits are present in the Lee Formation, as shown in this study, as well as the Breathitt Formation, as demonstrated by Greb and Chesnut (1992) and Martino and Sanderson (1993). However, the abundance and significance of tidal deposits in Pennsylvanian rocks of the central Appalachian Basin is still poorly understood.

For many decades, since the time of Weller (1930), rocks of the Mansfield Formation of southwestern Indiana

were considered nonmarine. However, recent work by Kvale et al., (1989), Archer and Kvale (1989), Barnhill, (1992), and Kvale and Barnhill (in press) suggests that the bulk of the Mansfield Formation is marine in origin, and comprised of tidal deposits. Braided fluvial deposits are also observed in the Mansfield Formation, but these appear to be largely confined to major, southwest-trending incised valleys that served to transport sediment to the Illinois Basin from source areas to the northeast (Fishbaugh et al., 1989).

A review of the literature suggests, then, that the facies distributions shown in Figs. 3.1 and 5.5 are generally representative of the Lee and the Mansfield Formations. The Corbin Sandstone Member, and probably the Lee Formation in general, is dominated by braided fluvial facies with a minor tidal component; conversely, the Mansfield Formation is dominated by tidal facies with a minor braided fluvial component. What is absent from both units is a significant wave or storm generated component. Wave-generated structures are present, but not abundant, in the Corbin Sandstone Member and the Mansfield Formation.

Wave-generated features observed in both units consist solely of oscillation ripples associated with tidal facies. Larger scale wave-generated features such as shoreface, foreshore, and backshore deposits, and storm generated features such as hummocky cross-stratification and washover deposits were not observed in either the Corbin Sandstone or

the Mansfield Formation.

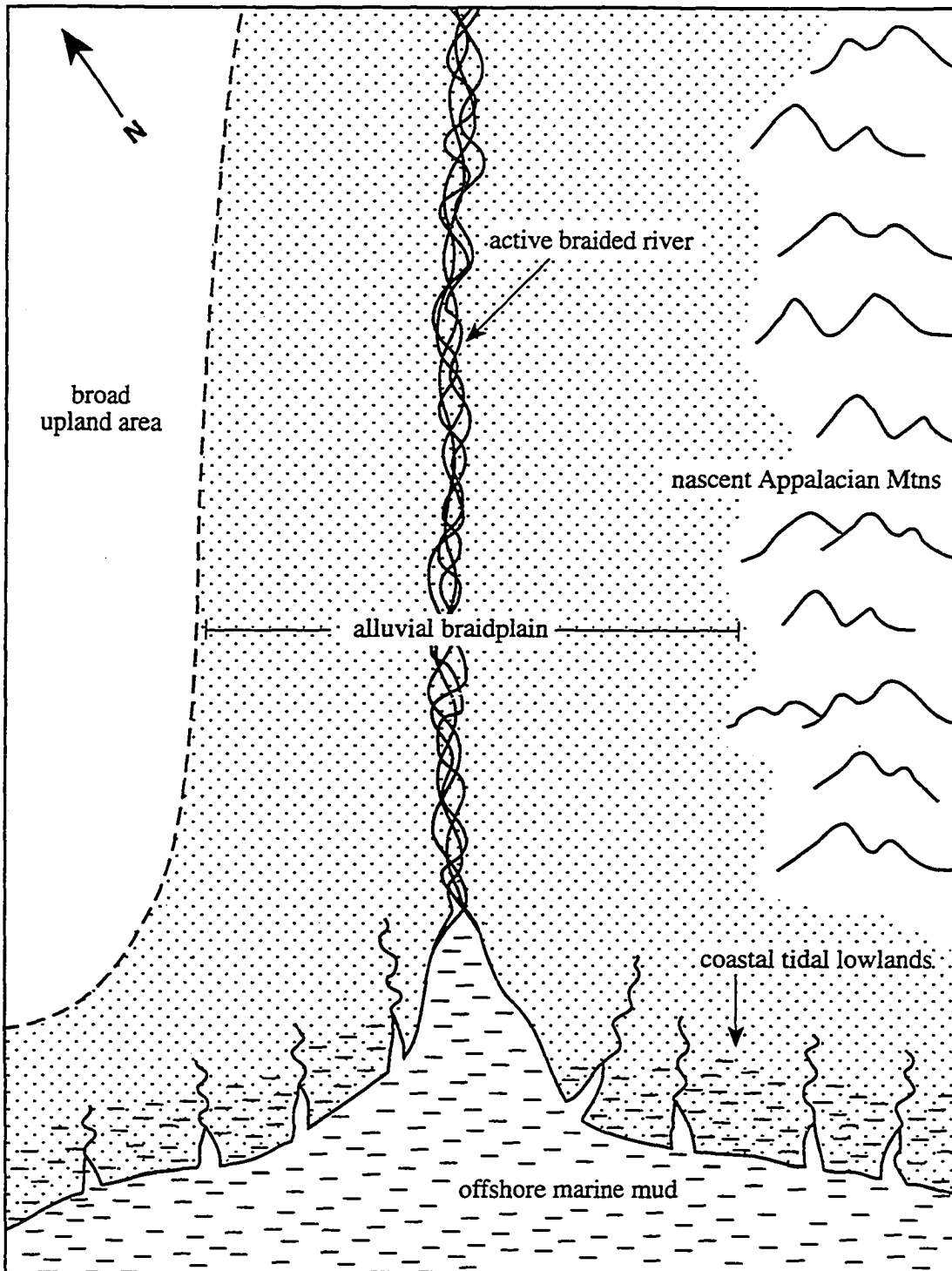
The absence of significant wave generated features suggests that the marine components of the Corbin Sandstone and Mansfield Formation were deposited in protected or embayed areas where wave activity was weak, or along tide-dominated coastlines. Generally speaking, where tidal ranges are high, wave formed features such as coastal barriers are less likely to form (Hays, 1975; 1979).

The general paucity of storm deposits in both units may be a function of paleolatitude. The central Appalachian Basin and the Illinois Basin were near an equatorial position during Morrowan/Atokan time. If these basins were located within the zone of intertropical convergence during deposition of the Mansfield Formation and the marine portion of the Corbin Sandstone Member, an absence of storm generated deposits would be expected.

Depositional Models of the Corbin Sandstone Member and the Mansfield Formation

The spatial and temporal distribution of facies present within the Corbin Sandstone Member can be explained by the model shown in Fig. 6.1. Located between the nascent Appalachian Mountains to the east and southeast, and the broad upland area of the Cincinnati Arch to the west and northwest, was an alluvial braidplain that existed during late Morrowan time. In places this braidplain was more than

Fig. 6.1 Depositional model for the Corbin Sandstone Member of eastern Kentucky. The model shows a broad braidplain unconfined by valley walls. To the south, the braided-fluvial environment changes to an estuarine environment with coastal tidal flats and offshore marine muds.



80km wide and contained a large, southwest-flowing, braided river that occupied a relatively small portion of the braidplain at any one time. This braided river moved laterally across the alluvial braidplain depositing a multistoried sheet sandstone, consisting primarily of superimposed channels and transverse bars, up to 300 feet thick.

At the southern margin of the braidplain was a tide-dominated coastal lowland area. The overall environment here may be considered estuarine in the broad context of Pritchard (1967), i.e. an area within which seawater is mixing with fresh water derived from land drainage. It should not be considered deltaic, however. The Corbin Sandstone is not progradational, and no evidence of prodelta, delta front, distributary channels, or interdistributary environments was observed.

The coastal tidal lowland area consisted of subtidal to intertidal sandflats and mixed flats that formed in an open coast or embayed environment. The lack of any significant wave generated features such as shoreface, foreshore and backshore deposits, combined with the absence of storm washover deposits, suggests the absence of a barred coastline. Offshore from the coastal lowland area, outer estuarine muds were deposited. These muds formed the Betsie Shale Member of the Breathitt Formation, which overlies the Corbin Sandstone.

When viewed in vertical succession, the lateral facies shown on the model in Fig. 6.1 represent a time regressive depositional continuum. The succession of facies observed in the Corbin Sandstone Member occurred because of a transgressive event resulting in landward migration of coastal tidal flats over braided fluvial deposits. The succession was capped by offshore muds represented by the Betsie Shale Member of the Breathitt Formation.

The spacial and temporal distribution of facies within the Corbin Sandstone Member can be explained with one depositional model invoking a single transgressive event. However, the distribution of facies within the Mansfield Formation suggests deposition in a much more complex setting involving multiple transgressive and regressive events.

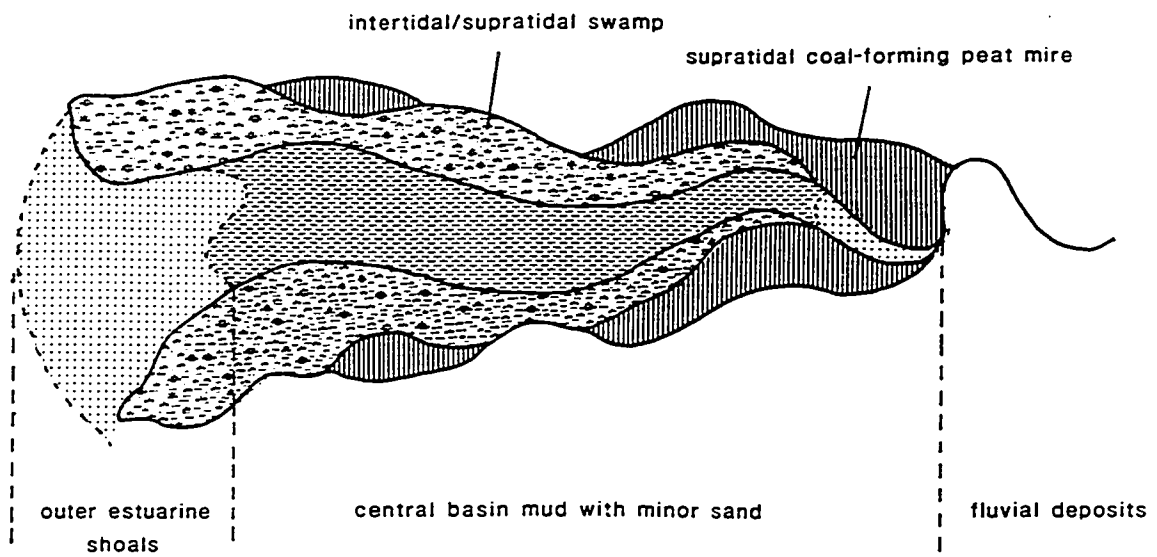
According to Dalrymple et al. (1992), an estuary can be defined as "the seaward portion of a drowned valley which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave, and fluvial processes" (p 1). This more narrow definition of estuary than that proposed by Pritchard (1967) is applicable to the lower Mansfield Formation within the study area. The lower part of the Mansfield Formation within the study area fills incised valleys carved into the underlying Mississippian rocks, and contains rocks with evidence of fluvial, tide and wave influence (Barnhill, 1992; Kvale and Barnhill, in press).

Figure 6.2 is a depositional model proposed for the estuarine fill phase of Mansfield Formation sedimentation. The model reflects the distribution of facies observed in the core and shows a rough tripartite zonation consisting of fluvial channel deposits, central basin muds with minor sand, and outer estuarine sand shoals. Marginal to the central basin muds and outer estuarine shoals are deposits of the intertidal/supratidal swamp and supratidal coal forming peat mires. Because the down-channel and cross-channel distribution of facies shown in the model is reflected in the vertical fill succession, a discussion of the depositional model necessarily involves a discussion of the estuarine fill deposits (see Fig. 5.7).

The estuarine-fill succession records a relative sea level rise drowning the incised valleys. This was followed by a relative sea-level drop indicated by the development of coal and subaerial exposure surfaces just below the transgressive shale (see datum on Fig. 5.7). The fill succession begins with a thin fluvial channel sandstone located at the bottom of the eastern paleovalley. (It is not shown in Fig. 5.7 but was observed in a deeper corehole located north of corehole IGS-7). No fluvial component was observed in the western paleovalley, probably because of a lack of corehole control in the deepest part of the paleovalley rather than an absence of the fluvial facies.

Above the fluvial facies are shales and sandstones of

Fig. 6.2 Depositional model for the estuarine-fill portion of Mansfield Formation deposition at the NSWC, Crane, Indiana. The model shows the distribution of facies within a tide-dominated estuarine setting.

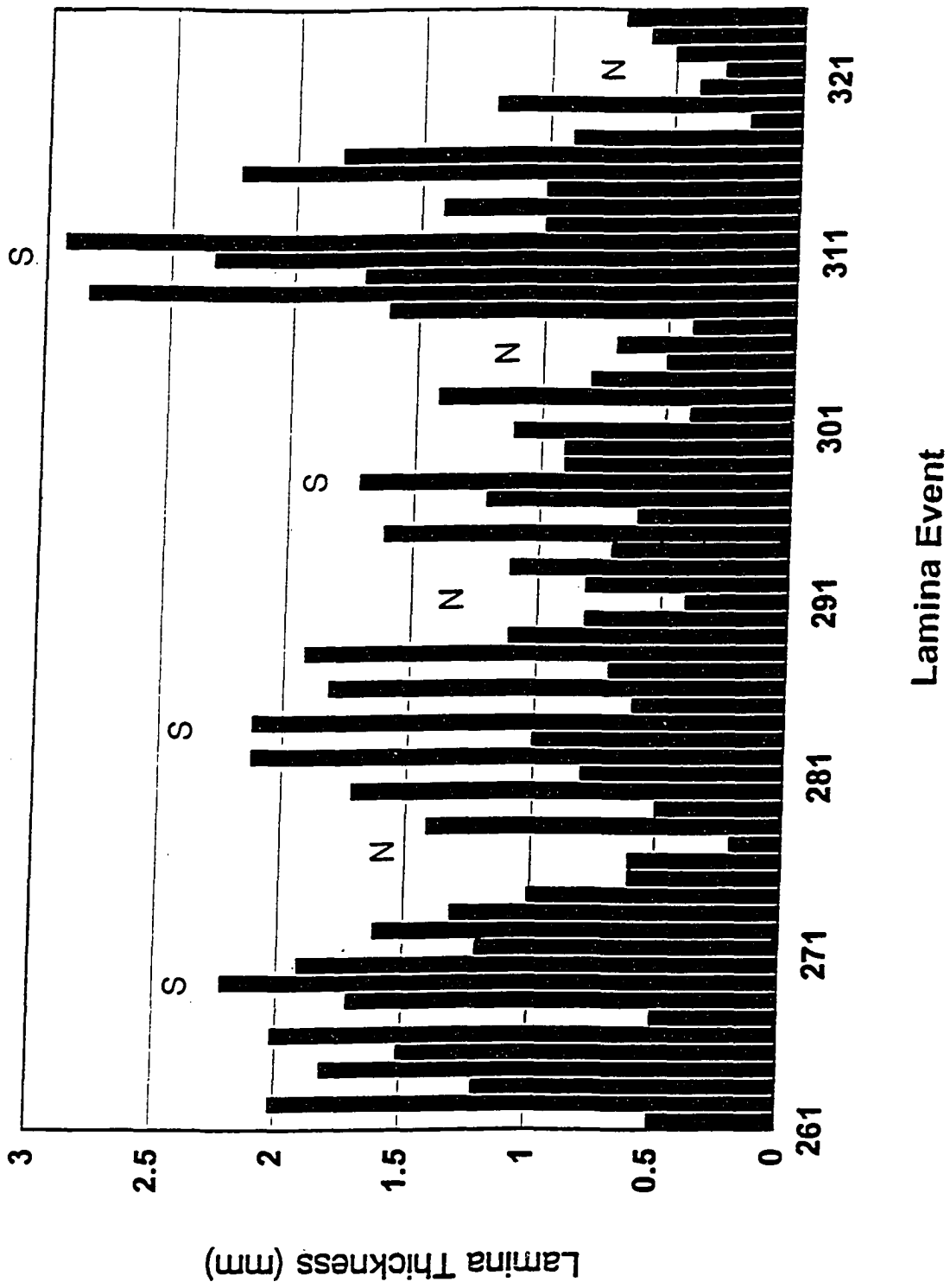


the central basin deposits (corresponding to the estuarine-fill interval of Fig. 5.7). These are predominantly tidal in origin as indicated by the presence of wavy-bedded sandstone, lenticular-bedded shale, and rhythmic-bedded mudstone showing well developed neap-spring-neap cyclicity (Fig. 5.6 h). Figure 6.3 shows lamina number versus lamina thickness for a rhythmic-bedded interval from the central basin deposits. The figure shows the well-developed neap-spring-neap cyclicity as well as alternating thick/thin couplets representing either dominant/subordinant events, or ebb/flood events. In addition, some sandstones within the central basin deposits show evidence of rooting, suggesting lateral migration of the fringing intertidal/supratidal swamp environment during deposition of the central basin deposits. This would most likely occur during periods of relative sea level lowstands.

The estuarine-fill depositional period ended with the landward migration of the outer estuarine shoal complex (Fig. 5.7) over the central basin deposits. The outer estuarine shoal complex consists of subtidal/intertidal sandflats and channels dominated by the massive and crossbedded sandstone facies and the ripple-bedded sandstone facies. The marine origin of these sandstones is indicated by the marine trace fossil assemblage and the sedimentary structures. Trace fossils include Conosticus, Teichichnus, and Rhizocorallium. The tidal origin of this facies is

Fig. 6.3

Bar graph showing lamina number versus lamina thickness for a rhythmic-bedded interval (see Fig 5.6h for example) in the western valley-fill succession at the NSWC, Crane. The bar graph shows systematic thickening and thinning of lamina corresponding to spring-neap (S-N) cycles, and alternating thick/thin couplets corresponding to ebb-flood or dominant-subordinant events (Kvale and Barnhill, in press)



indicated by ripples which show herringbone crossbedding (Fig. 5.6e). In addition, some crossbed sets show reactivation surfaces with clay drapes, suggesting large-scale tidal bundle development (Boersma, 1969; Terwindt, 1971; de Boer et al., 1989, etc.).

The landward migration of the outer estuarine shoal complex occurred after the incised valleys were almost completely filled with central basin muds (see Fig. 5.7). Furthermore, the shoal complex, centered over the interfluvial high that separated the eastern and western Paleovalleys, migrated both landward and laterally.

The landward migration of the outer estuarine shoal complex over the estuarine fill deposits marked the maximum relative sea-level position during the valley fill phase. A relative sea level drop after deposition of the estuarine shoal complex is indicated by the presence of erosional and oxidized surfaces on top of the shoal sandstone, (position of datum in coreholes IGS-1, and IGS-4 in Fig. 5.7), and the presence of coals at the same stratigraphic position in coreholes IGS-7, WES-10C-40, and WES-6C-8.

The valley-fill succession is overlain by a transgressive marine shale of the dark gray shale facies that was located seaward of the outer estuarine shoal complex. The shale is widespread over a large part of the NSWC, Crane, and represents the most offshore marine facies observed in the Mansfield Formation within the study area.

Samples of this shale were processed for microfossils and contained conodonts and foraminifera which suggest fully marine salinities (Carl Rexroad, pers. communication, 1993).

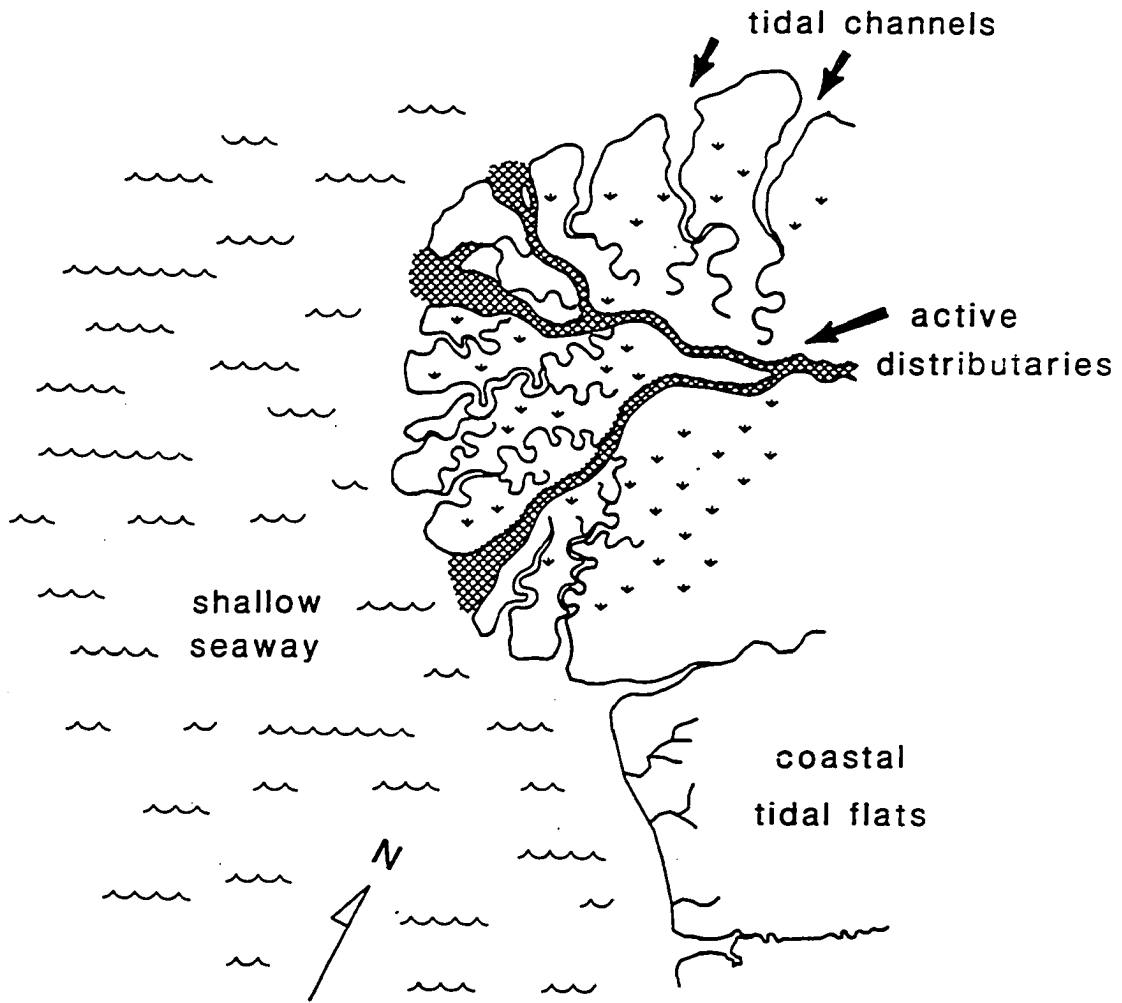
The transgressive marine shale is overlain by an extremely complex, progradational, lithofacies assemblage of the tide-influenced deltaic deposits (discussed in chapter 5). Figure 6.4 is a depositional model of the tide-influenced delta. The model shows the two major types of channels observed in the core. The first type are the highly sinuous channels forming tidal point bars documented at the Rockeye site (see Fig. 5.13). These formed in the interdistributary areas where tidal energy dominated. For example, the small tidal point bar shown in Fig. 5.13 represents a single point bar that would have formed in the sinuous upper parts of a tidal channel located in the interdistributary area shown on the model in Fig. 6.4.

The second type of channels are the large distributary channels which are typically relatively straight and dominated by fluvial processes (Fig. 6.4). The thick sandstone located at the top of corehole WES-6C-8 in Fig. 5.7 is interpreted as a fluvial dominated, distributary channel-fill sandstone (as discussed in chapter 5).

Associated with the tidal channels, and located between the distributary channels, are other facies shown in the cross-section in Fig. 5.7. These include the subtidal to intertidal flats dominated by lenticular, wavy, and flaser

Fig. 6.4

Depositional model for the tide-influenced deltaic phase of Mansfield Formation deposition at the NSWC, Crane. The model shows sinuous tidal channels in the interdistributary area, as well as fluvial-dominated active distributary channels. Coal-forming peat swamps occur in the interdistributary area. Open coasts tidal flats are shown marginal to the delta although these were not observed in the Mansfield Formation.



bedding, and the rooted underclays of the intertidal to supratidal environment. Peat accumulating in the supratidal environment associated with the tidal point bars would also have formed in the interdistributary area.

Freshwater peat-swamps forming in association with tidal point bars in the interdistributary area of a tide-influenced delta seems counter-intuitive. However, Staub and Esterle (1993), have documented the presence of abundant, thick (1 m or more) peat accumulations in interdistributary environments in the tide-dominated Rajang River Delta, Sarawak, East Malaysia. Here, tidal range is 2 to 6 meters and tidal influence is observed 120 kilometers inland. However, elevated, low-ash, peat-forming swamps are located in coastal interdistributary areas directly adjacent to the South China Sea.

The models presented and discussed in this section point to significant differences between the Corbin Sandstone Member of eastern Kentucky and the Mansfield Formation of the Illinois Basin. The Corbin Sandstone is, primarily, an extensive, sand-dominated, sheet-like, braided-fluvial deposit which displays a relatively simple spacial and temporal stratigraphic relationship with finer-grained deposits of the intertonguing Breathitt Formation. Conversely, the Mansfield Formation is, primarily, a shale-dominated unit containing numerous, discontinuous, marginal marine environments with complex geometries showing extreme

lithostratigraphic variability over very short lateral and vertical distances. In spite of these significant differences, however, there are similarities between the Mansfield Formation and the Corbin Sandstone Member, particularly if the Mansfield Formation is compared to the Corbin Sandstone Member and associated rocks of the intertonguing Breathitt Formation.

Braided River Deposits of the Mansfield Formation, and the Role of Tides in the Illinois and Central Appalachian Basins

The Mansfield Formation outside the study area is not composed exclusively of tide-dominated estuarine and deltaic deposits. Incised valleys carved into the Mississippian unconformity, both north and south of the study area, contain fill successions interpreted as braided river deposits (Fishbaugh et al., 1989; Kvale and Eggert, 1988; Kvale, pers. communication, 1993.). According to Fishbaugh et al., (1989), these sandstones are fine to medium grained, moderately well sorted, and composed primarily of trough and planar crossbedding. In addition, they have erosional basal contacts and contain rounded quartzite clasts. Paleocurrent directions are predominantly unimodal to the west-southwest, and thicknesses range up to 60 feet or more.

The braided fluvial sandstones described above bear a strong resemblance to the Corbin Sandstone specifically, and the Lee Formation in general, regarding both textures and

sedimentary structures. They differ from the Corbin Sandstone in that they were deposited in relatively narrow incised valleys, rather than across a broad braidplain.

It is entirely possible that the braided fluvial deposits of the Mansfield Formation share a common provenance with the Lee Formation. The most likely ultimate source area would have been to the northeast, the present day Canadian Shield area. That Lower Pennsylvanian fluvial deposits of the Illinois and central Appalachian Basins share a common provenance has been previously proposed (Chesnut, 1988; Pryor and Potter, 1979; Pryor and Potter, 1974; Potter and Siever, 1956).

The similarity of textures and sedimentary structures within fluvial deposits of the Mansfield and Lee Formation, combined with the presence of rounded quartzite clasts and southwest directed paleocurrent directions within both units, support the interpretation that basal Pennsylvanian fluvial sandstones of the Illinois Basin in general, and those of the Mansfield Formation specifically, share a common provenance with fluvial sandstones of the Lee Formation of the central Appalachian Basin. The presence of thick, braided fluvial deposits of the same age in both the Illinois and central Appalachian Basins is significant because it suggests that these basins were linked, and that the depositional processes operating at that time were wide ranging.

One of the most significant findings in the Illinois Basin in recent years has been the discovery of tidal rhythmites in the fine grained rocks of the Mansfield and overlying Brazil Formations in Indiana (Kvale et al., 1989; Archer and Kvale, 1989; Kvale and Archer, 1990). These deposits record daily, monthly, seasonal, and yearly cycles within laminated mudstones and siltstones and are commonly associated with coals. Significant also is the fact that these deposits appear to be common. The result of this discovery has been a reevaluation of environmental interpretations for lower Pennsylvanian rocks in the Illinois Basin. The presence of tidal deposits within fine grained rocks in the lower Pennsylvanian in Indiana suggests that marine influence, particularly tidal influence, is more important in these deposits than previously thought.

If fine grained lower Pennsylvanian rocks of the Mansfield Formation in the Illinois Basin, previously considered predominantly fluvio-deltaic, show strong evidence of tidal influence, could the fine grained lower Pennsylvanian rocks of the central Appalachian Basin, previously considered predominantly fluvio-deltaic also show significant evidence of tidal influence too? The answer appears to be yes.

Two recent studies suggest that marine (tidal) influence in the lower Pennsylvanian rocks of the central Appalachian Basin has been underestimated. Greb and Chesnut

(1992), examined 18 fine-grained, shallow, channel-fill sequences within the Breathitt Formation of eastern Kentucky. These channel-fill sequences contain marine to brackish water trace and body fossils, suggesting deposition in a marine coastal environment, rather than fresh water floodplain deposition. Furthermore, heterolithic strata in some channels show vertically accreting, rhythmic bedding showing evidence of neap-spring-neap cyclicity. Flaser, wavy and lenticular bedding were also observed, and paleocurrent measurements indicate a bimodal pattern.

Additional evidence for tidal influence is provided by Martino and Sanderson (1993), who examined a 15 to 23 meter thick unit of the Breathitt Formation in northeastern Kentucky. This unit consists of heterolithic strata containing wavy and flaser bedding, but dominated by vertically accreting small-scale tidal rhythmites. Fourier and autocorrelation analyses reveal four cycles of thickness variation. These cycles correspond to daily (ebb-flood or dominant-subordinant), bimonthly (neap-spring), monthly (elliptical), and seasonal (solstitial and equinoctial) events. Furthermore, a diverse marine trace fossil assemblage is observed, as well as bimodal paleocurrent patterns.

The two recent studies discussed above, combined with the presence of tidal deposits in the Lee Formation documented in this study, suggest that tidal processes may

have been more common during early and middle Pennsylvanian sedimentation in the central Appalachian Basin than previously thought. Additional work is needed to determine how abundant and widespread these deposits are.

In summary, the two units examined for this study appear highly contrasting. The Corbin Sandstone is predominantly a widespread, multistory, medium grained sandstone dominated by trough and planar crossbedding deposited across a broad braidplain. The Mansfield Formation at the NSWC, Crane, Indiana consists primarily of fine grained deposits dominated by dark gray shale, wavy bedding, lenticular bedding and rooted intervals deposited in an estuarine and tide influenced deltaic setting. However, when the Mansfield Formation as a whole is compared with the Lee and Breathitt Formations collectively, important similarities emerge. The braided fluvial deposits of the Mansfield Formation are very similar to the Lee Formation. In addition to braided river deposits, both the Mansfield Formation, and Lee and Breathitt Formations contain tidal deposits. Tidal deposits in the Mansfield Formation appear to be abundant (Barnhill, 1992; Kvale and Barnhill, in press; Kvale et al., 1989; Fishbaugh et al. 1989), whereas the abundance of tidal deposits within the Breathitt Formation and other members of the Lee Formation is still largely unknown.

CONCLUSIONS

Outcrop examination and subsurface mapping of the Corbin Sandstone Member of the central Appalachian Basin, eastern Kentucky, and core analysis and subsurface mapping of the Mansfield Formation of the Illinois Basin, southwestern Indiana, has led to the following conclusions regarding these two early to middle Pennsylvanian age units. These conclusions are divided into four parts: 1) the sedimentology of the Corbin Sandstone, 2) tectonic controls on sedimentation of the Corbin Sandstone, 3) sedimentology of the Mansfield Formation, and 4) the comparison of the Lee Formation of the central Appalachian Basin to the Mansfield Formation of the eastern Illinois Basin.

Conclusions Regarding the Depositional Environment Corbin Sandstone Member of the Lee Formation

1. The Corbin Sandstone Member of the Lee Formation is, predominantly, a multistory, braided-fluvial sheet sandstone dominated by planar and trough crossbedding that ranges from 0 to 300 feet in thickness.
2. The abundant planar crossbedding in the Corbin Sandstone is the product of transverse bar deposition within a braided fluvial setting. Planar crossbedding may represent deposition by cross-channel bars, mid-

channel bars, or alternate bank-attached bars.

3. A fourfold hierarchy of channels is recognized in the Corbin Sandstone Member. This hierarchy consists of:
 - 1) a first order channel consisting of the broad (60km wide) alluvial braidplain across which the sandstone was deposited;
 - 2) second order braid channels active during low-flow;
 - 3) third order braid channels inactive during low-flow that were straight or meandering, mud or sand filled, which scoured the flanks of transverse bars, and;
 - 4) fourth order braid channels which scoured the tops of transverse bars during waning-flow. The existence of a hierarchy of channels provides powerful supporting evidence for the braided fluvial origin of the Corbin Sandstone Member.

4. The Corbin Sandstone Member contains a marine (tidal) component which appears to be confined to the upper portion of the unit, but that is not present in all outcrops. This tidal component consists of sandflats and mixed flats containing flaser bedding, wavy bedding, lenticular bedding, large scale tidal bundles, vertically accreting small-scale sandy tidal rhythmites, and ripple bedding that shows a trimodal paleocurrent pattern.

5. Trace fossils are rare in the Corbin Sandstone, and were observed in the tidal facies only. The trace fossil assemblage appears to be monospecific; Cochlichnus is the only identifiable trace fossil observed.

6. Southwest-directed paleocurrent patterns indicate a northeastern source area for the Corbin Sandstone. This is supported by quartz pebble size measurements which show a decrease in size from northeast to southwest along the outcrop belt.

7. A unimodal paleocurrent pattern for those facies interpreted as braided-fluvial provides additional support for the predominantly fluvial origin of the Corbin Sandstone Member.

8. Coal palynology indicates a wet climate during Corbin Sandstone Deposition, and suggests that the Corbin Sandstone is early middle Morrowan in age (early Westphalian B).

9. Examination of more than 500 gamma-ray well-logs through the Corbin Sandstone Member suggests that gamma-ray well-log curves are either bell-shaped or blocky. Comparison of gamma-ray well-logs with

outcrops suggests that upward-fining profiles usually represent single or multistory channel deposition. Blocky profiles are interpreted to represent superimposed transverse bars, or superimposed transverse bars with associated third order and fourth order channels. The tidal facies of the Corbin Sandstone is identifiable on gamma-ray well-logs if the interbedded sandstone and shale facies (interbedded sandflats and mixed-flats) is preserved in the succession. This facies can be recognized on gamma-ray well-logs by its "spiky" character.

Conclusions Concerning Tectonic Controls on the Sedimentology of the Corbin Sandstone Member of the Lee Formation

10. Subsurface mapping indicates that intrabasinal tectonic elements exerted a powerful influence on the Corbin Sandstone Member. Uplifts and faults controlled the sediment thickness distribution patterns, sediment dispersal trends, and paleocurrent directions within the Corbin Sandstone Member. This occurred primarily by capturing and diverting the flow of southwest directed channels, to the west, along the axes of major lineaments such as the Kentucky River and Irvine-Paint Creek Faults. The existence of modern analogs for

structural elements controlling flow directions in active rivers (such as the Kentucky River Fault controlling the flow of the modern day Kentucky River) provides powerful support for the predominantly fluvial origin of the Corbin Sandstone Member.

11. Subsurface stratigraphic correlation shows extreme thickening in the Pennsylvanian section just south of the Irvine-Paint Creek Fault. This suggests that the Irvine-Paint Creek Fault was active during early Pennsylvanian sedimentation, and acted as a hinge-line separating an actively subsiding basin to the south, from a stable platform to the north.

Conclusions Concerning the Depositional Environment of the Mansfield Formation

12. The Mansfield Formation is, predominantly, a tidally influenced fine-grained unit dominated by dark gray shale, lenticular shale, wavy bedded sandstone, ripple bedded sandstone, and rooted intervals.
13. Rocks of the Mansfield Formation rest directly on Mississippian age rocks where they fill paleovalleys up to 100 feet or more deep, and up to 1 mile wide. In the study area, the Mansfield Formation ranges from 0

to 300 feet thick.

14. Two major environments of deposition are recognized for the Mansfield Formation within the study area. The lower portion of the unit is comprised of incised valley-fill successions deposited in relatively small, tide-dominated estuaries. The upper portion of the unit is composed of a complex lithofacies assemblage deposited in a tide-influenced deltaic environment. These two units are separated by a transgressive marine shale that is correlatable over most of the study area.

Conclusions Concerning The Lee Formation and Age Equivalent Rocks of the Central Appalachian Basin and the Mansfield Formation of the Eastern Illinois Basin

15. A comparison of facies reveals that the Mansfield Formation is dominated by fine grained deposits of predominantly tidal origin whereas the Corbin Sandstone is dominated by coarser grained deposits of predominantly fluvial origin. Examination of the literature suggests that generally speaking, Morrowan/Atokan rocks of the central Appalachian Basin are dominated by fluvial and fluvial-deltaic deposits, whereas rocks of the same age in the eastern Illinois Basin appear to have a larger marine (tidal) component.

16. The vertical succession of facies within the Corbin Sandstone Member suggests deposition within a single, time-transgressive depositional continuum. Braided fluvial facies grade southward into a coastal, estuarine lowland area dominated by tidal sandflats and mixed flats. Offshore from the tidal flats were marine muds that transgressed over the tidal flat facies forming the overlying Betsie Shale Member of the Breathitt Formation.

The vertical succession of facies in the Mansfield Formation suggests multiple transgressions and regressions. An initial transgressional phase resulted in marine drowning of the incised valleys and deposition of central basin muds over fluvial deposits. Continued transgression resulted in landward migration of outer estuarine shoal deposits over the estuarine central basin deposits. A relative sea-level drop after deposition of the outer estuarine shoal deposits resulted in the development of subaerial exposure surfaces, and coal deposits. Another transgressional phase resulted in deposition of a marine shale that is correlatable over most of the study area. A final, regressional phase resulted in progradation of tide-influenced deltaic deposits over the transgressional marine shale.

17. When the Mansfield Formation in general, is compared to the Lee Formation and associated intertonguing rocks of the Breathitt Formation, collectively, important similarities emerge. The Mansfield Formation outside the study area contains braided river deposits very similar to the those of the Lee Formation. Furthermore, the fine grained rocks of the Breathitt Formations contain tidal deposits consisting of small scale tidal rhythmites in rocks previously considered fluvio-deltaic. These deposits are very similar to those of the fine grained rocks of the Mansfield Formation.

18. The primary physical processes operating during Morrowan/Atokan in the central Appalachian Basin and eastern Illinois Basin appear to have been fluvial and tidal. Wave processes were of secondary importance. Tidal processes appear to have been dominant in the eastern Illinois Basin, whereas fluvial processes appear to have been dominant during the same time in the central Appalachian Basin. This suggests that tectonic setting strongly influenced deposition in the eastern Illinois Basin and central Appalachian Basin during Morrowan/Atokan time.

19. The dissimilarity in the dominant physical processes in

the Illinois Basin and the central Appalachian Basin during Morrowan/Atokan time suggests that the Cincinnati Arch was emergent, and effectively separated the two basins.

20. Some linkage across the Cincinnati Arch is suggested by the presence of braided-river deposits in the Mansfield Formation that contain quartz pebbles, occupy northeast-to-southwest oriented paleovalleys, and have southwest-directed paleocurrent directions.

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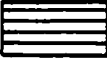


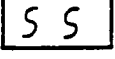


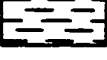


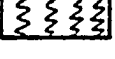




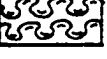

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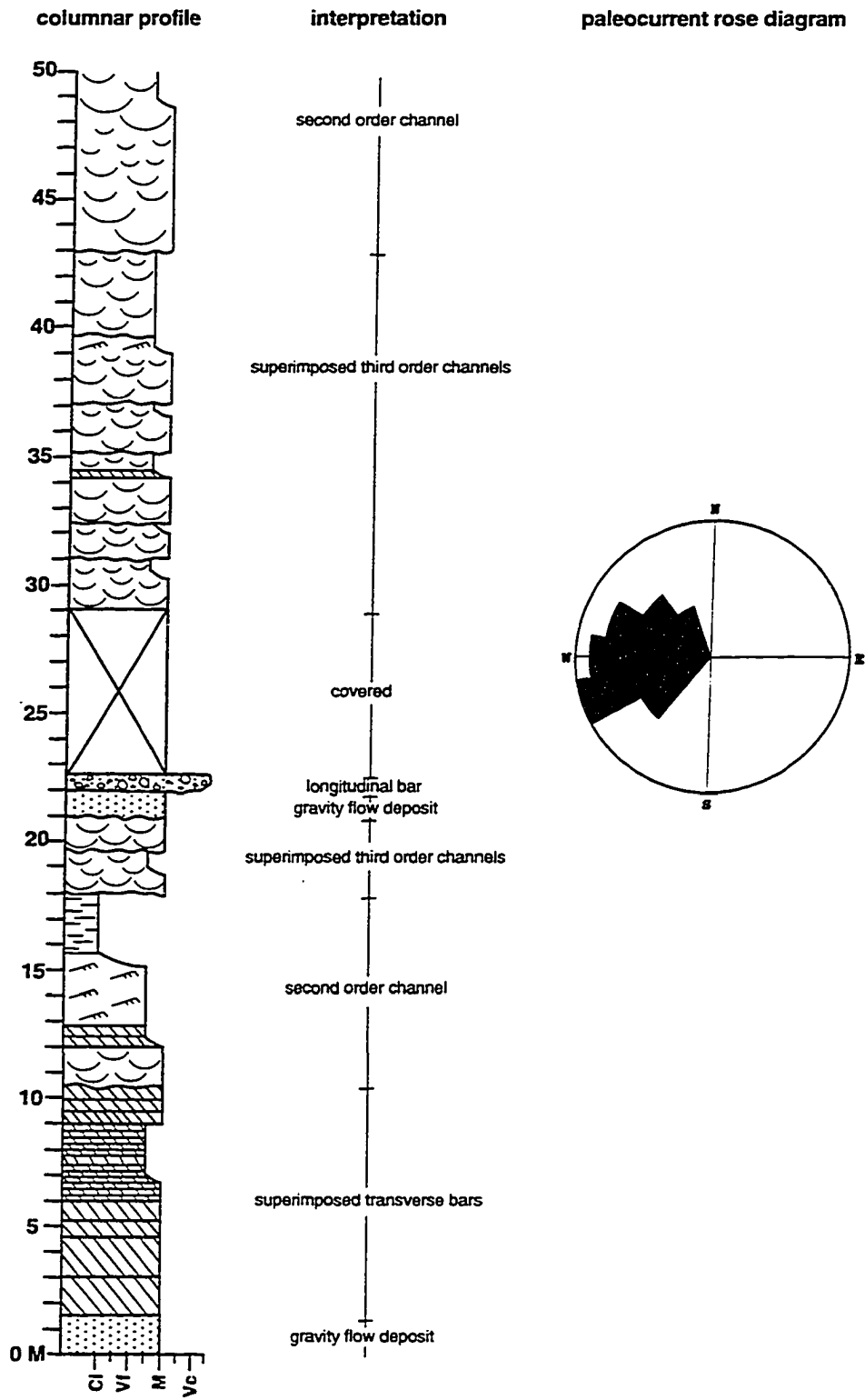
APPENDIX A

Columnar Profiles of Outcrops of the Corbin Sandstone

LEGEND

	Trough/Tangential Crossbedding		Rooting
	Planar Crossbedding		Coal
	Horizontal Bedding		Plant Debris
	Ripple Bedding		Trace Fossils
	Quartz Pebble Conglomerate		Siderite Nodules
	Shale		Coal Spars
	Wavy Bedding		Underclay
	Flaser Bedding		Tree Limbs
	Massive Bedding		Shale and Mudstone Intraclasts
	Disrupted Bedding		Lenticular Bedding

ZA-3 (page 1 of 2)

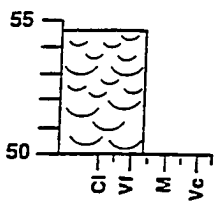


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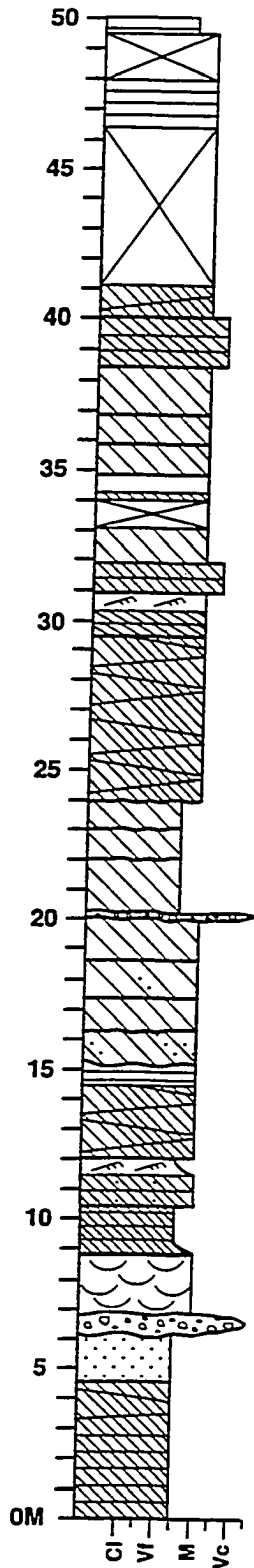
columnar profile

interpretation

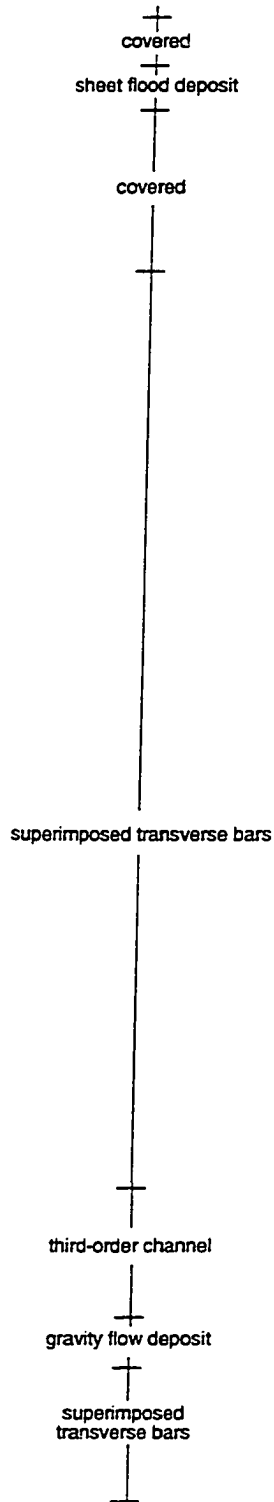
paleocurrent rose diagram



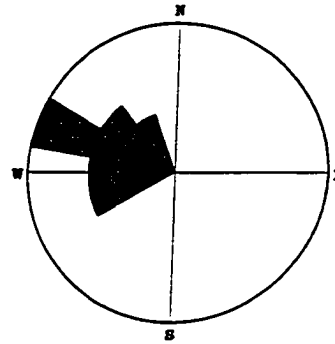
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interpretation



paleocurrent rose diagram



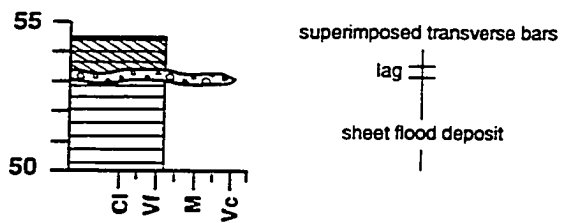
SL-2 (page 2 of 2)

columnar profile

interpretation

paleocurrent rose diagram

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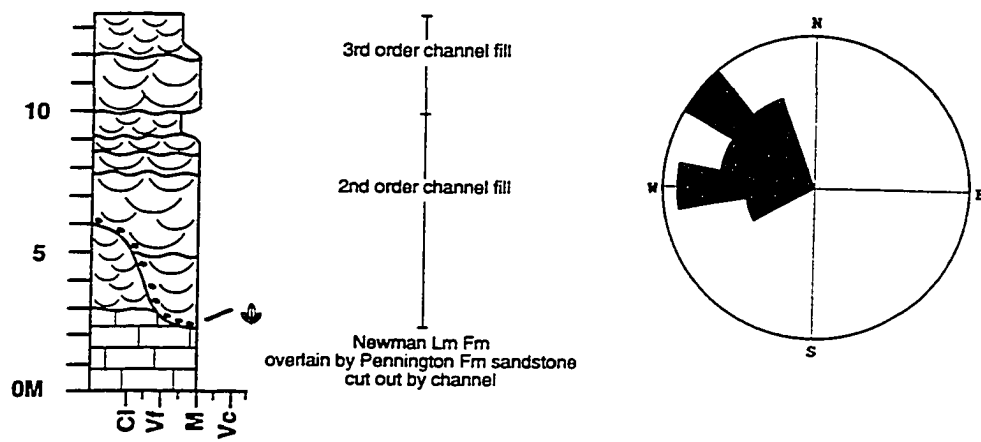


BA-2

columnar profile

interpretation

paleocurrent rose diagram

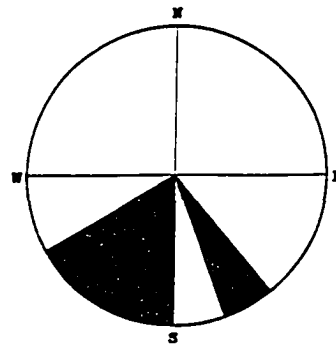
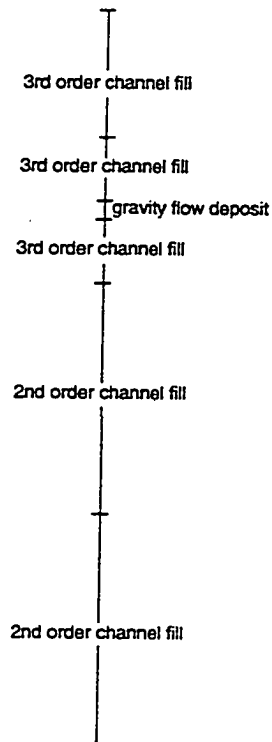
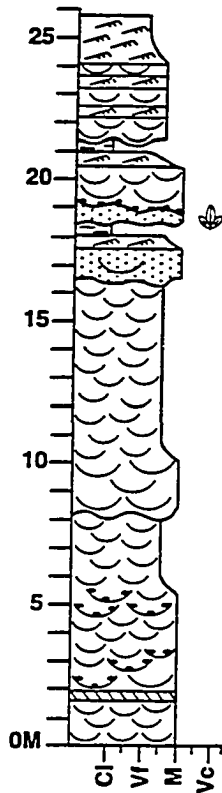


VO-1

columnar profile

interpretation

paleocurrent rose diagram

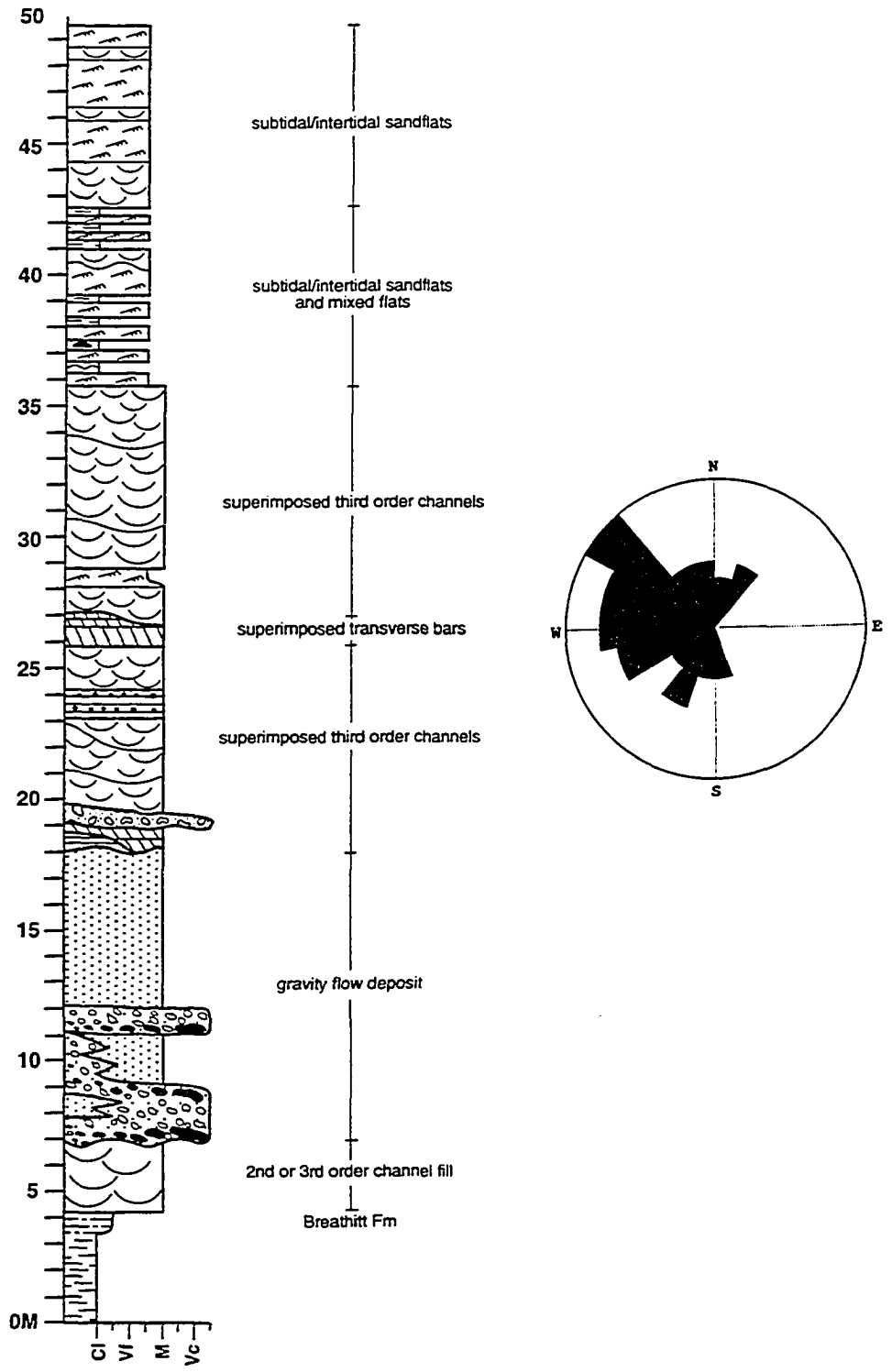


BA-3

columnar profile

interpretation

paleocurrent rose diagram

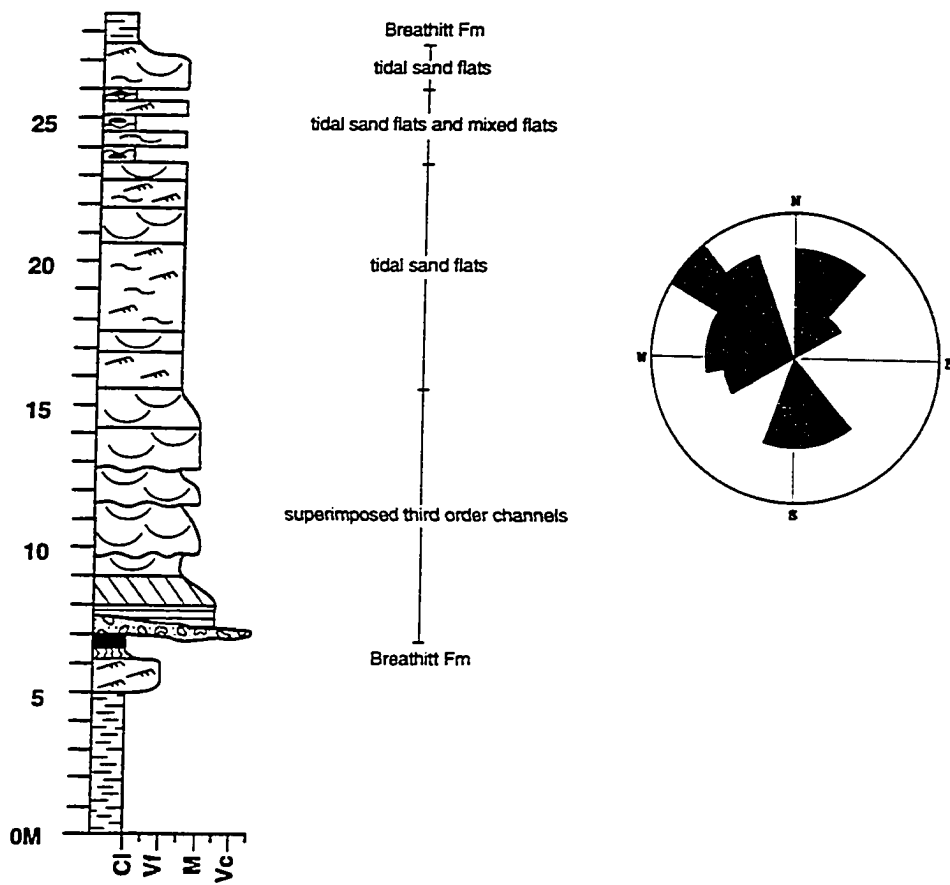


SC-1

columnar profile

interpretation

paleocurrent rose diagram

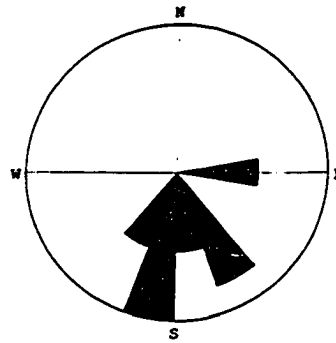
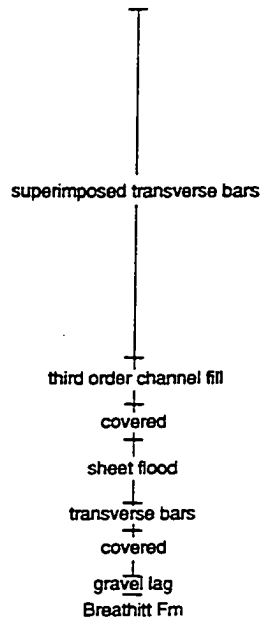
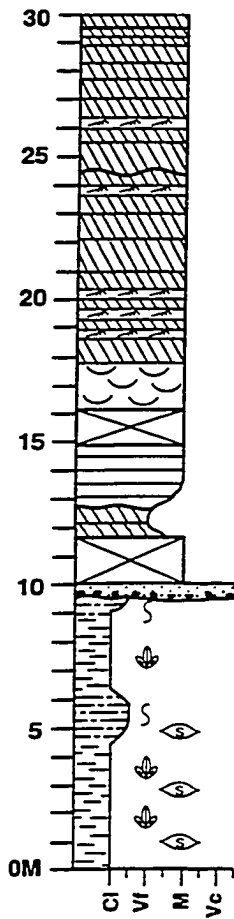


MC-1

columnar profile

interpretation

paleocurrent rose diagram

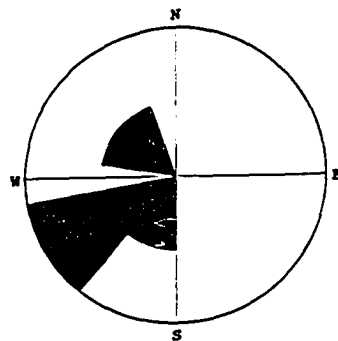
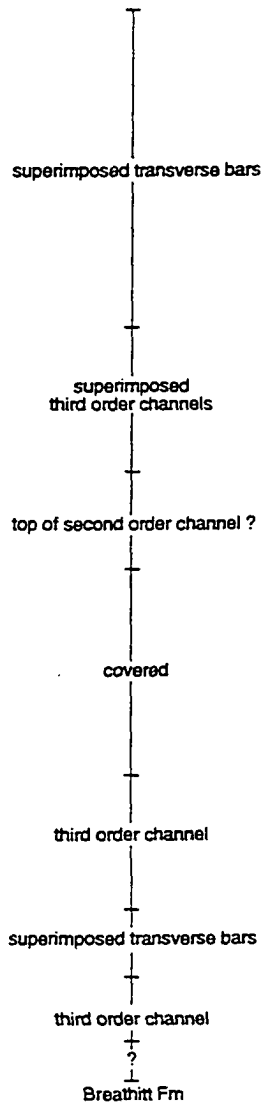
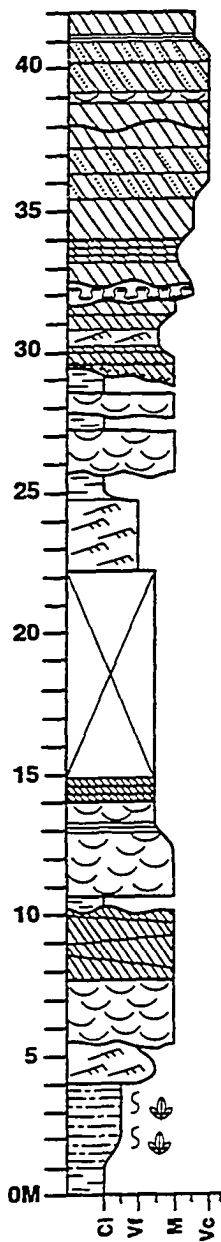


COB-1

stratigraphic column

interpretation

paleocurrent rose diagram

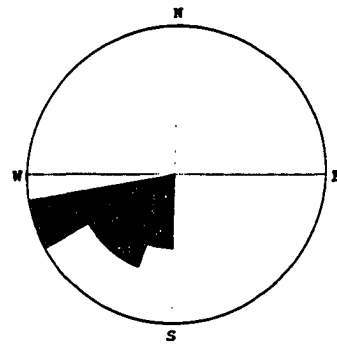
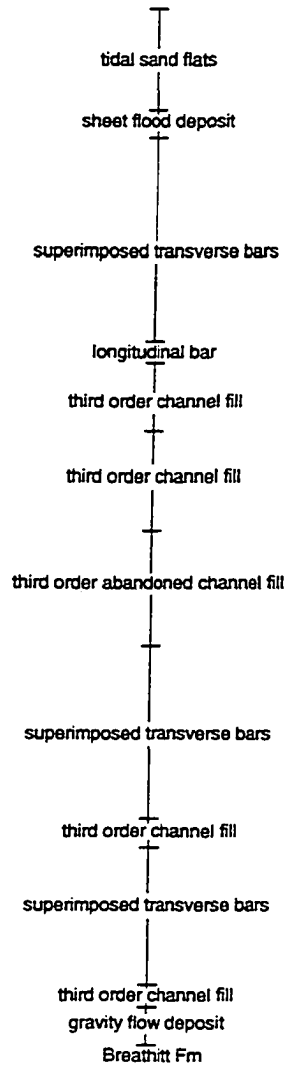
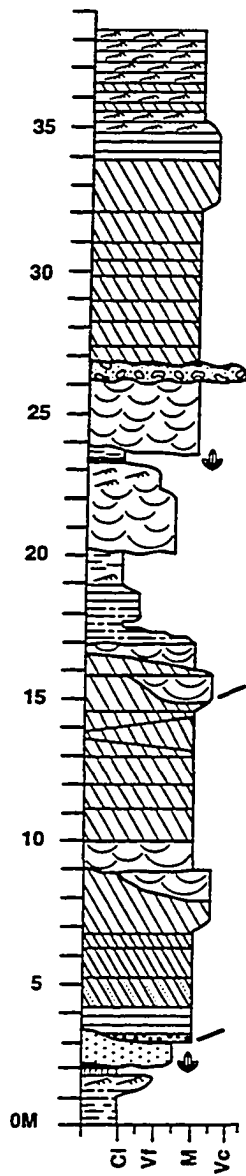


EZ-1

columnar profile

interpretation

paleocurrent rose diagram

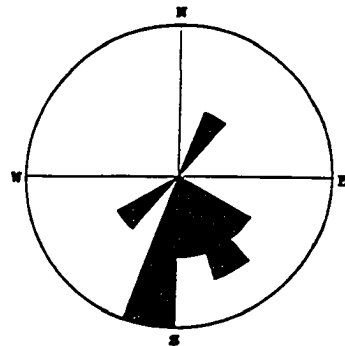
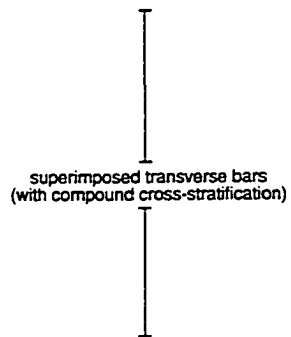
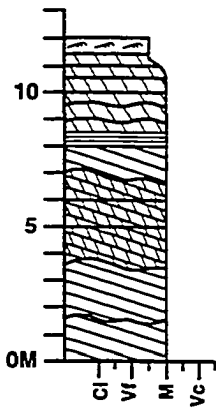


SA-1

columnar profile

interpretation

paleocurrent rose diagram

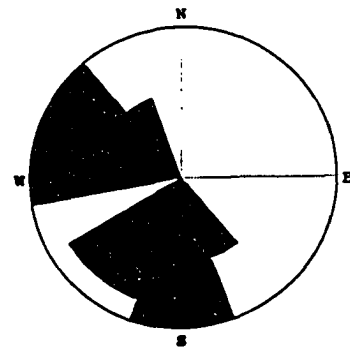
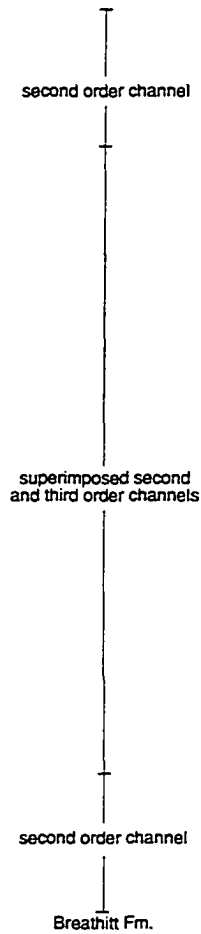
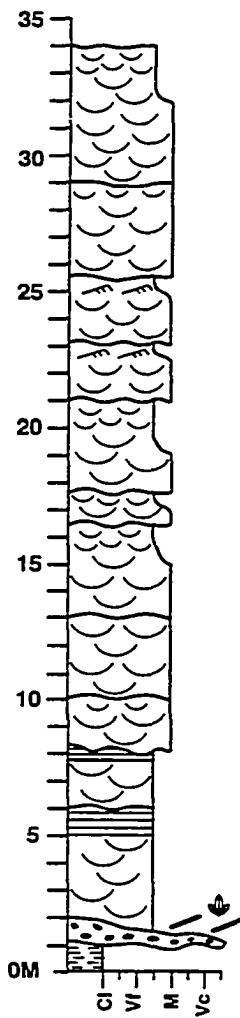


ZA-2

columnar profile

interpretation

paleocurrent rose diagram

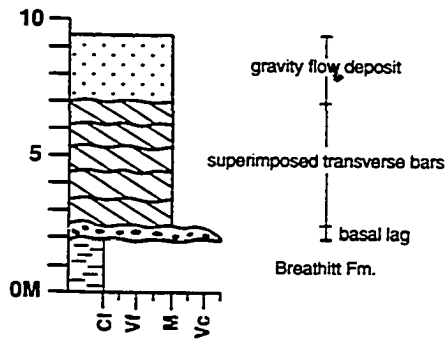


BE-3

columnar profile

interpretation

paleocurrent rose diagram



APPENDIX B

Petrology of the Corbin Sandstone Member and
the Mansfield Formation

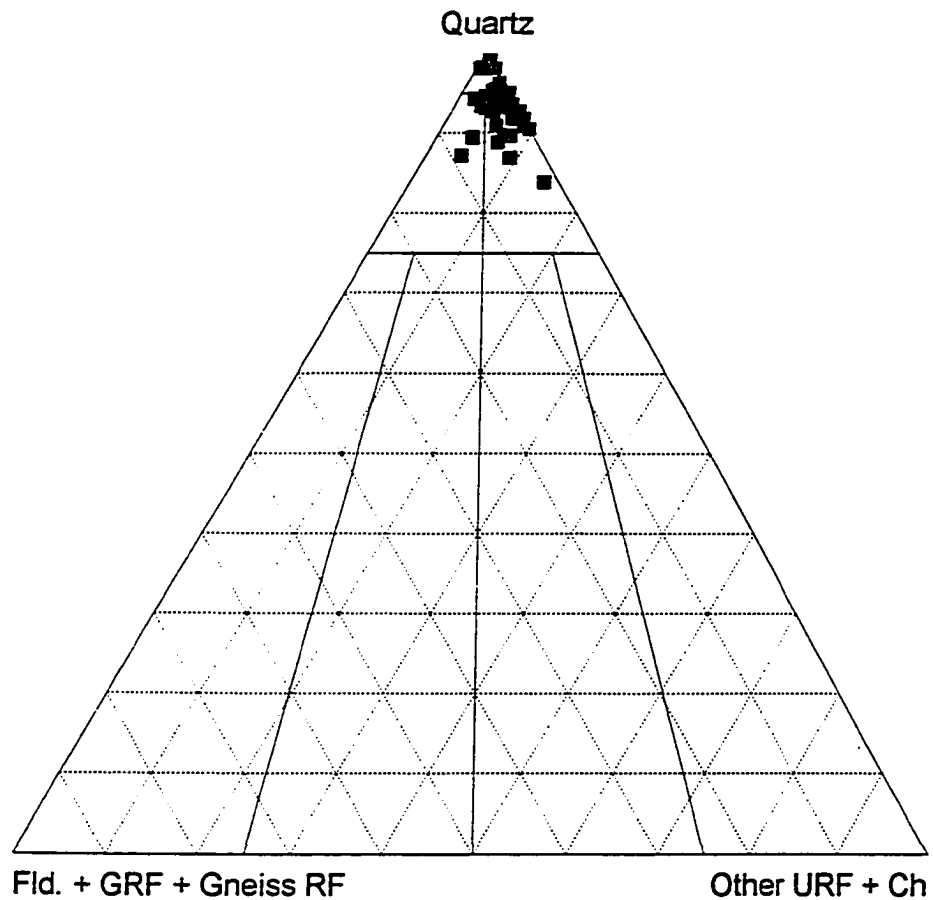


Fig. A Petrology of the Corbin Sandstone based on point counts of 35 thin sections (300 points/slide). Sandstone classification after Folk (1974)

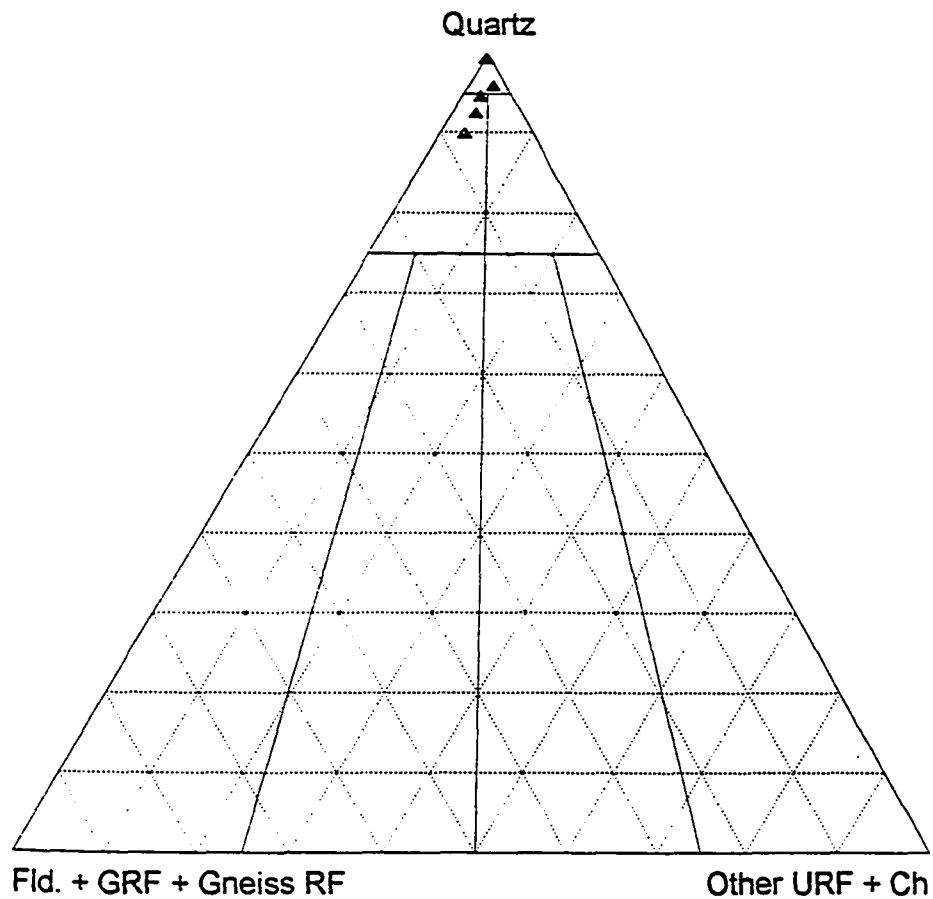


Fig. B Petrology of Mansfield Formation Sandstones from point counts of five thin sections (300 points/slide). Sandstone classification after Folk (1974).

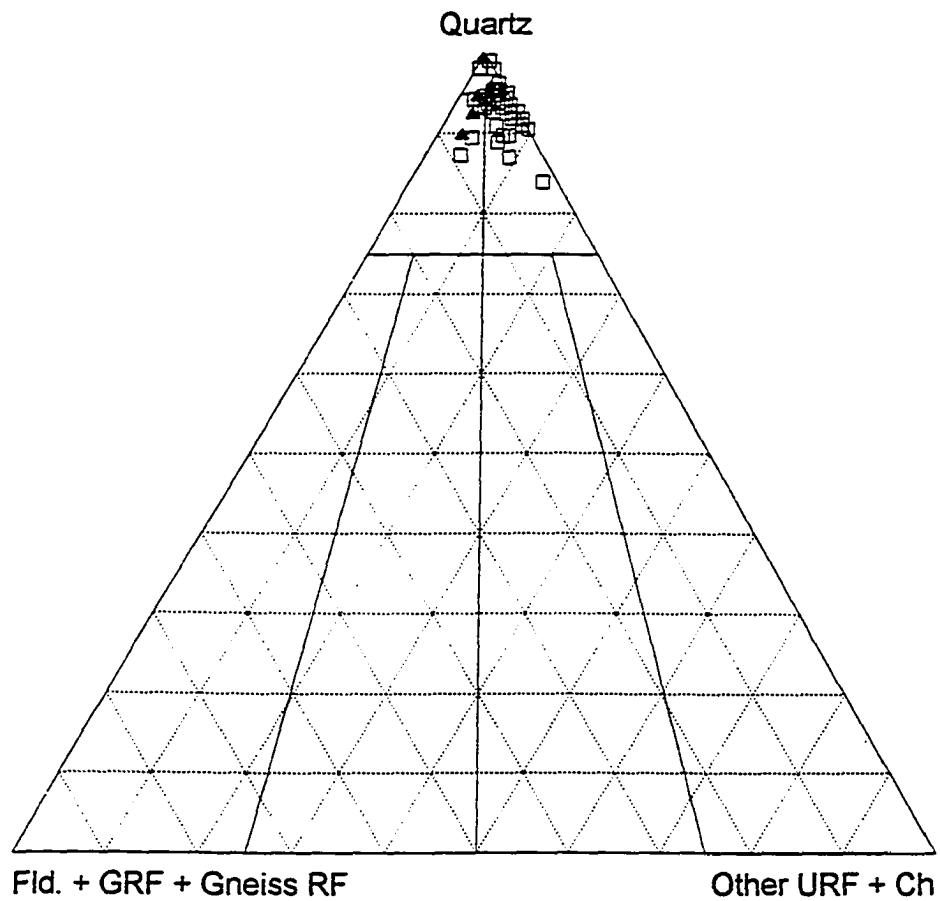


Fig. C Petrology of the Corbin Sandstone and Mansfield Formation combined. Open squares represent samples from the Corbin Sandstone, triangles represent samples from the Mansfield Formation. Sandstone Classification after Folk (1974).

PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

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Black and white photographic prints (17" x 23") are available for an additional charge.

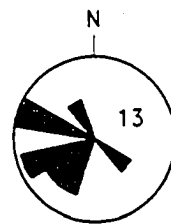
University Microfilms International

PLATE 1, ISOPACH MAP OF THE CORBIN SANDSTONE MEMBER, LEE FORMATION, EASTERN KENTUCKY

By Mark Barnhill
1993

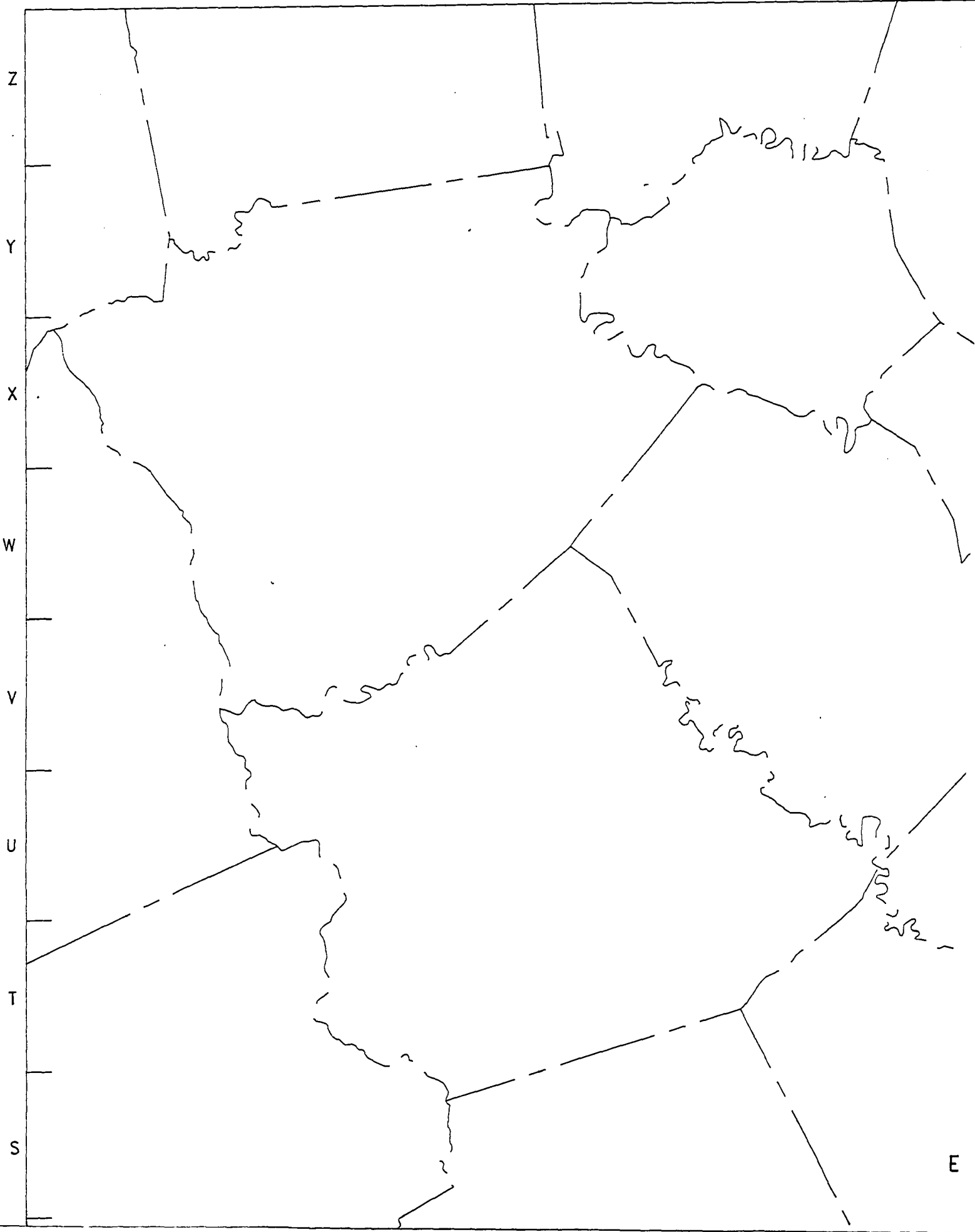
EXPLANATION

- ▲ Measured sections
- Other outcrops examined
- ↙ Paleodispersal trends

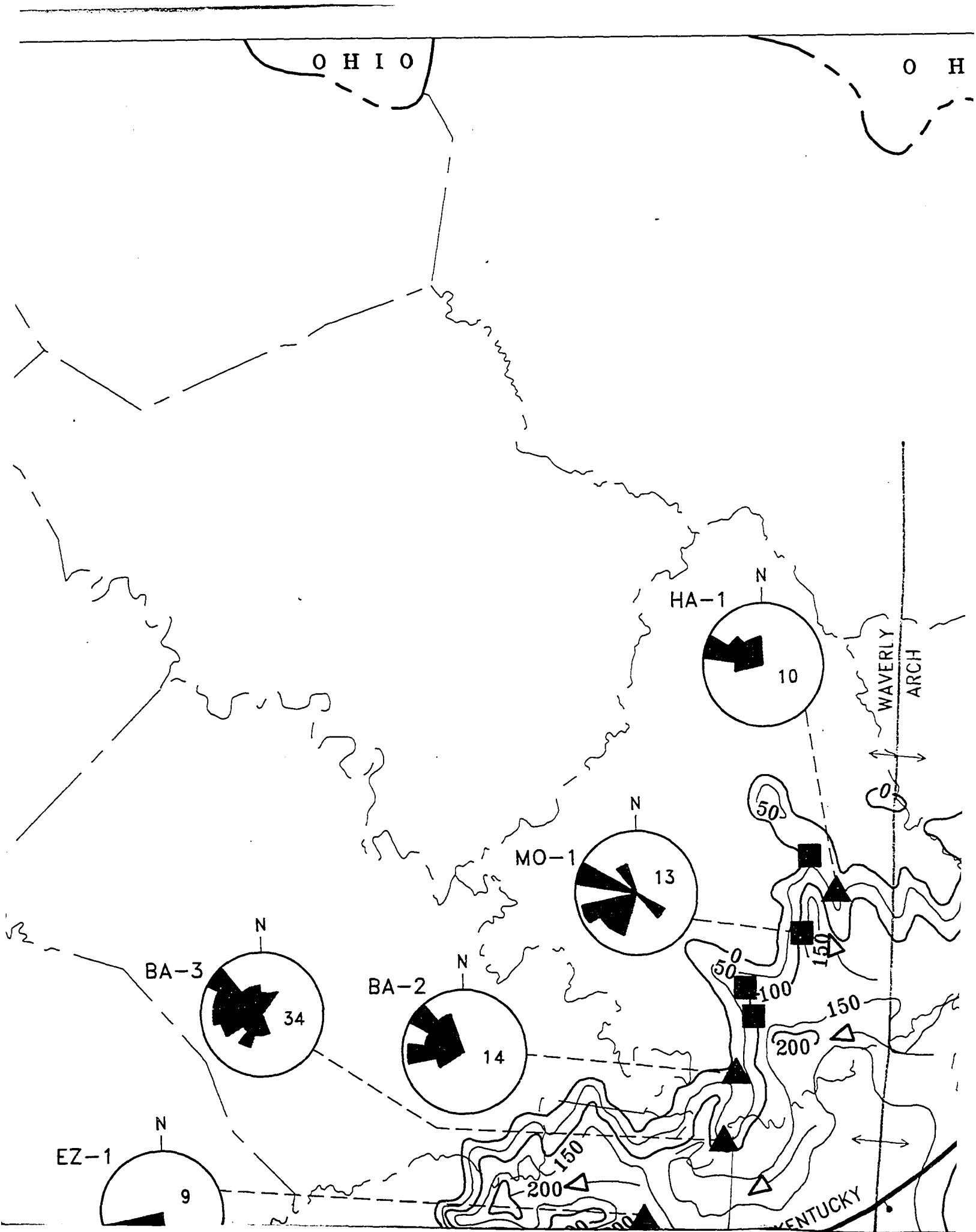


Paleocurrent Rose Diagram

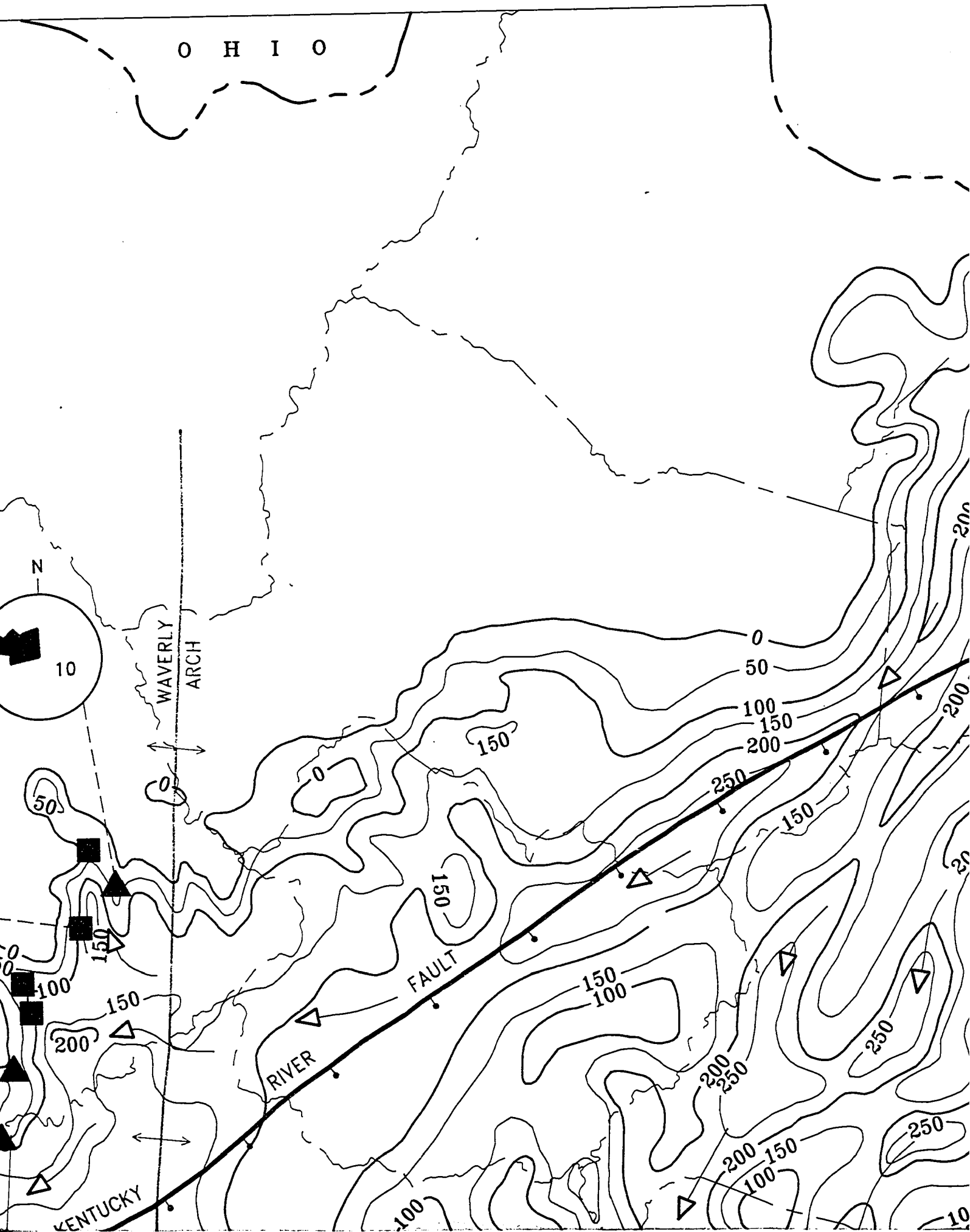
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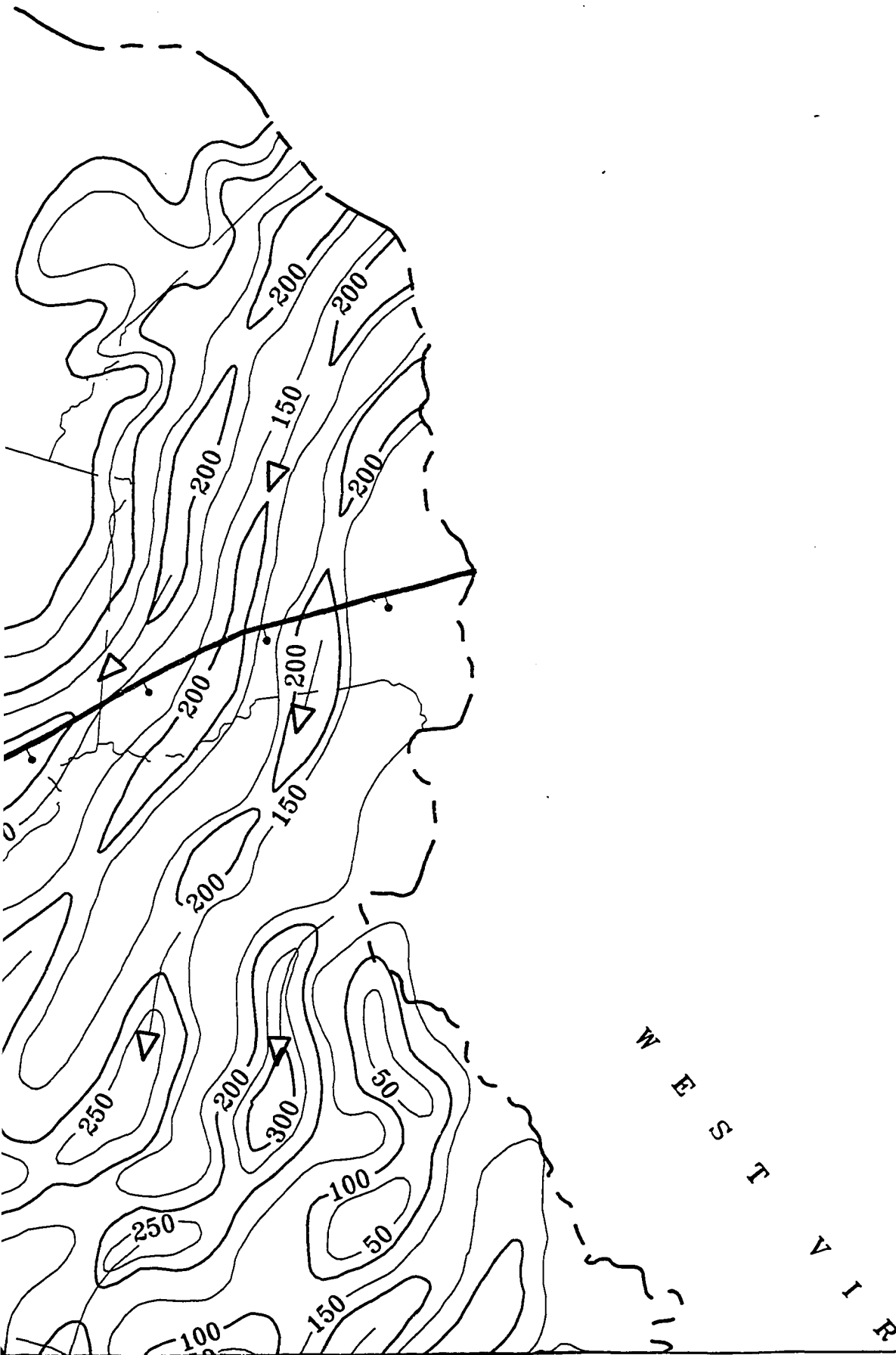
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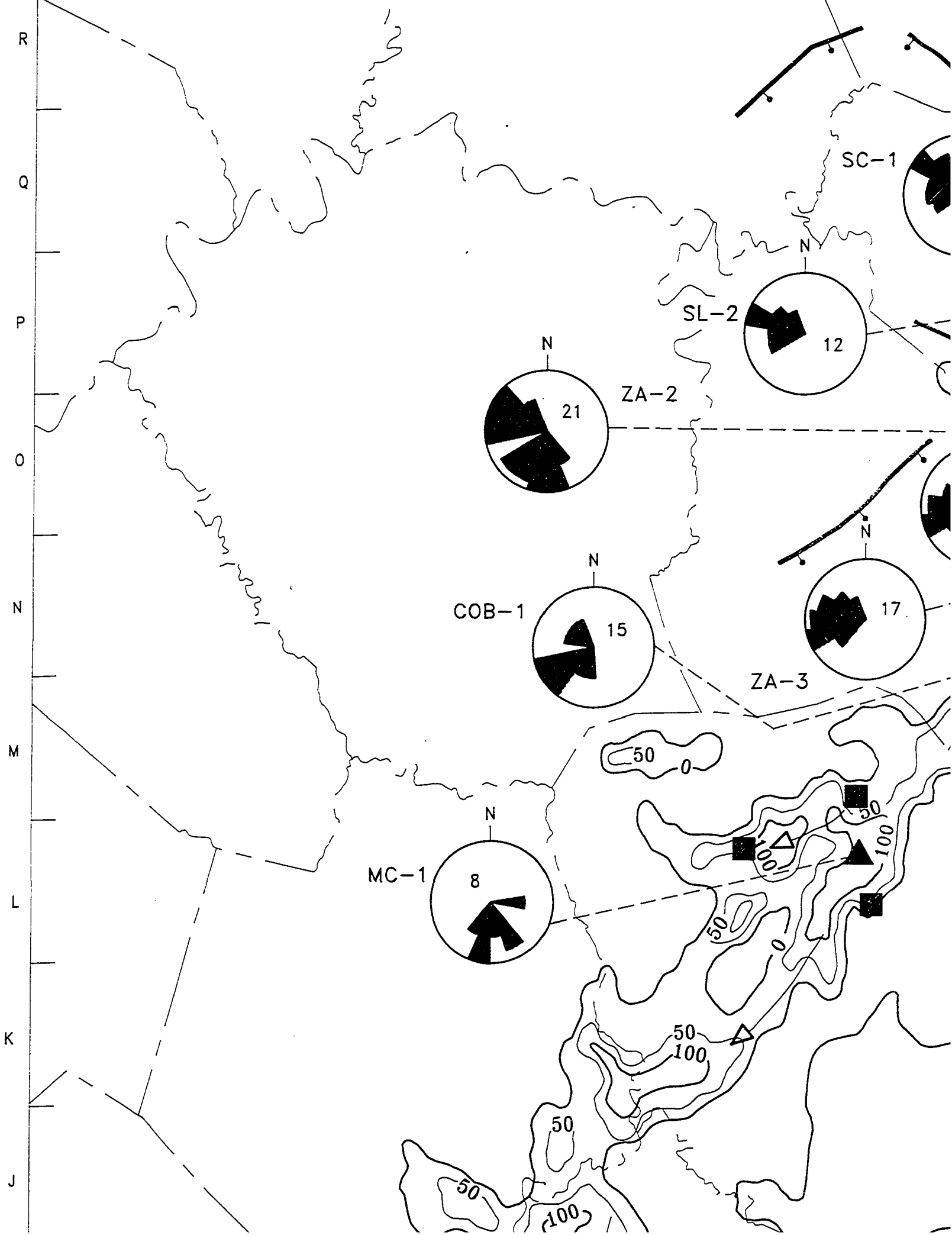


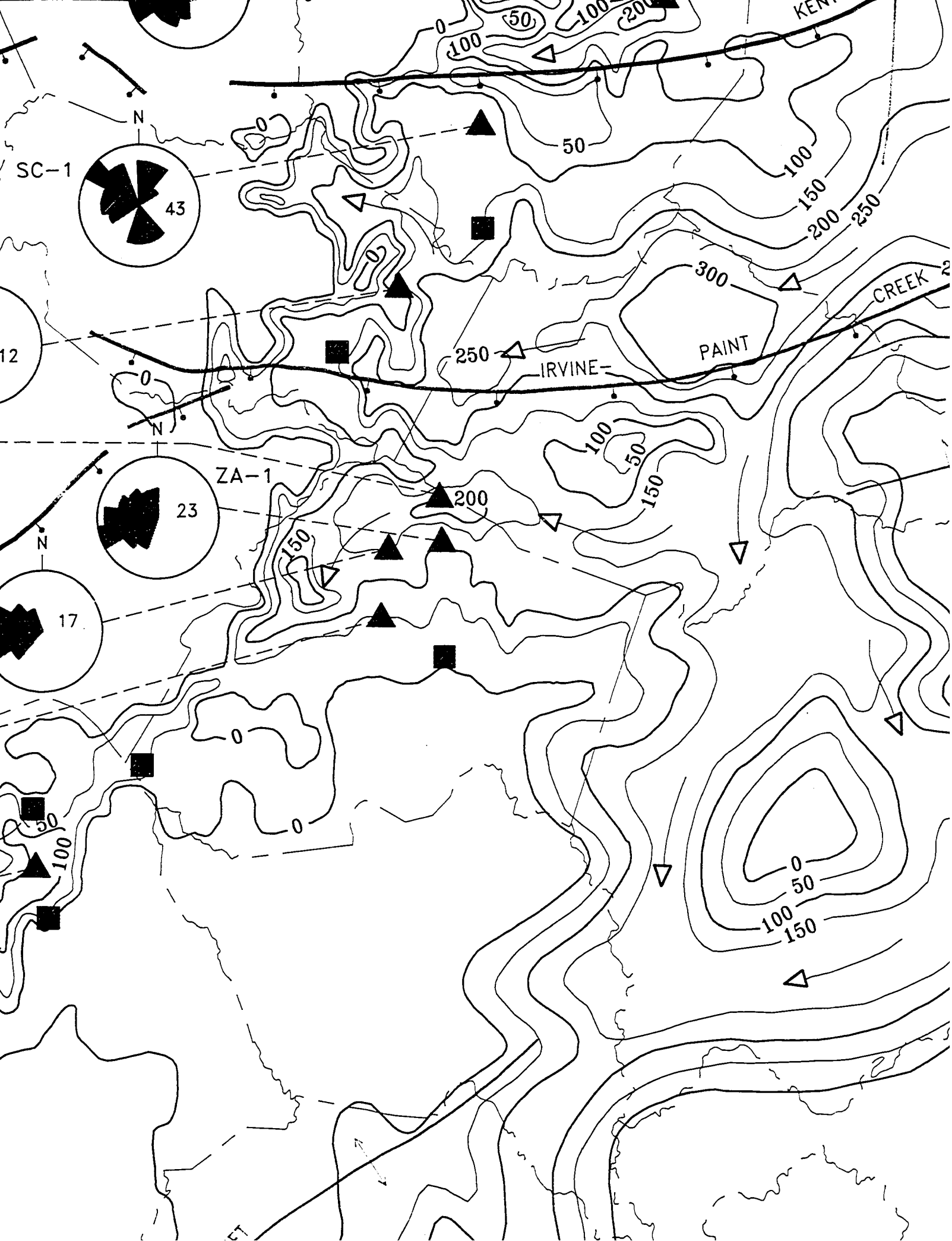
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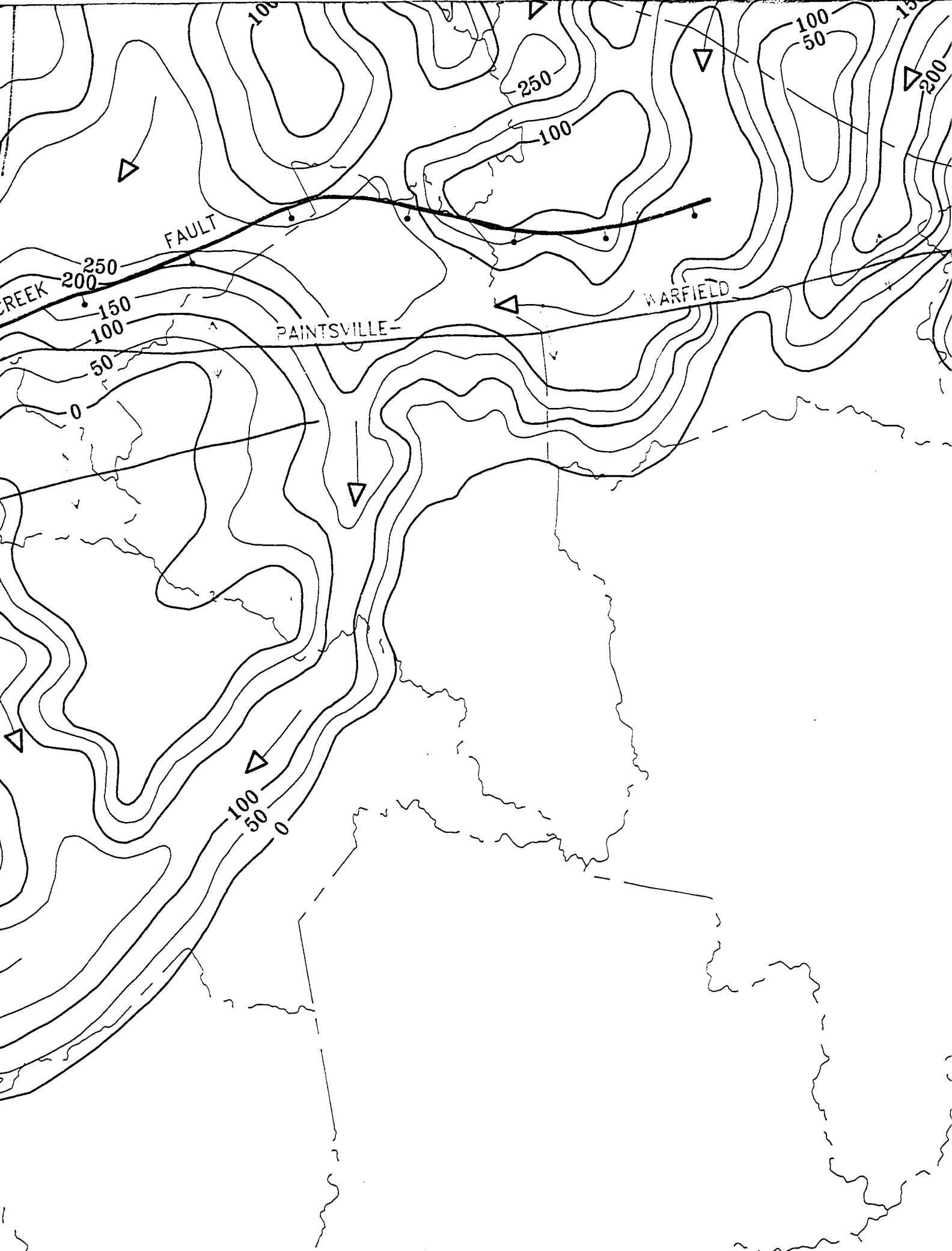


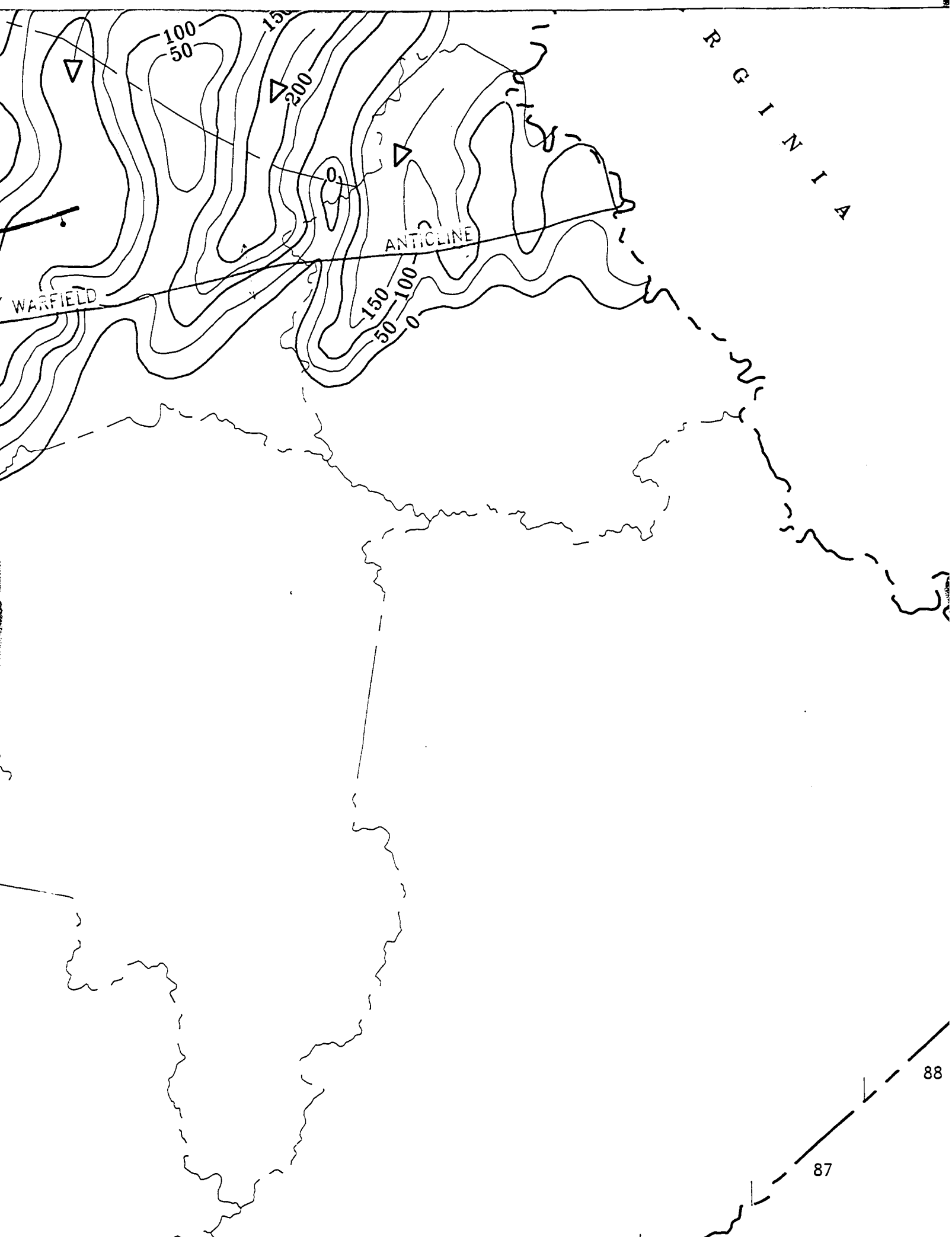
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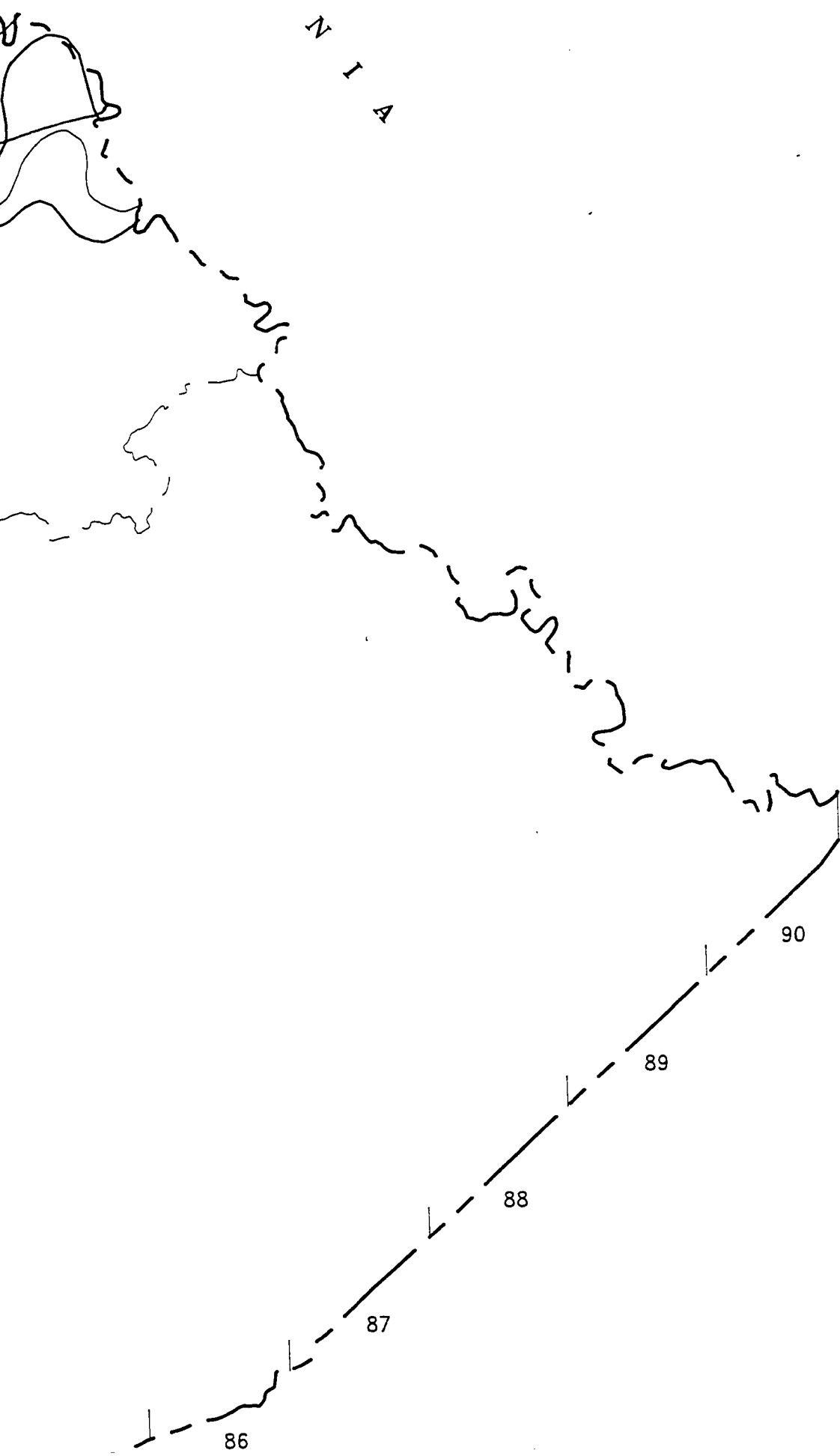


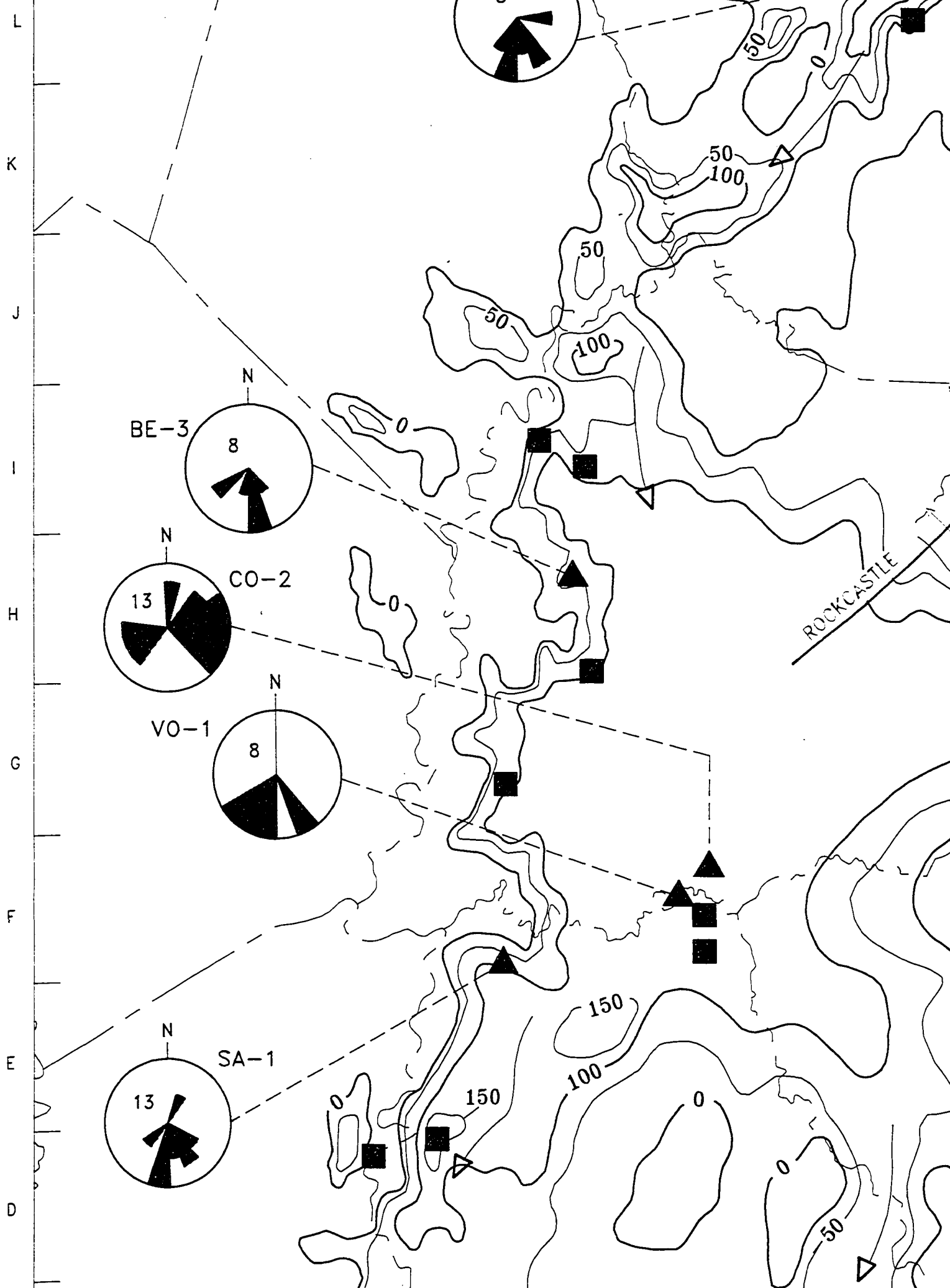




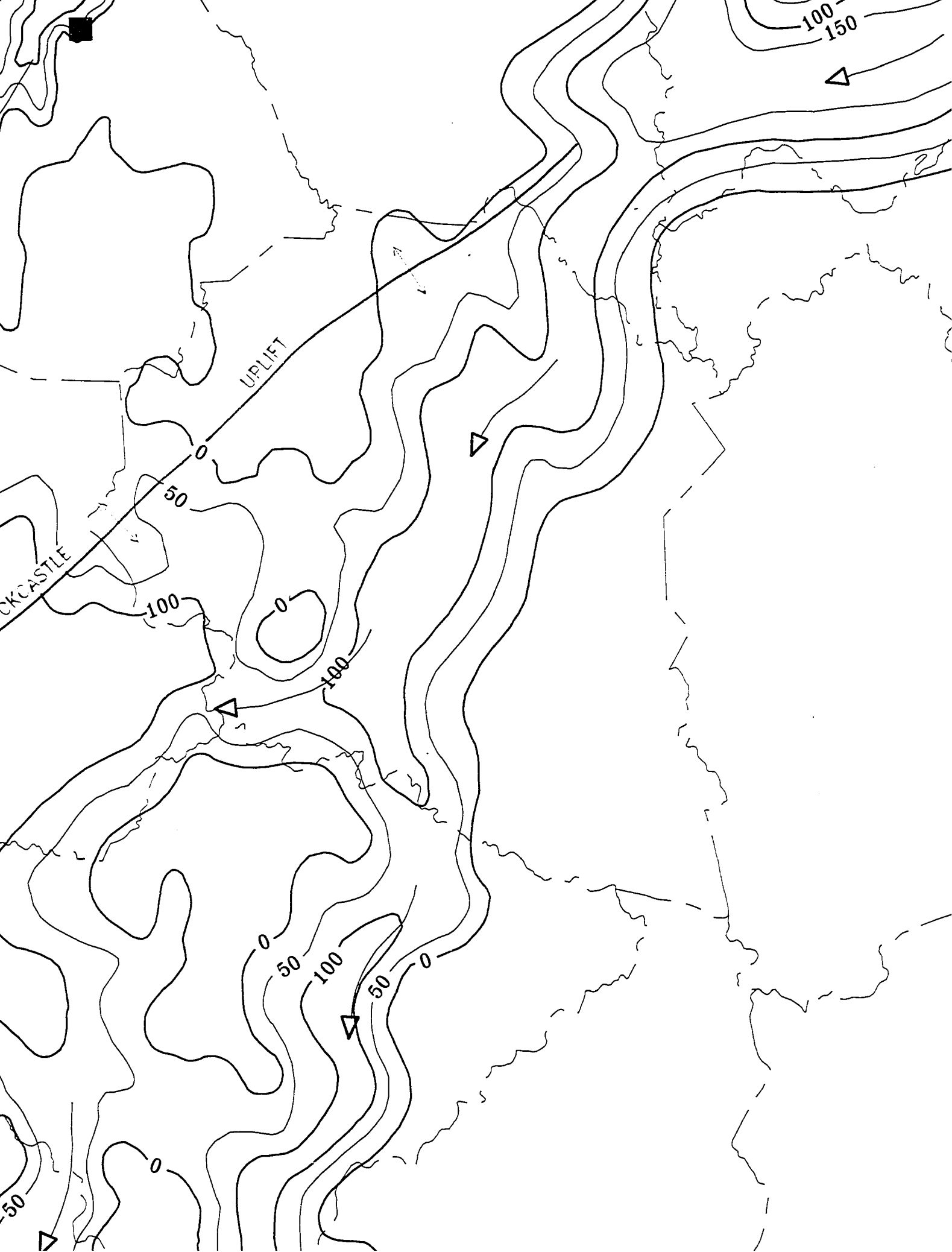


SIERRA LEONE





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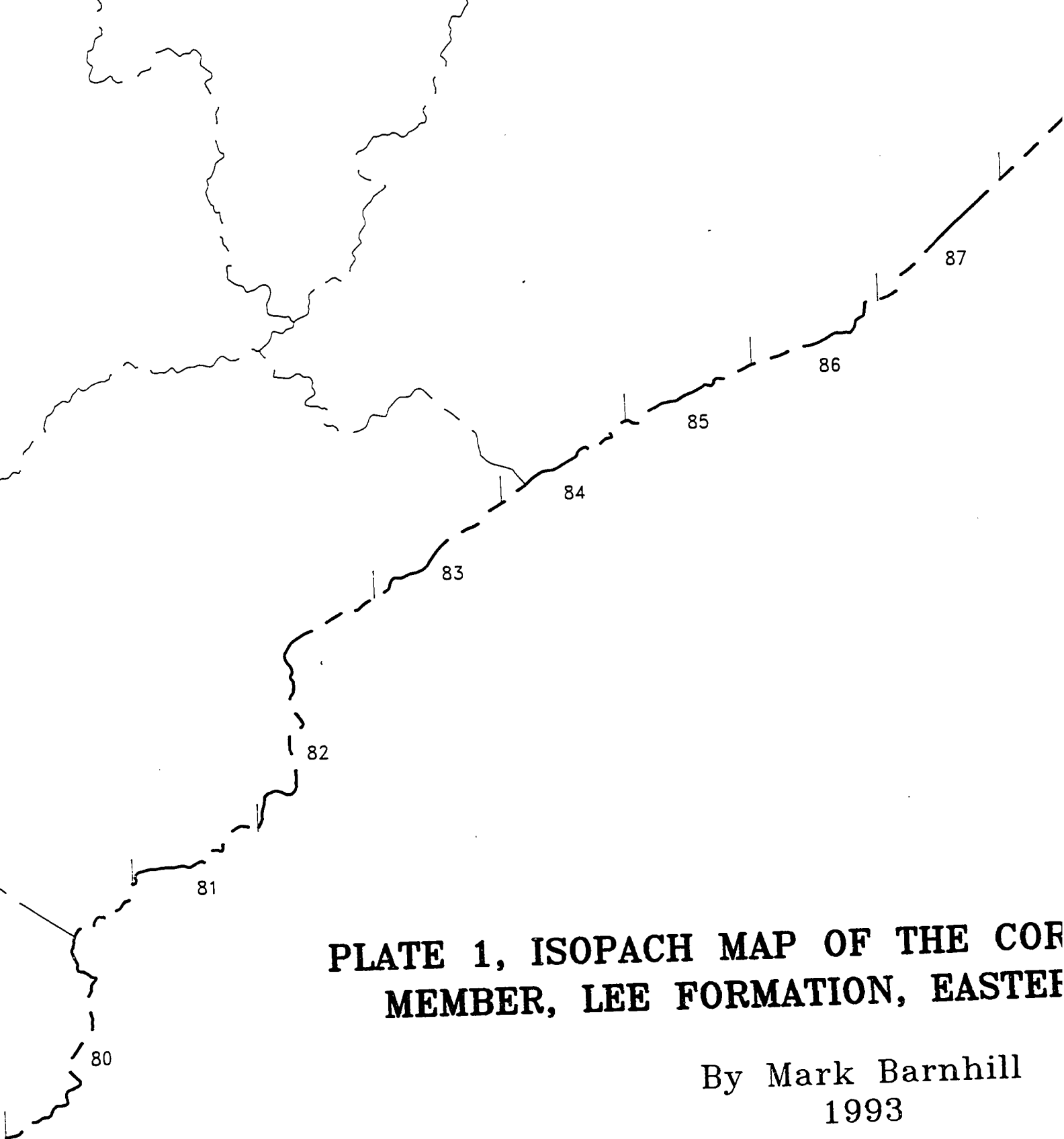
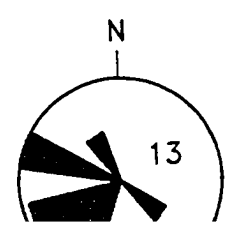


PLATE 1, ISOPACH MAP OF THE COROMANTEE MEMBER, LEE FORMATION, EASTERN LIBERIA

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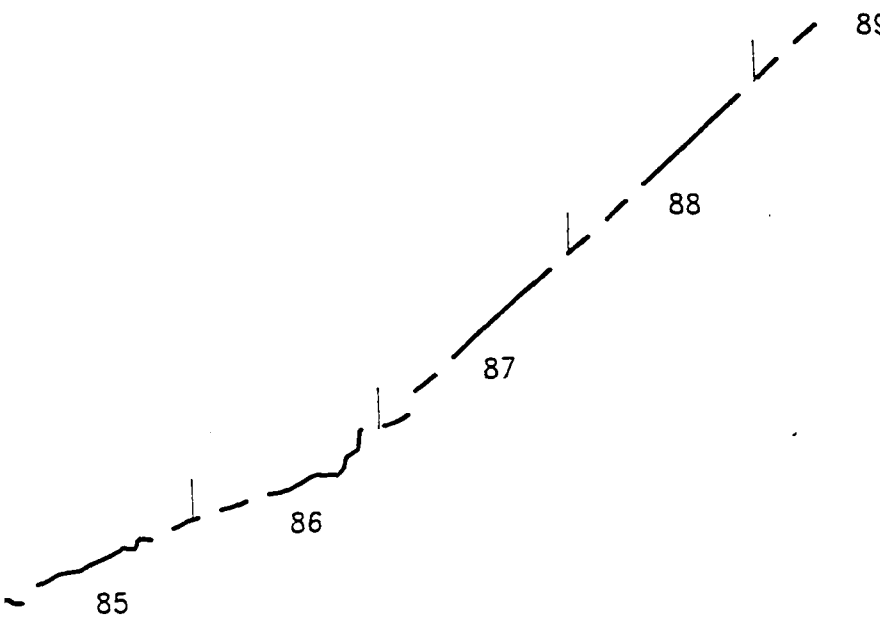
EXPLANATION

- ▲ Measured sections
- Other outcrops examined



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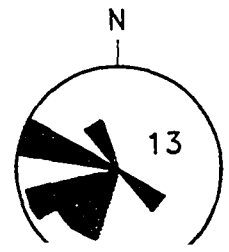


MAP OF THE CORBIN SANDSTONE FORMATION, EASTERN KENTUCKY

By Mark Barnhill
1993

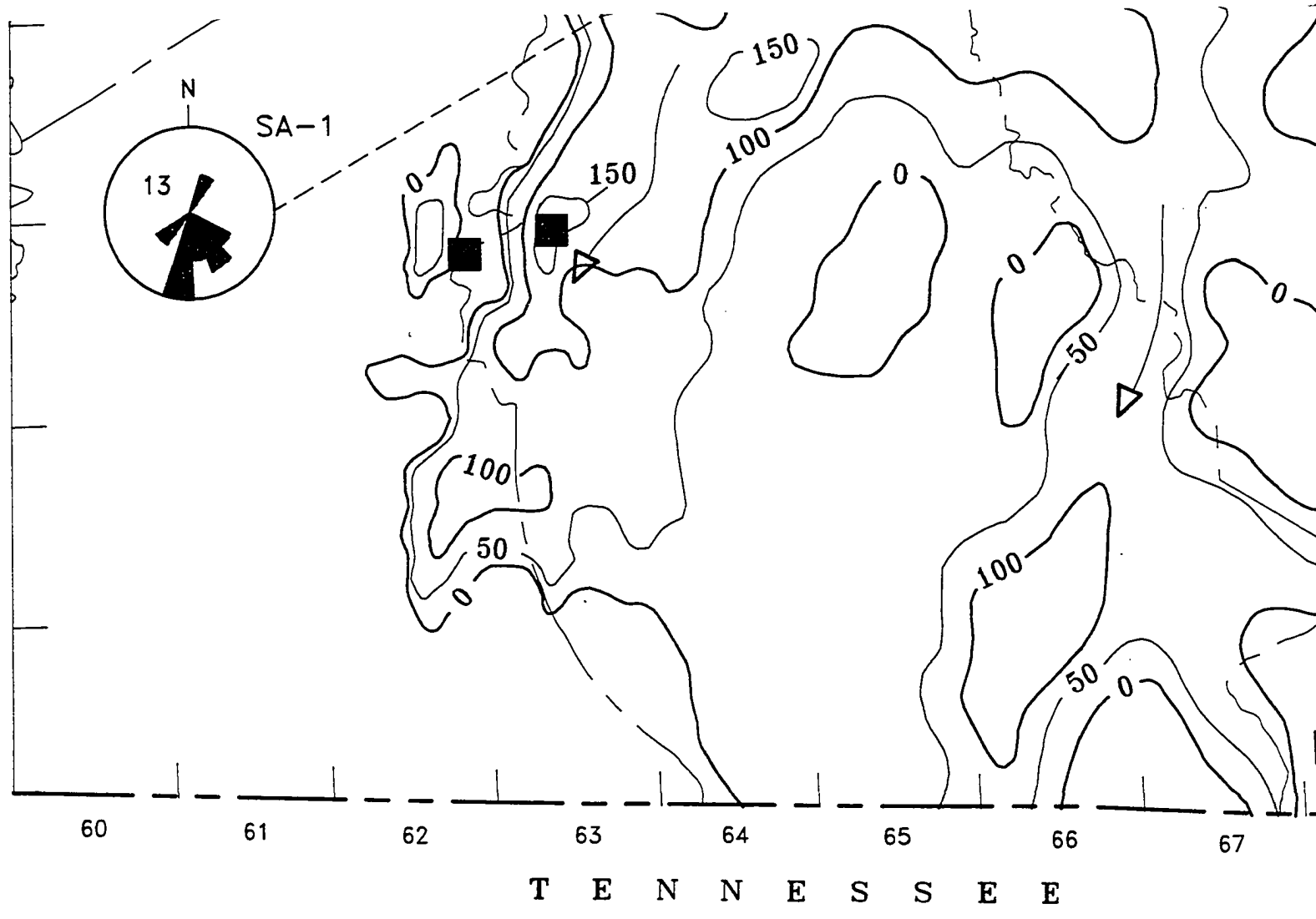
EXPLANATION

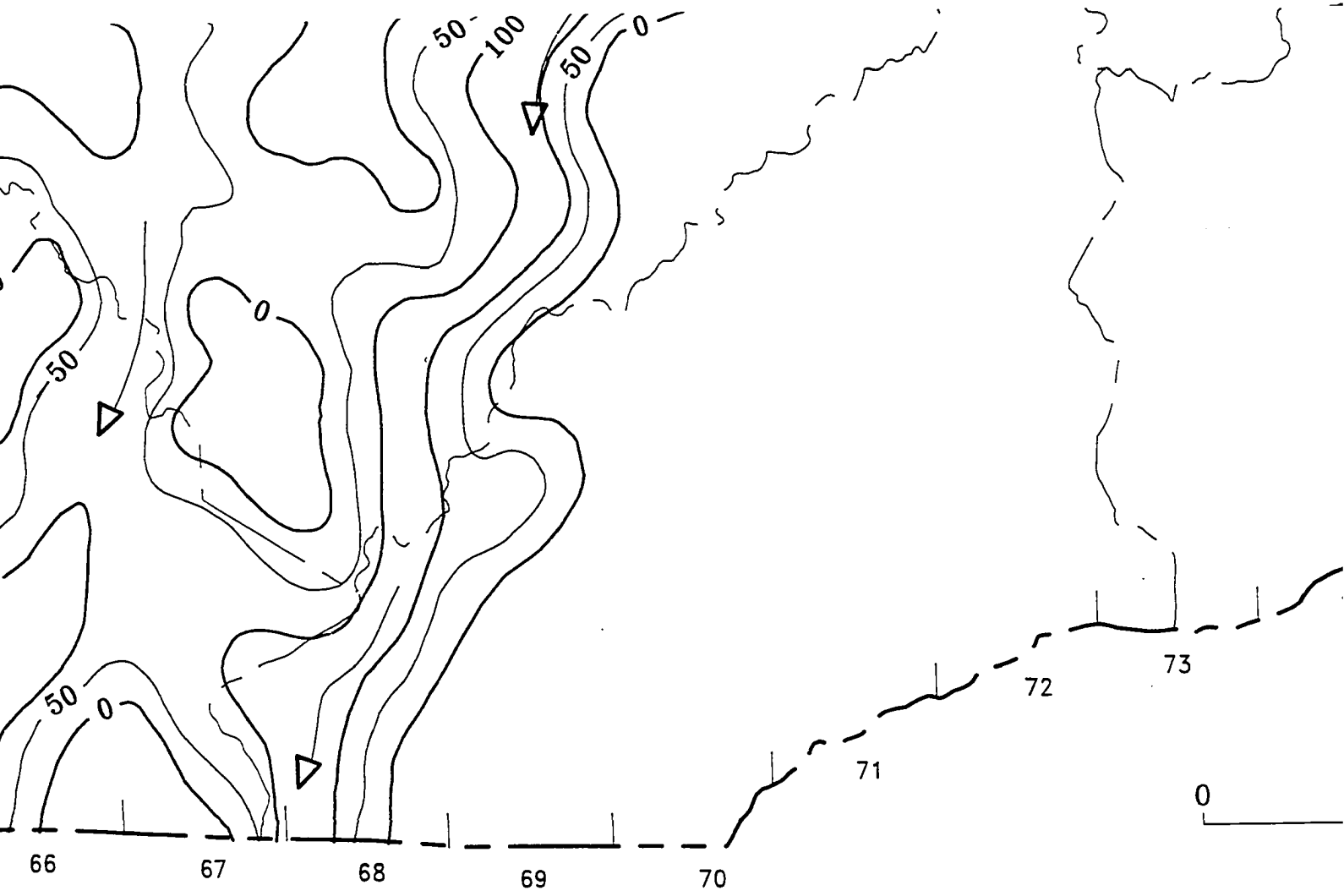
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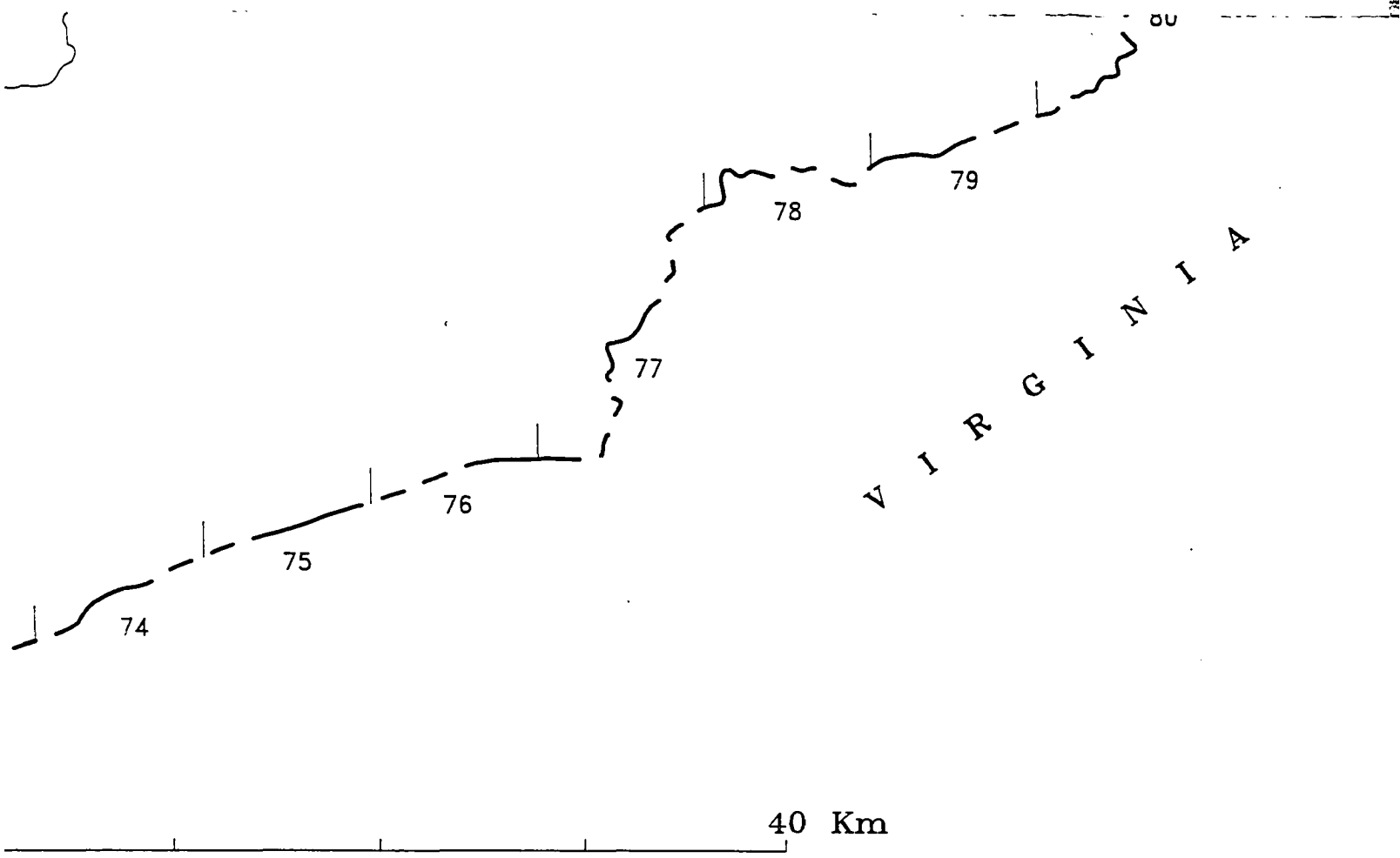
Paleocurrent Rose Diagram

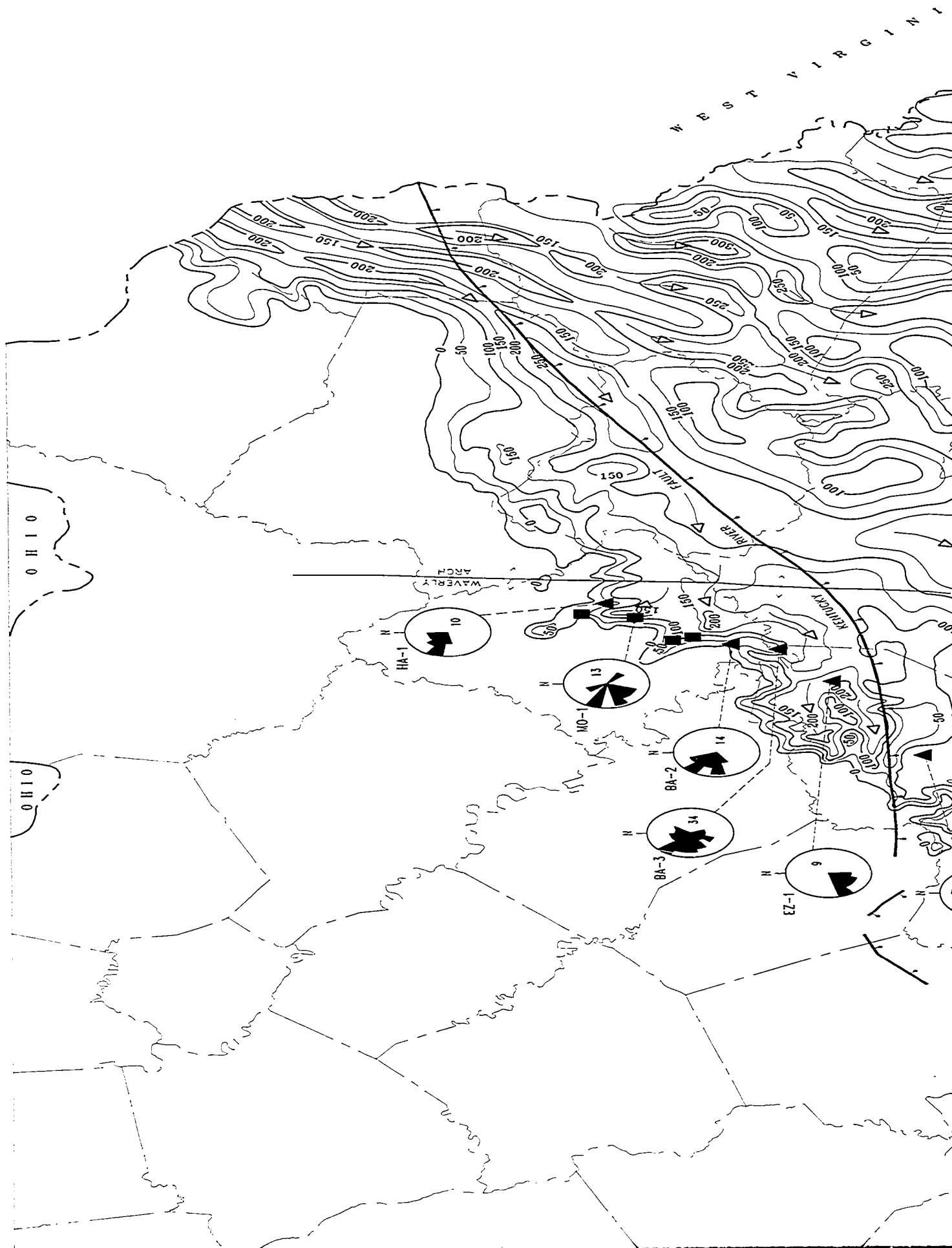
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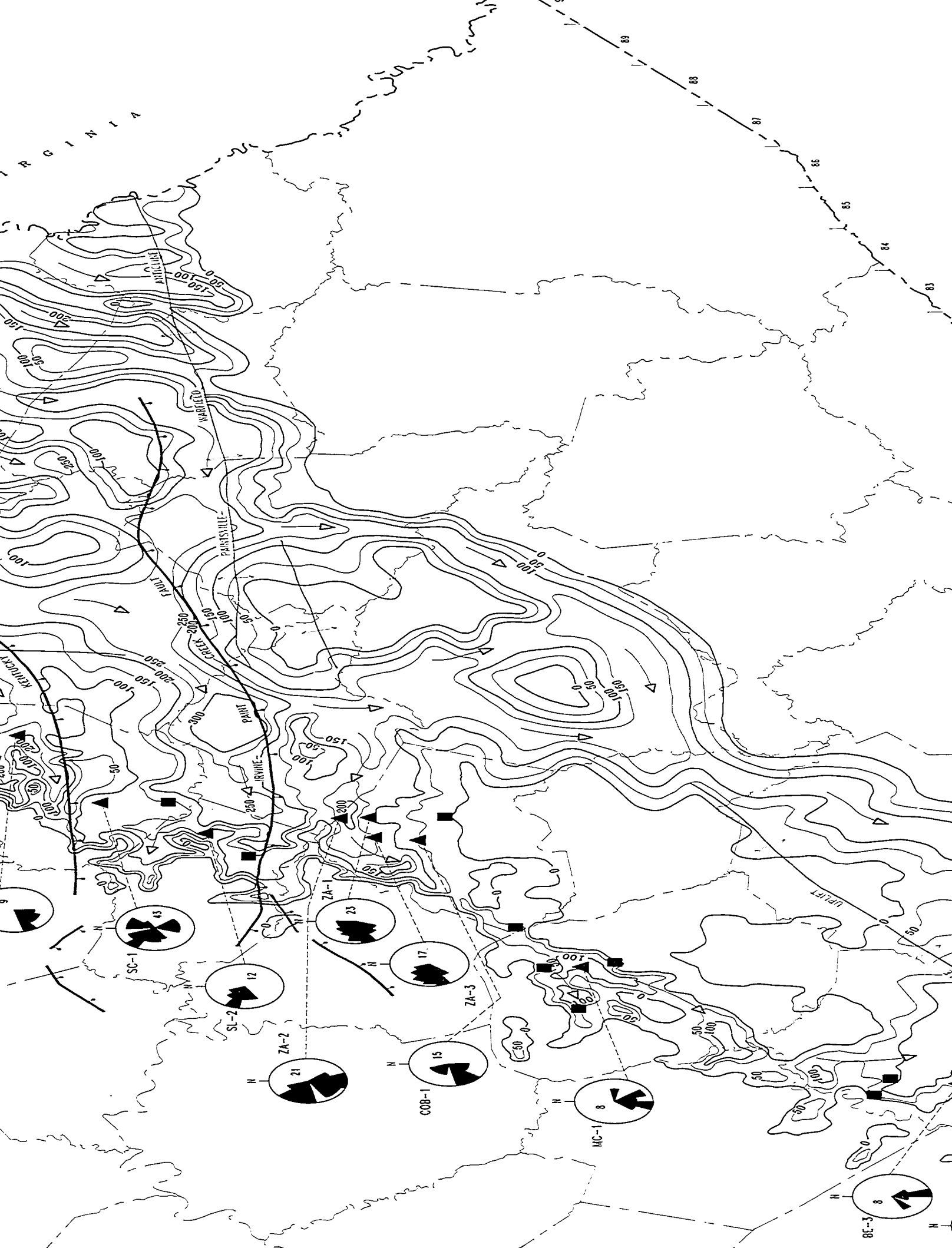




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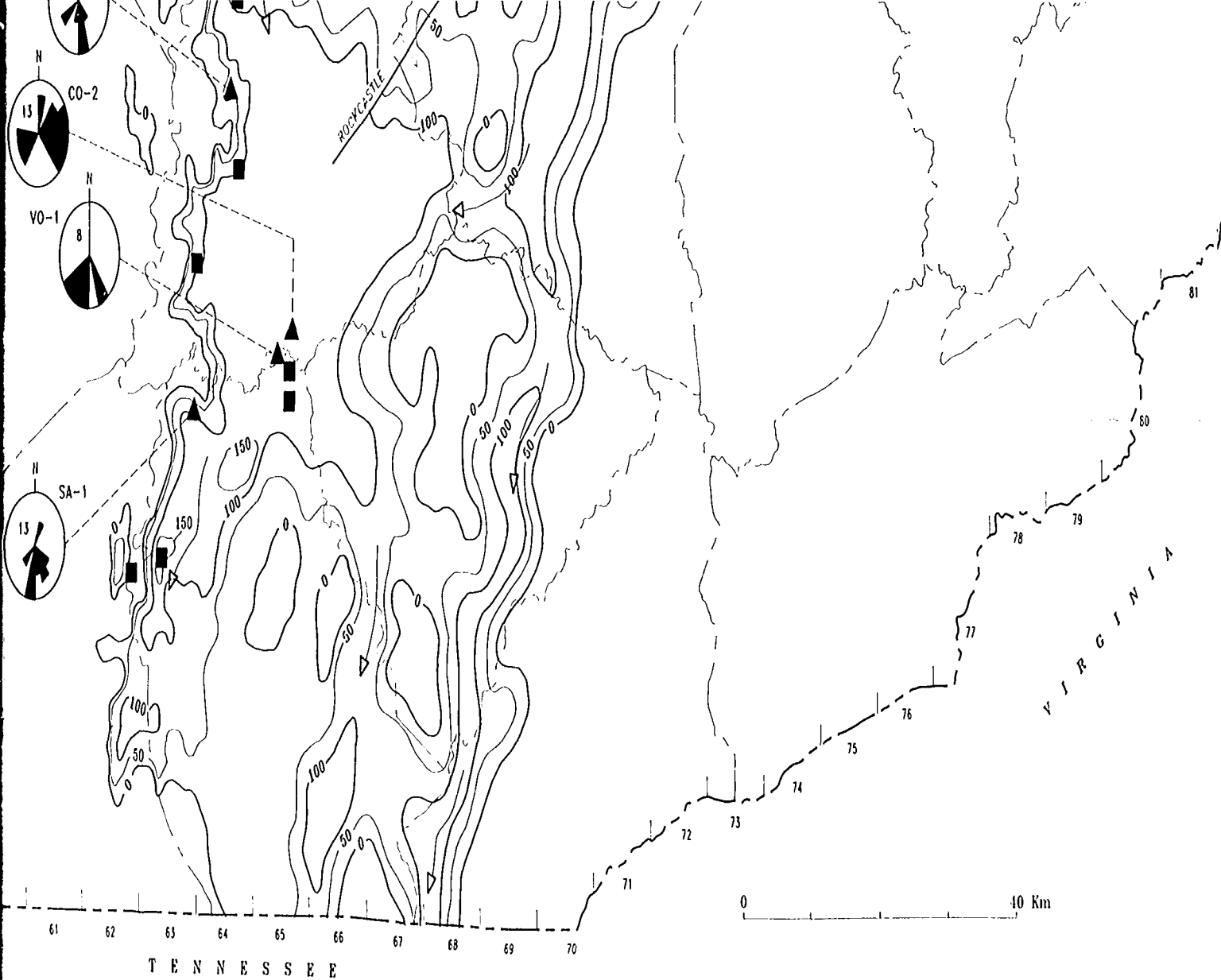
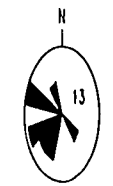


PLATE 1, ISOPACH MAP OF THE CORBIN SANDSTONE MEMBER, LEE FORMATION, EASTERN KENTUCKY

By Mark Barnhill
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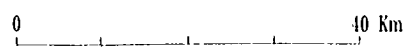
EXPLANATION

- ▲ Measured sections
- Other outcrops examined
- Paleodispersal trends



Paleocurrent Rose Diagram

Contour interval = 50 feet



BARNHILL, MARK L.
9424549 c 1994