

**Tidal Sedimentation in the Mid-Pennsylvanian Breathitt Group,  
eastern Kentucky**

by

Rhonda M. Adkins

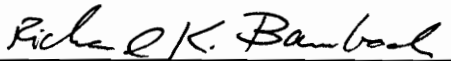
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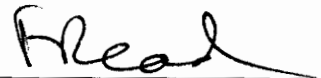
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# **TIDAL SEDIMENTATION IN THE MID-PENNSYLVANIAN BREATHITT GROUP, EASTERN KENTUCKY**

by

Rhonda M. Adkins

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(ABSTRACT)

The Magoffin Member (Four Corners Formation, Breathitt Group) outcrops in eastern Kentucky as a coarsening-upward succession of rhythmically interstratified sandstone, siltstone, and mudstone. Primary sedimentary structures, trace fossils, vertical successions of facies, and sediment body geometries suggest that these sediments were deposited in a delta-front/distributary-mouth-bar setting. Within the study area, the Magoffin Member ranges in thickness from 20 to 40 m. Where thickest, the Magoffin Member tends to be sandier and contain rhythmite intervals that are thicker and more complete than where it is thin. The member displays several orders of cycles that are consistent with semi-diurnal, diurnal, semi-monthly, and monthly tidal periodicities. Half-synodic (semi-monthly) and anomalistic (monthly) lunar periodicities are manifested by the systematic thickening and thinning of shorter duration cycles. The rhythmite interval records up to 4 months of deposition. Accumulation rates for the rhythmites typically ranged from 1 to 7 cm per day, but reached rates of over 30 cm per day where the Magoffin Member is thickest and the most proximal deltaic facies are preserved. Tidal cyclicity was also studied within the Betsie Shale and Kendrick Shale Members of the Breathitt Group. The Betsie Shale Member displays semi-diurnal through monthly tidal cycles. The Kendrick Shale Member displays semi-diurnal through semi-monthly tidal cycles. The nature of tidal bundling within the Breathitt Group rhythmite successions suggests that they accumulated in mixed, predominantly semi-diurnal tidal systems where lunar phases and declination influenced tidal cyclicity.

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## INTRODUCTION

The recognition of tidal rhythmites has been one of the most important advancements in sedimentology in recent years. Tidal rhythmites are packages of laminated to thin-bedded, vertically accreted sandstones, siltstones, and mudstones which display cyclic variations in bed and lamina thickness and in grain size (Williams, 1991). These variations can be attributed to strong tidal influences on sedimentation and reflect differences in tidal velocities forced by earth/moon/sun orbital parameters (Lanier, Feldman, and Archer, 1993)

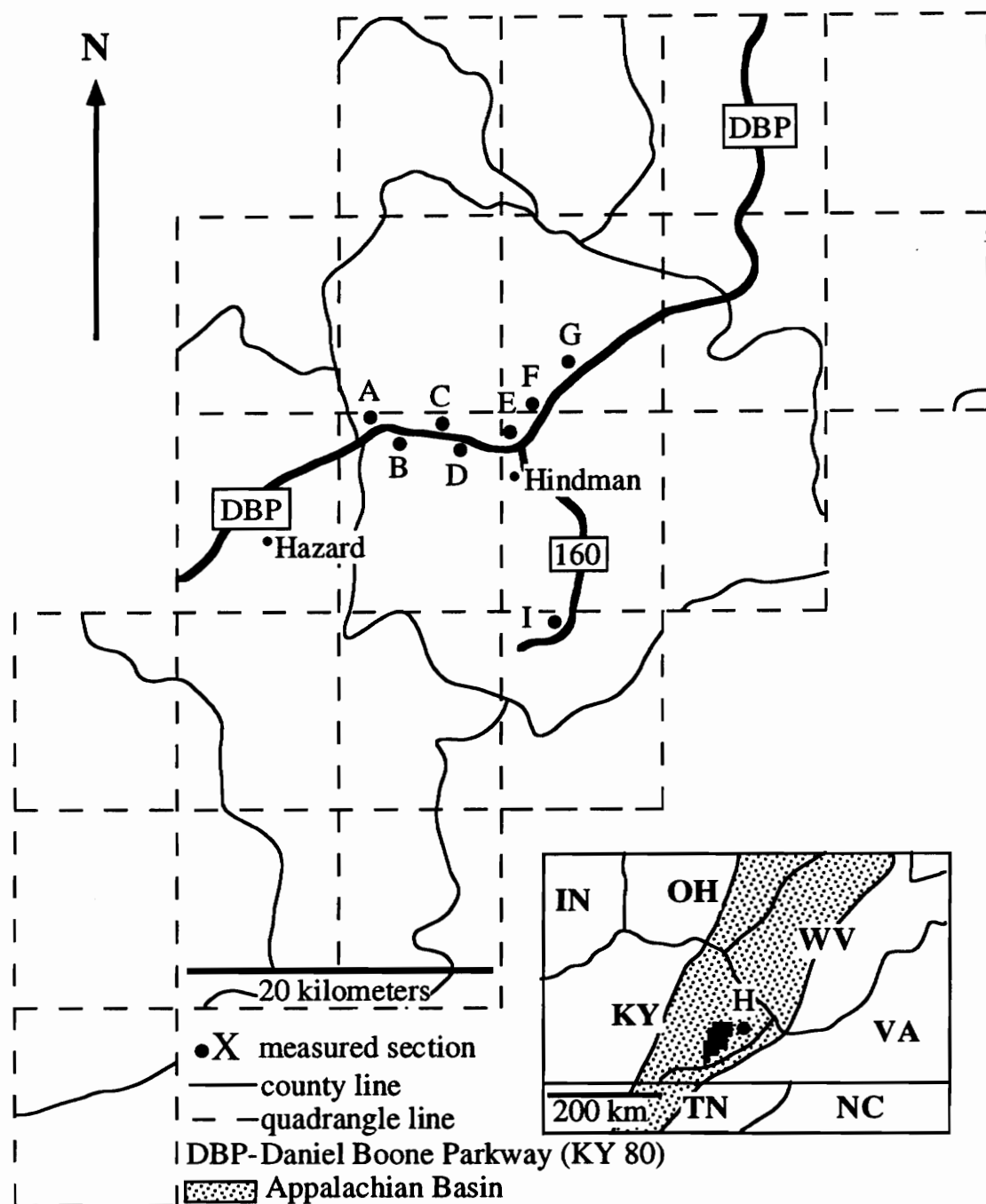
Siliciclastic tidal rhythmites have been identified from a range of geologic time periods, including from the Proterozoic of Australia (Williams, 1989, 1990) and the western United States (Chan et al., 1994); the Carboniferous of southeastern England (Allen, 1981) and the eastern United States (Kvale et al., 1989; Kvale and Archer, 1991; Martino and Sanderson, 1993; Greb and Archer, 1995); the Jurassic of the western United States (Kreisa and Moiola, 1986); and the Tertiary of France (Tessier and Gigot, 1989). Modern tidal rhythmites also have been reported from the Bay of Fundy (Dalrymple et al., 1990, 1991); Schoorl dam, NW Netherlands (Roep, 1991); and Mont-Saint-Michel Bay (Tessier, 1993). Well-preserved tidal rhythmites provide high-resolution depositional records of paleotidal periodicities and the evolution of the earth-moon system (Williams, 1991; Sonnet et al., 1996). Such quantitative information has greatly added to our knowledge of the earth's rotational history (Sonnet et al., 1996) which was previously based largely upon growth banding of marine invertebrate fossils (e.g., Wells, 1963; Scrutton, 1964; Lamar and Merifield, 1966; Panella et al., 1968). Rhythmites have proven to be useful paleoenvironmental indicators, providing evidence of marine processes in the form of tidal rhythms in fine-grained nonfossiliferous facies. Absolute rates of local sedimentation also can be deduced from these successions

(Williams, 1989). Recent work on rhythmites within Carboniferous strata of the Mid-continent and eastern U.S.A. indicates that these successions are often characterized by rapid sedimentation rates and provide relatively complete records of continuous deposition, ranging from several months to tens of years (Kvale and Archer, 1990; Miller and Eriksson, 1997).

The mid-Pennsylvanian Breathitt Group of eastern Kentucky has traditionally been interpreted as a fluvio-deltaic deposit (e.g., Cobb et al., 1981; Tankard, 1986). The Breathitt Group contains several intervals of rhythmically interstratified sandstone, siltstone, and mudstone, up to 20 m thick. One of these rhythmic intervals, within the upper portion of the Magoffin Member (Four Corners Formation; Breathitt Group), is the main focus of this study. Within this interval, a record of tidal cyclicity is manifested by a systematic thickening and thinning of mudstone-draped sandstones. This interval provides a relatively short (up to 4 months) but complete record of mid-Pennsylvanian, ebb-tidal activity and displays laminae-bundling patterns that are consistent with semi-diurnal, diurnal, semi-monthly, and monthly tidal periodicities. This paper discusses the nature of these depositional cycles and demonstrates that the thickest and most complete depositional cycles are developed where the Magoffin Member is the thickest. Similar intervals within the Betsie Shale Member of the Pikeville Formation and the Kendrick Shale Member of the Hyden Formation (Breathitt Group; eastern Kentucky) also will be briefly discussed.

#### METHOD OF STUDY

This study is primarily based upon field investigations of the Magoffin Member where it is exposed in a series of roadcuts along KY 80 and other secondary roads in Knott County, Kentucky (locations A through G; Fig. 1). These outcrops were logged



**FIG. 1.**—Location map of measured sections of Breathitt Group rhythmites, in eastern Kentucky.

for lithology, fossils, trace fossils, sedimentary structures including laminae and bed thickness variations, vertical stacking of facies, and sediment body geometries.

Locations A through G were measured from the base of the Magoffin Member (where identifiable) up to the overlying fluvial-channel deposits to determine lateral thickness variations of the Magoffin Member within the study area. Sub-surface (strip-log) data also was gathered from 21 surrounding quadrangles to determine areal thickness variations of the Magoffin Member. Exposures of the Magoffin Member exhibit well-defined decimeter- to meter-scale cyclicity. Cycles were analyzed to determine the number of layers per neap-spring-neap bundle and the variations in laminae and bundle thicknesses. The rhythmite intervals were logged at a millimeter-scale at five locations (A, C, D, E, and G; Fig. 1) along KY 80 (distance between outcrops ranges from 0.25 to 3.0 km) to determine lateral changes in rhythmite thicknesses and bundling patterns. Detailed rhythmite analyses were not conducted at locations B and F. For comparison, tidal cycles within the Betsie Shale Member of the Pikeville Formation and the Kendrick Shale Member of the Hyden Formation also were analyzed. The rhythmite interval within the Betsie Shale Member was logged at a millimeter-scale at one location (location H; Fig. 1-inset) on KY 3227. The rhythmite interval within the Kendrick Shale Member was logged at a millimeter-scale at 1 location (location I; Fig. 1) on KY 160. Measurements for all members were plotted on bar graphs to aid in the identification of cyclic patterns. Harmonic analyses using the fast-fourier transform program described by Horn and Baliunas (1986) were performed on the data sets to confirm cyclicities. This program is able to differentiate and separate cycles with closely spaced periodicities as discussed by Archer (1994a). These periodicities are expressed as laminae per cycle.

## TIDAL THEORY

Oceanic tides generate currents that are capable of transporting, eroding, and depositing sediment. Rhythmically-bedded, small-scale sedimentary structures, referred to as tidal rhythmites, record tidally-influenced deposition (Kvale et al., 1996). Individual tidal events are represented by fining-upward sandstone/mudstone couplets. These couplets often bundle into systematically thickening and thinning packages that are consistent with known tidal periodicities.

### *Paleorotation of the Earth*

Tidally-influenced deposits record short-term (semi-diurnal through yearly) and long-term changes in the earth-moon-sun rotational system. One long-term change that can be recorded by tidal rhythmite sequences is the gradual decrease in the rate at which the earth rotates (cf., Williams, 1991; Sonnet et al., 1996). The Late Proterozoic year contained 400 solar days, while the modern year contains 365 solar days (Williams, 1991). However, during this time period, the number of days per month has not changed significantly. The Late Proterozoic month contained 30.5 solar days while the modern month contains 29.5 solar days (Williams, 1991). It can be assumed that the difference in the number of days per month between the Mid-Pennsylvanian (~300 Ma) and the present is less than 1 and therefore is inconsequential for this study. Since these rhythmic intervals have been interpreted as mixed tidal deposits (see *Tidal Settings* below) and probably do not provide a complete record of tidal inundations, the number of days per semi-monthly cycle has been estimated to be 14 (two weeks). This estimation should simplify analyses in this study without interfering in the identification of preserved tidal cycles.

### *Tidal Settings*

Tidal systems can be classified as diurnal, semi-diurnal, or mixed (cf., Dalrymple, 1992). In a diurnal system, there is one tidal inundation per day. In a semi-diurnal system, there are two tidal inundations per day. Most tidal systems are mixed, averaging more than 14 but less than 28 tidal inundations per fortnight (semi-monthly cycle).

Usually, one couplet is deposited per tidal inundation, recording either ebb or flood tidal flow. Therefore, in a diurnal system, up to 14 couplets can be deposited per fortnight; in a semi-diurnal system, up to 28 couplets can be deposited per fortnight; and in a mixed system, somewhere between 14 and 28 couplets can be deposited per fortnight (cf., Dalrymple, 1992).

### *Tidal Cyclicality*

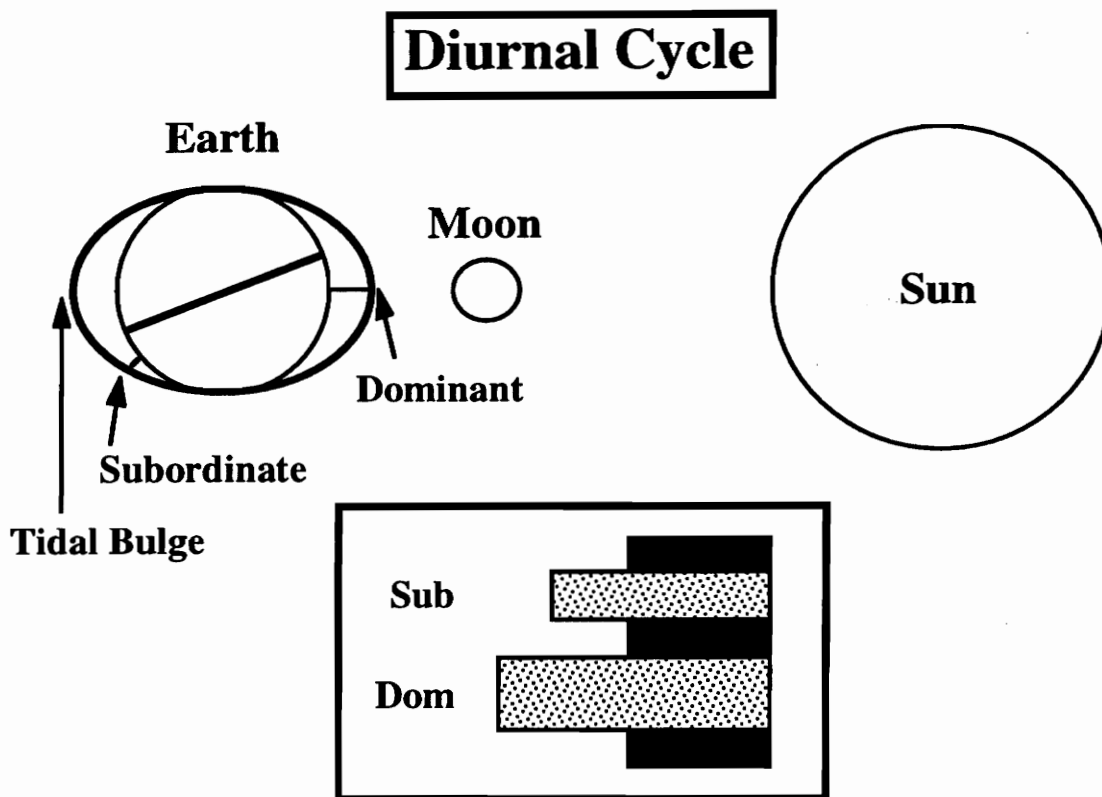
Rhythmite successions within the Breathitt Group are interpreted to have been deposited in subtidal, mixed, semi-diurnal tidal settings. Up to four orders of tidal cyclicality are preserved by these rhythmite successions: semi-diurnal, diurnal, semi-monthly, and monthly.

*Semi-diurnal Cycle:* The gravitational attraction of the moon and sun generates periodic fluctuations in water level on the earth's surface. These fluctuations are known as tides. The most commonly observed period for one complete tidal cycle is the semi-diurnal cycle (cf., Dalrymple, 1992). During peak tidal flows, usually silt- to sand-sized sediment can be deposited from plumes. During the subsequent slackwater phases, thin mudstone drapes may accumulate from suspension fallout over the sandy layers (Kvale

et al., 1989). Where only the ebb or flood tidal flow is recorded, each semi-diurnal cycle is represented by one sandstone/mudstone couplet.

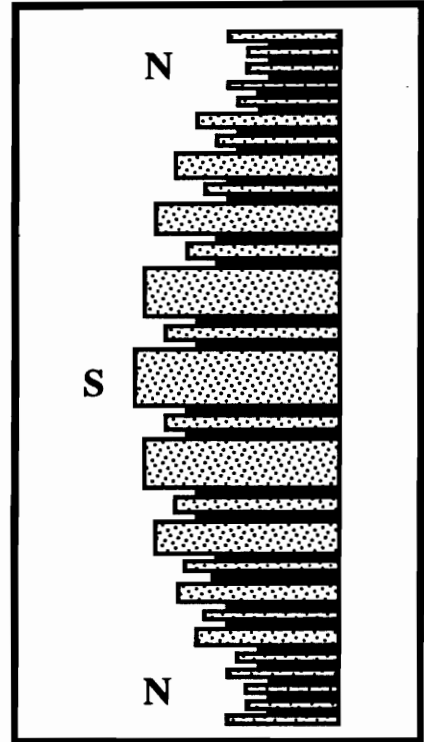
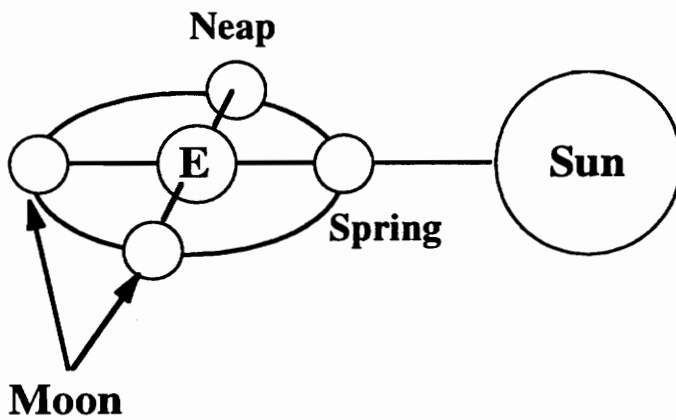
*Diurnal Cycle:* The gravitational attraction of the moon and sun upon oceanic water masses, combined with a centrifugal force resulting from the rotation of the earth and moon around their common center of gravity, causes two centers of tidal heaping to occur on the Earth's surface (e.g., De Boer et al., 1989; Dalrymple, 1992; Fig. 2). The points of maximum tidal bulge are aligned with the position of the moon relative to the earth. Since the earth spins on an inclined axis, any given point on its surface will usually be subjected to two unequal tidal forces within a 24 hour period. Resulting tidal currents of unequal velocity can produce thick/thin pairs of rhythmite couplets (cf., De Boer et al., 1989; Kvale et al., 1989). The thick/thin pairing of individual couplets is demonstrative of the diurnal inequality of the tide found within mixed, predominantly semi-diurnal tidal settings (cf. Kvale et al., 1989). As lunar declination changes, the relative thickness of each semi-diurnal couplet should also change.

*Semi-monthly Cycle:* Semi-monthly neap-spring-neap cycles reflect the half-synodic lunar orbit around the earth (Allen, 1981; Fig. 3). Thick spring couplets develop during periods of syzygy when the earth, moon, and sun are aligned (Lanier et al., 1993; Kvale et al., 1995). During these periods gravitational attraction and therefore tidal forces are at a maximum. Thin neap couplets develop at times of minimum gravitational attraction (Lanier et al., 1993) and minimum tidal forces when the earth, moon, and sun form a right angle (Kvale et al., 1995). There are approximately 14 days between subsequent syzygies. Approximately 28 tidal inundations are expected per fortnight (two per day for 14 days) in subtidal, mixed, predominantly semi-diurnal settings



**FIG. 2.**—Diagram of diurnal cyclicality. The thick/thin pairing of semi-diurnal couplets is demonstrative of the diurnal inequality of the tide. Two centers of tidal heaping occur on the Earth's surface due to gravitational attraction of the sun and the moon. Any given point on the earth's surface will usually be subjected to two unequal tidal forces within a 24 hour period, resulting in the deposition of thick/thin pairs of rhythmite couplets. Diagram adapted from Kvale et al. (1995).

## Semi-monthly Cycle Synodic Month

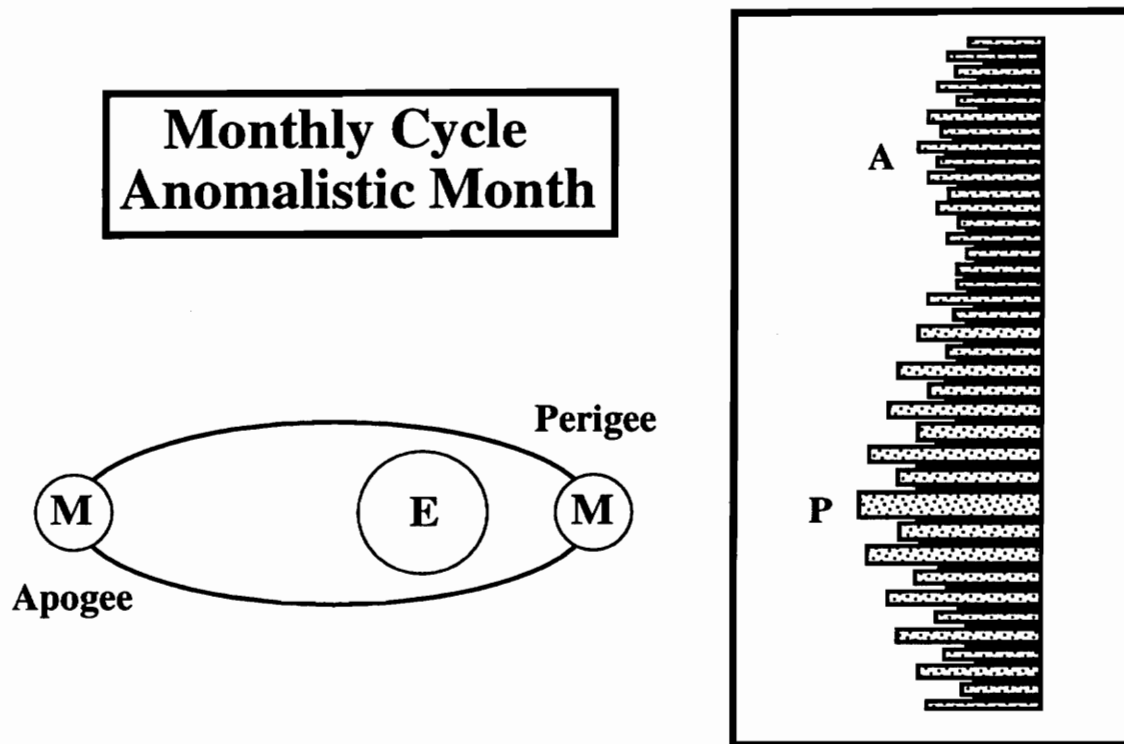


**FIG. 3.**—Diagram of semi-monthly cyclicality. Semi-monthly neap-spring-neap cycles reflect the half-synodic lunar orbit around the earth. Thick spring couplets develop when the earth, moon, and sun are aligned. Thin neap couplets develop when the earth, moon, and sun form a right angle. Diagram adapted from Kvale et al. (1995).

(Dalrymple, 1992). Therefore, up to 28 individual couplets may be preserved (two per day for 14 days) per neap-spring-neap event.

*Monthly Cycle:* Many consecutive, neap-spring-neap bundles display a thick/thin relationship. This thick/thin relationship reflects the anomalistic monthly periodicity of the moon which is based upon its elongated elliptical orbit around the earth (Fig. 4). Perigean (minimum lunar distance) periods are characterized by higher than average tides due to increased gravitational attraction. During perigean periods, relatively thick neap-spring-neap bundles are deposited. Apogean (maximum lunar distance) periods, in contrast, are characterized by lower than average tides due to decreased gravitational attraction. During Apogean periods, relatively thin neap-spring-neap bundles are deposited (Archer et al., 1991; Kvale et al., 1995).

*Preservation of Ebb and Flood Tidal Flows:* Occasionally, both the ebb and flood tidal flows are recorded (cf., Archer, 1994b). In a mixed, predominantly semi-diurnal tidal setting, each semi-diurnal cycle is then represented by two sandstone/mudstone couplets (one deposited during the ebb tidal flow; one deposited during the flood tidal flow). Up to four sandstone/mudstone couplets can be deposited per day (ebb and flood tidal flows for both the dominant and subordinate tides), and up to 56 couplets can be preserved during one neap-spring-neap event (four per day-two ebb deposits and two flood deposits-for 14 days). Usually, either the ebb or flood tidal flow is stronger, resulting in the deposition of thick couplets relative to the thin couplets deposited during the weaker tidal flow (Archer, 1994b). Couplets deposited by the dominant flow will still display the thick/thin relationship demonstrative of the diurnal inequality of the tides.



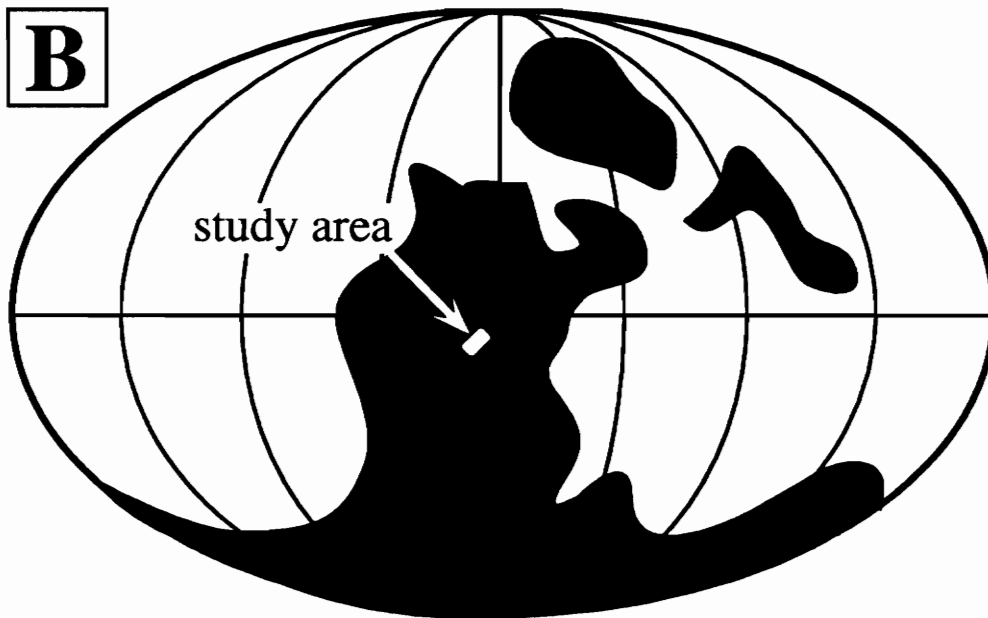
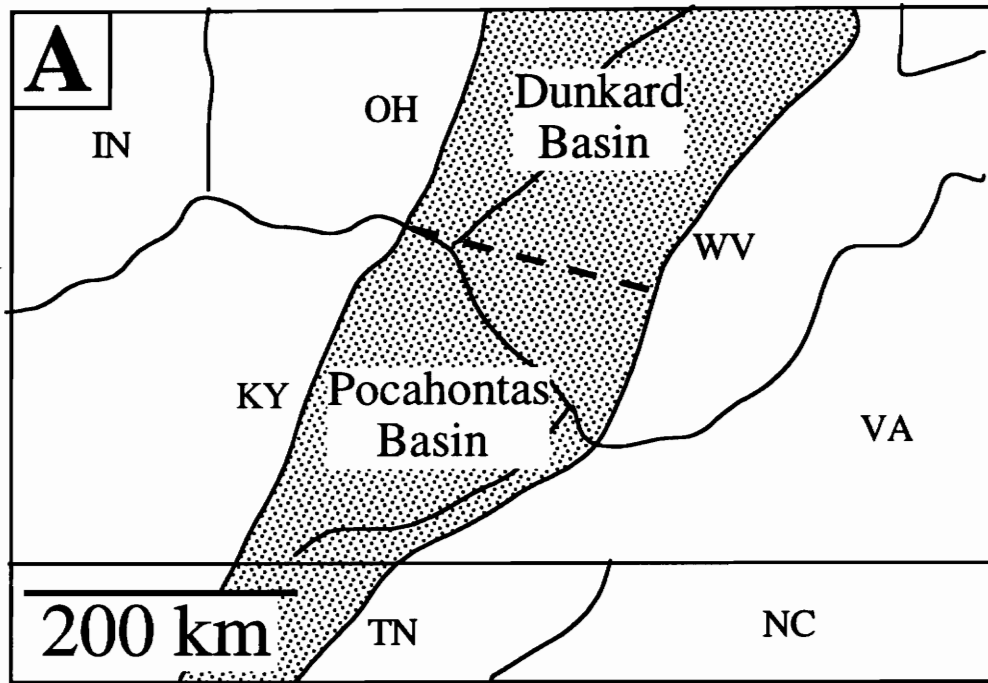
**FIG. 4.**—Diagram of monthly cyclicality. Monthly cycles reflect the anomalistic periodicity of the moon which is based upon its elongated elliptical orbit around the earth. During perigean periods, relatively thick neap-spring-neap bundles are deposited. During apogean times, relatively thin neap-spring-neap bundles are deposited. Diagram adapted from Kvale et al. (1995).

## BACKGROUND INFORMATION ON THE PENNSYLVANIAN SYSTEM OF THE APPALACHIAN BASIN

### *General Geology*

The Appalachian Mountains experienced several episodes of orogenic deformation during the Paleozoic (e.g., Glover, 1989). The Alleghenian Orogeny which spanned from the middle Mississippian to the Permian, was the last of these major deformational events. During the Alleghenian Orogeny, the eastern continental margin of North America collided with west Africa causing up to 12 km of uplift along the Appalachian mountain chain and downwarping of the adjacent basin (Quinlan and Beaumont, 1984; Beaumont et al., 1987; Chesnut, 1991a). Even though deposition of a thick clastic wedge in the central Appalachian Basin provides evidence for the Mid-Mississippian onset of the Alleghenian Orogeny, it was not until the Late Pennsylvanian that continent/continent collision occurred in the central Appalachian region (Chesnut, 1991a).

The central Appalachian Basin consists of two interconnected basins that formed in response to Alleghenian overthrusting. These two basins were centers of subsidence and deposition during the Alleghenian Orogeny (Fig. 5). The Dunkard Basin, located in present-day West Virginia, Ohio, and Pennsylvania, primarily contains strata that are Late Pennsylvanian to Permian in age (Donaldson et al., 1985). The Pocahontas Basin, bounded by the Appalachian fold and thrust belt to the southeast and the Cincinnati-Waverly Arch to the northwest (Tankard, 1986), is located in present-day Kentucky, Tennessee, Virginia, and West Virginia. It is approximately 100 to 150 km wide (Chesnut, 1991a) and contains strata that are mostly mid-Mississippian to mid-Pennsylvanian in age (Donaldson et al., 1985).



**FIG. 5.**—Paleogeographic maps of the central Appalachian depositional basins during the Mid-Pennsylvanian. A) Map showing the location of the Dunkard and Pocahontas Basins. B) Map showing the position of the basins relative to the equator. Both diagrams adapted from Bennington (1995).

### *General Stratigraphy*

Within most of the Pocahontas Basin, Lower Pennsylvanian strata unconformably overlie the Upper Mississippian Pennington Group (Fig. 6). The Pennington Group is a heterogeneous unit of red, green, and gray shale, sandstone, limestone, and dolostone with rare, thin coal seams. The red and green shales and lack of well developed coals distinguishes the Mississippian Pennington Group from overlying Pennsylvanian strata (Chesnut, 1992).

During Early Pennsylvanian time, downwarping of the basin resulted in the development of a northeast to southwest flowing river system in Virginia, Kentucky, and Tennessee. This river system deposited broad belts of fluvial sands over the regional lower Pennsylvanian unconformity (Rice, 1984; Tankard, 1986; Chesnut, 1992). Marginal marine facies were deposited at the tops of each of these fluvial sandstones as relative sea-level rose and an associated decrease in extra-basinal sediments led to the development of local estuaries and marine reworking (Greb and Chesnut, 1996). These thick fluvial deposits, predominantly consisting of quartzose sandstone and quartz pebble conglomerates (Bennington, 1996; Chesnut, 1992), interfinger with developing coal-bearing deposits of the Breathitt Group (Bennington, 1996). These coal-bearing units consist of repetitive sequences of mudstone, siltstone, sandstone, coal, and underclay with minor occurrences of limestone and flint clay (Chesnut, 1989; Englund, 1979). The Norton Formation of Virginia and the Pocahontas and New River Formations of West Virginia are the stratigraphic equivalents of these coal-bearing sequences of the lower Breathitt Group (Henry et al. 1991).

By Mid-Pennsylvanian time, the Pocahontas basin was covered by a shallow epicontinental sea (Englund and Thomas, 1989) and was being filled by siliciclastic debris from the adjacent Appalachian highlands. Repetitive coal-bearing strata of the

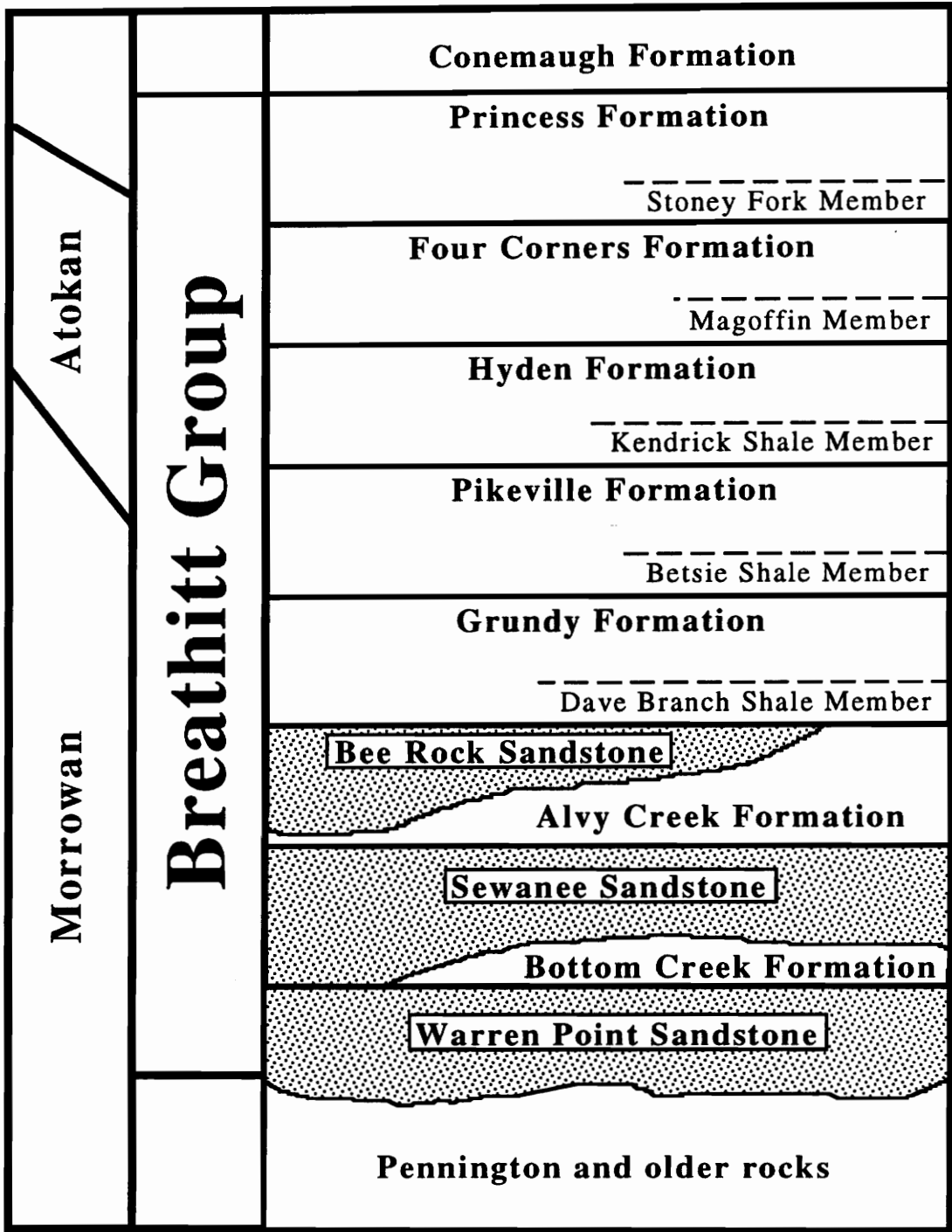


FIG. 6.—Stratigraphic framework of Pennsylvanian rocks in eastern Kentucky. Thick sandstone units subdivide the lower Breathitt Group and widespread marine units, such as the Magoffin, Kendrick Shale, and Betsie Shale Members, subdivide the Upper Breathitt Group into constituent formations. Diagram adapted from Chesnut (1992).

Breathitt Group were deposited in eastern Kentucky (Chesnut, 1992) along with the stratigraphically similar Norton and Wise Formations of Virginia and the Kanawah and Allegheny Formations of West Virginia (Henry et al., 1991). Glacio-eustatic sea-level changes resulted in these sediments being deposited in a basin that fluctuated between underfill (restricted marine) and overfill (nonmarine) conditions. Sediment transport was predominantly west to northwest (Englund and Thomas, 1989). By upper Middle Pennsylvanian time, the deposition of thick fluvial sands was once again prominent throughout the basin (Miller, 1979; Arkle et al., 1979).

Upper Pennsylvanian strata of the Pocahontas Basin in Kentucky and West Virginia consist of the Conemaugh and Monongahela Formations (Fig. 6; Chesnut, 1992). The Conemaugh Formation is marked by the appearance of green shales. It contains less mineable coal and less dark carbonaceous material than the underlying formations (Rice et al., 1980). The Conemaugh Formation grades upsection into the Monongahela Formation which marks a return of more calcareous lithologies, fresh water limestone, dark shales, and mineable coals similar to Middle Pennsylvanian strata (Arndt, 1979; Arkle et al., 1979).

### *Pennsylvanian Paleogeography*

During the Middle Pennsylvanian, North American coal was deposited in humid equatorial regions, while evaporites were deposited in more northern arid regions (Witzke, 1990). The abundance of Mid-Pennsylvanian coal within the Pocahontas Basin indicates that it was located at tropical latitudes (between the equator and 15° south latitude) during this time (Scotese and McKerrow, 1990; Fig. 5). Although North America appears to have drifted slowly northward throughout most of the Late Paleozoic, the Pocahontas Basin remained between 15° south and north

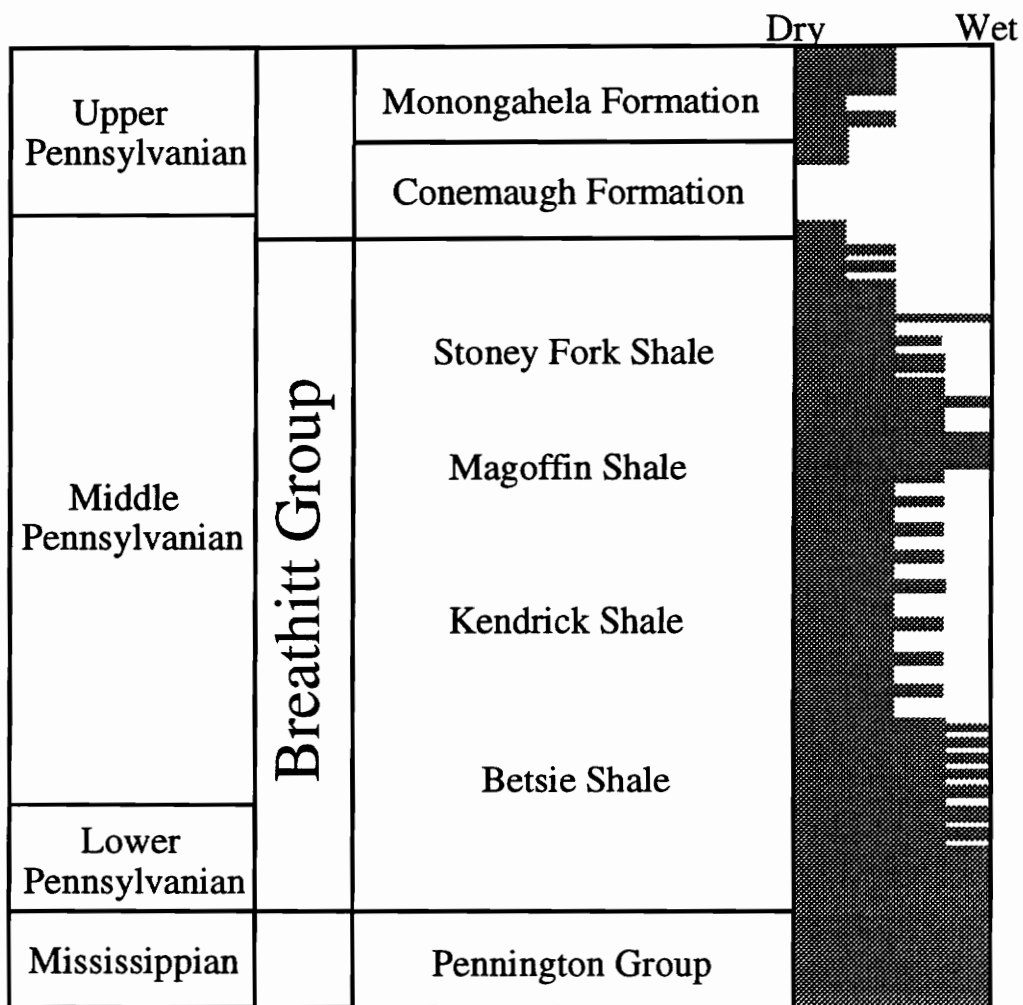
latitude from the Early Pennsylvanian until sometime in the Early Triassic (Scotese and McKerrow, 1990).

### *Paleoclimatology of the Pennsylvanian*

Pennsylvanian strata of the Pocahontas Basin record a complex history of climate change (Fig. 7). The arid seasonal climate of the Mississippian became increasingly ever-wet as the continent drifted into low tropical latitudes at the beginning of the Pennsylvanian (Cecil, 1990). Cecil proposed (1990) that changes in sedimentation resulted from changes in the seasonal balance between relatively wet and dry times. During wet periods, extensive coal swamps developed. However, during alternating wet/dry periods, large volumes of clastic material were transported into the basin preventing the accumulation of organic matter.

Late Mississippian deposits contain many arid climate indicators, such as thin impure coals, lacustrine limestones, gray-red calcareous shales, nodular caliche-like paleosols, and a xerophytic paleoflora (Cecil, 1990; Cecil et al., 1985; Donaldson et al., 1985). By the early Pennsylvanian, the presence of thick, low-ash, low-sulfur coals combined with the occurrence of more abundant gray sandstone, siltstones, and shales marks the transition into an ever-wet climate (Cecil; 1990; Cecil et al., 1985). Lower to Middle Pennsylvanian non-marine strata also contain abundant siderite with little pyrite or calcium carbonate, indicating a wet depositional environment (Cecil et al., 1985).

At the beginning of the Late Pennsylvanian, the disappearance of thick, low-ash, low-sulfur coals, an increasing occurrence of calcareous and pyritiferous non-marine strata, and the presence of splint coals and alumina-rich clays mark the return of a more arid climate (Cecil et al., 1985). The upper Pennsylvanian Conemaugh Formation contains arid climate indicators such as red, green, and gray siltstones and shales (Rice,



**FIG. 7.**— Pennsylvanian climate change in the central Appalachian Basin plotted against the eastern Kentucky stratigraphic column. Diagram adapted from Bennington (1995).

1986), sub-aerial exposure features, calichefied paleosols, and thin, discontinuous, high sulfur, high ash coals (Cecil et al., 1985).

The Upper Pennsylvanian Monongahela Formation once again records the return to wetter conditions (Fig. 7). Abundant, thick, laterally-extensive coal beds and fresh water limestones (Donaldson et al., 1985) mark this transition. The absence of caliche-type paleosols also provides evidence that the climate was much wetter (Cecil et al., 1985).

Cyclothem-scale cyclic lithological variations within the Pocahontas Basin can be correlated with cyclothem-scale cyclic variations of the Eastern Interior. This correlation indicates that cycles within the Appalachian basin may, at least in part, represent continent-wide climatic (Phillips and Pepper, 1984) and/or glacio-eustatic fluctuations (Heckel, 1983).

### *The Breathitt Group*

The Breathitt Group, of Early to Mid-Pennsylvanian age, outcrops along the western edge of the Pocahontas Basin in eastern Kentucky, northern Tennessee, and southwestern West Virginia. It consists of repetitive, coarsening-upward sequences of shale, coal, siltstone, and argillaceous and lithic sandstone with minor occurrences of limestone and siderite (Chesnut, 1992). The Breathitt Group which reaches a thickness of up to 950 meters in parts of eastern Kentucky (Wanless, 1975), contains the majority of the coal found within the central Appalachian Basin (Chesnut, 1992). At the base of the Breathitt Group, four thick orthoquartzose sandstone bodies (previously assigned as members of the Lee Formation but now considered to be members of the Breathitt Group) interfinger with the more typical coal-bearing strata of this group (Fig. 6). These sandstone bodies, as well as several widespread transgressive marine units, can

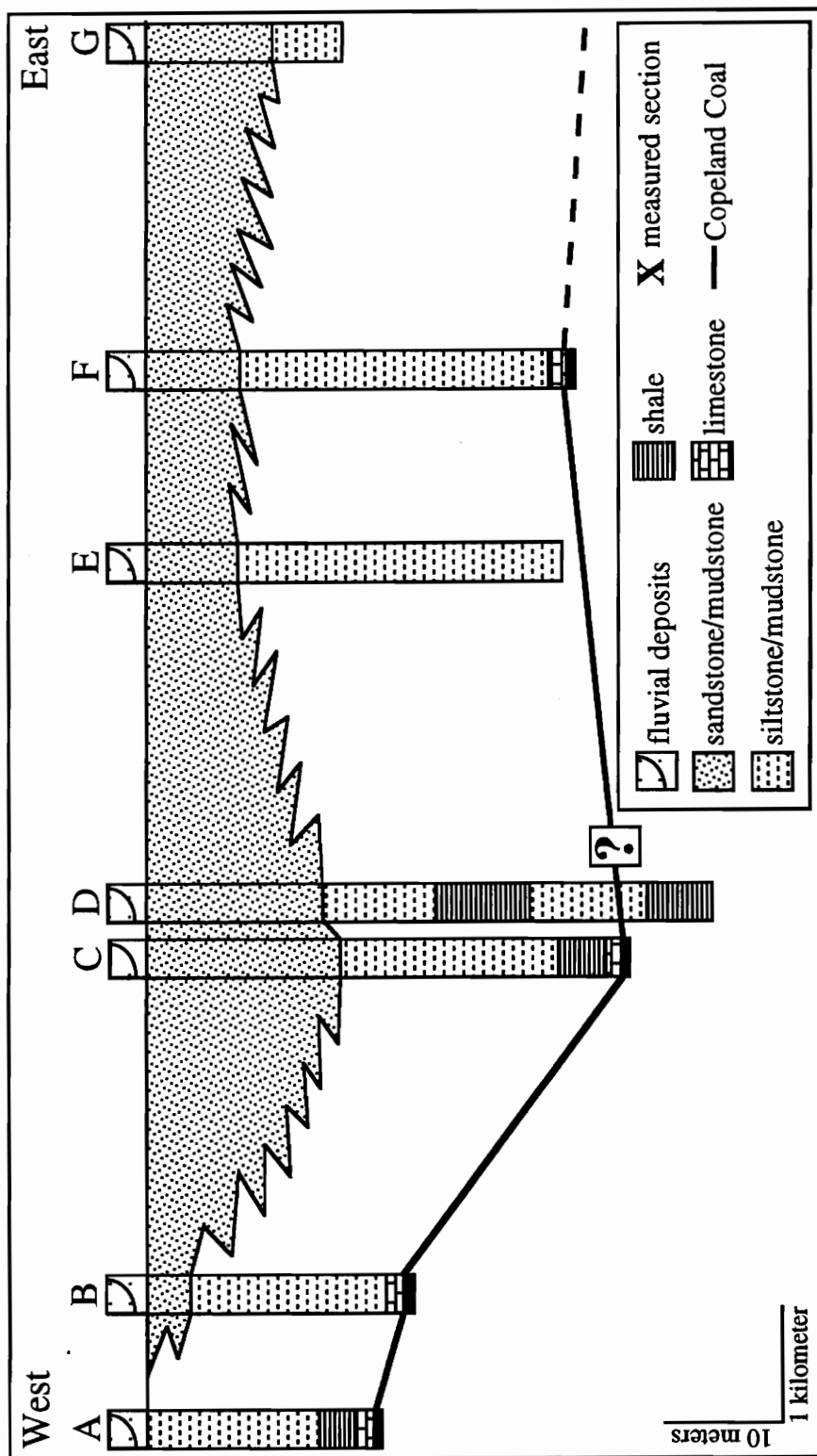
be used to divide the coal-bearing strata into eight formations of approximately equal thickness (Chesnut, 1992; Fig. 6). The orthoquartzose sandstones divide the lower part of the Breathitt Group into the Pocahontas, Bottom Creek, Alvy Creek, and Grundy Formations whereas the widespread marine members divide the upper portion of the Breathitt Group into the Pikeville, Hyden, Four Corners, and Princess Formations. The Pocahontas Formation does not outcrop in eastern Kentucky (Chesnut, 1991b; Chesnut, 1992). The Magoffin Member, located at the base of the Four Corners Formation (Fig. 6), is the most laterally extensive of the marine members. It differentiates the Four Corners Formation from the underlying Hyden Formation (Chesnut, 1992) and contains the rhythmites that are the main focus of this thesis.

For comparison, tidal cyclicity was also studied within two other marine units of the Breathitt Group: the Betsie Shale Member and the Kendrick Shale Member. The Betsie Shale Member, located at the base of the Pikeville Formation, differentiates the Pikeville Formation from the underlying Grundy Formation. The Kendrick Shale Member, located at the base of the Hyden Formation, differentiates the Hyden Formation from the underlying Pikeville Formation (Chesnut, 1991b; Chesnut, 1992; Fig. 6).

## THE MAGOFFIN MEMBER

### *Lithofacies*

Within the study area, the Magoffin Member is typically 25 to 40 m thick and consists of a generally coarsening-upward succession (Fig. 8). The base of the Magoffin Member is placed at a thin (<25 cm) dark, highly fossiliferous limestone, containing marine bivalves, crinoids, brachiopods, and ammonoids, that directly overlies the Copeland Coal Zone. Multi-story, cross-bedded sandstones are located



**FIG. 8.**—Cross-section (east to west) through measured Magoffin outcrops, extending from the underlying Copeland Coal to the overlying incised-valley succession. The thickness of the Magoffin Member is highly variable within the study area. Where it is thickest, a thick succession of interlaminated mudstones and sandstones is developed at the top of the Magoffin Member. The rhythmic packages are thickest and most complete at these locations.

below the Copeland Coal Zone. In the absence of the limestone, the base of the Magoffin is taken to be the top of the Copeland Coal Zone (Dennis, 1975; Chesnut, 1992; Bennington, 1996). The limestone, where present, is gradationally overlain by a 1 to 2 meter-thick layer of dark gray shale with abundant marine fossils (similar to those in the limestone) and disseminated carbonaceous plant fragments. This shale becomes lighter in color towards the top of the 1 to 2 meter-thick interval, and a more shallow-marine depositional environment is indicated by the fauna (Bennington, 1996).

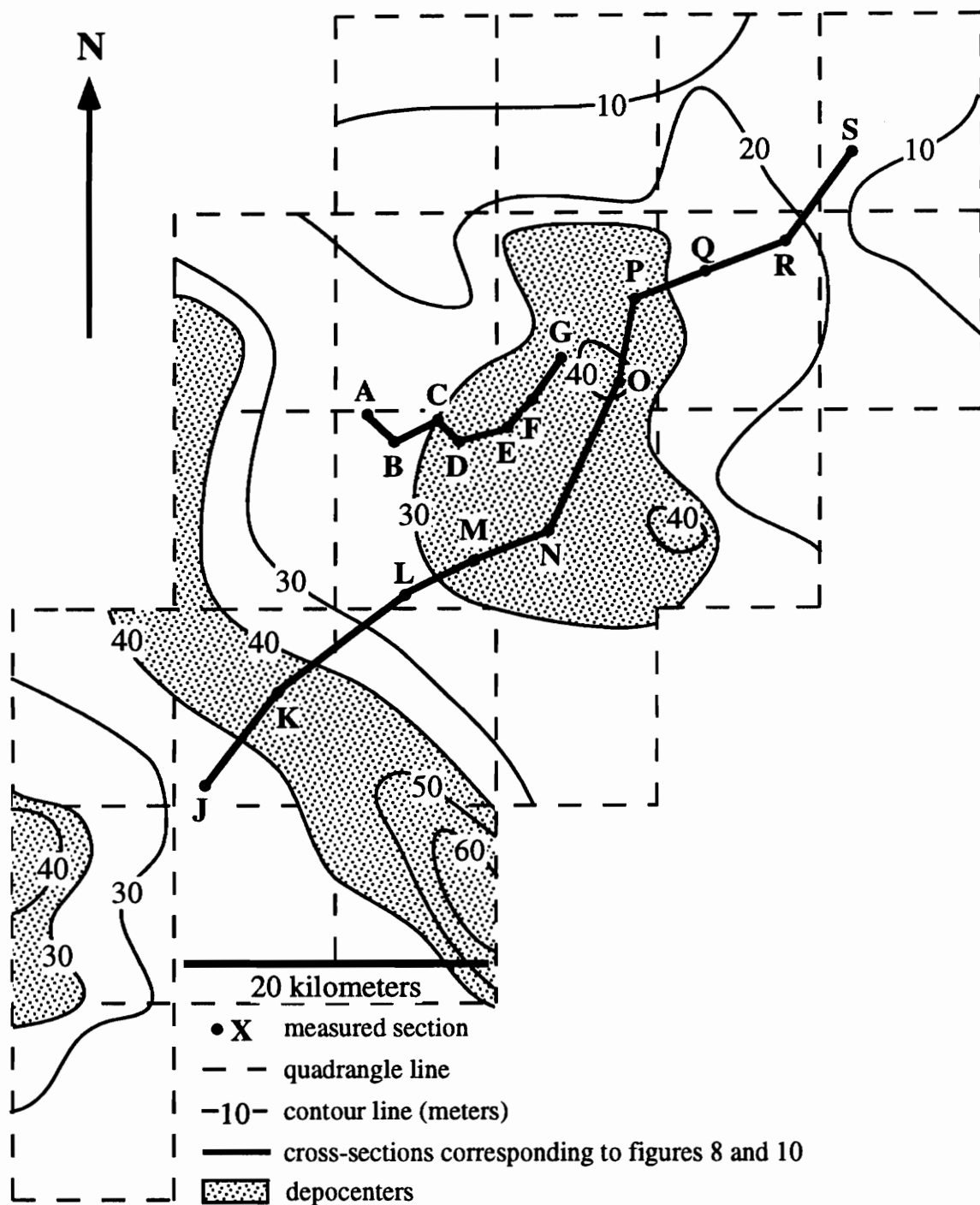
This basal fossiliferous zone is gradationally overlain by a succession of coarsening-upward interstratified mudstones and siltstones up to 30 m thick (Fig. 8). This interval contains abundant siderite concretions, disseminated and carbonaceous plant fragments, and some marine fossils. Thin (up to 2 cm thick), laterally continuous siderite beds and nodular stringers (up to 2 cm thick) occur every few centimeters throughout this interval. Large siderite and limestone concretions, up to 1 by 3 m (Aitken and Flint, 1995), occur along distinct horizons. Bi-directional tool marks located on the bottom of several siltstone beds at location 1 indicate a northwest paleoflow direction (major trend at 315°). There is some evidence of rhythmic cyclicity within this interval, but the beds/laminae are thin and laterally discontinuous making it difficult to obtain thickness measurements.

The succession of interstratified mudstones and siltstones grades upwards into an interval of coarsening upward, rhythmically interstratified mudstones and sandstones up to 20 m thick (Fig. 8). The sandstones are comprised of predominantly subangular quartz grains with abundant mica, and disseminated carbonaceous plant fragments. Individual beds range in thickness from less than 1 cm to greater than 20 cm. At the base, this interval contains some wavy and flaser bedding but towards the top all beds are tabular. Beds have a depositional dip of approximately 5° to the west to northwest

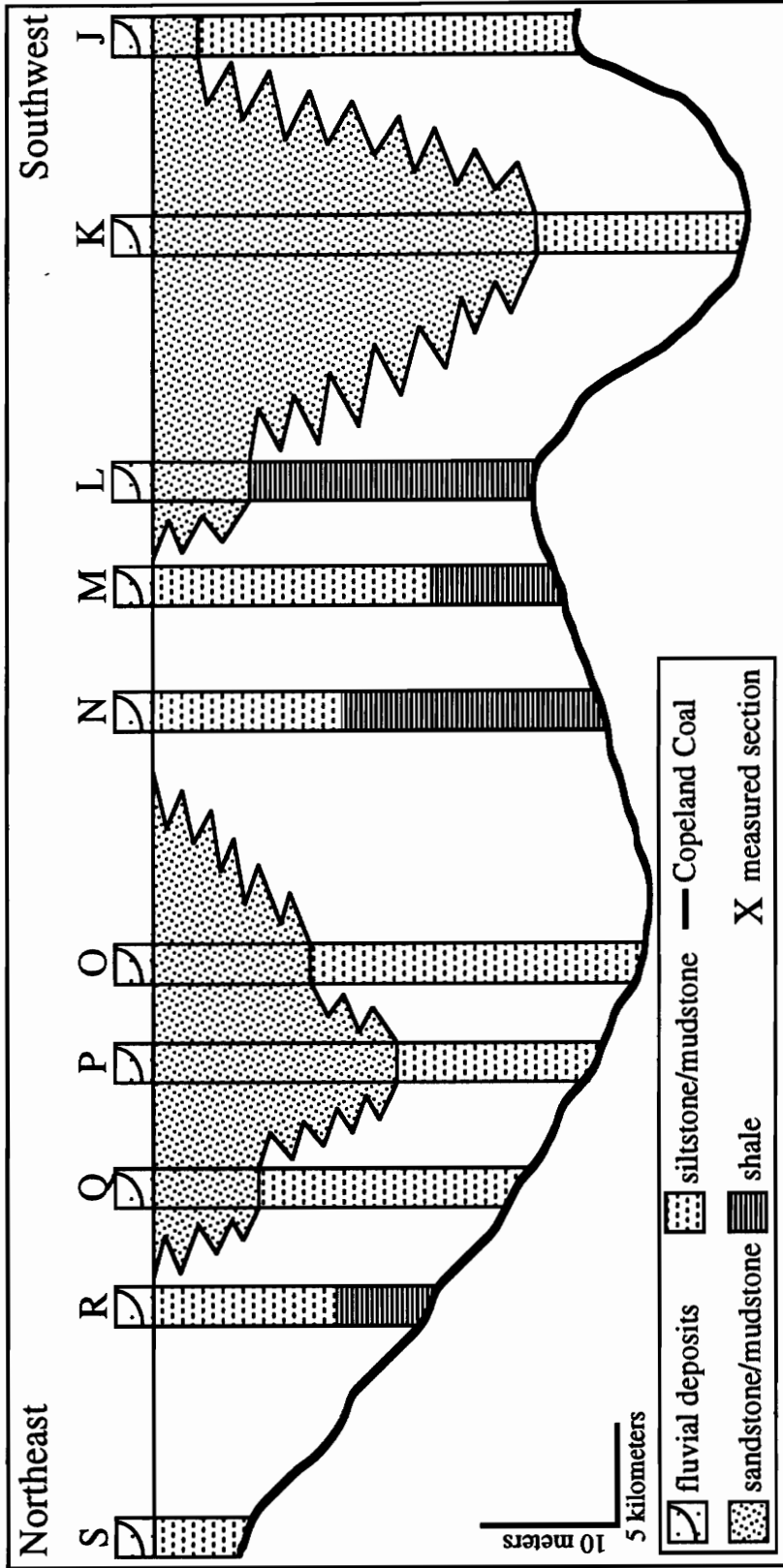
(Aitken and Flint, 1995). Scattered siderite beds occur within this unit but are not as abundant as below. Large-scale siderite concretions, up to 4.5 by 1.5 m (Aitken and Flint, 1995), also occur along distinct horizons. Small-scale dewatering structures are found throughout this interval. Rare climbing ripples, at the base of a few beds, indicate a generally westward paleoflow direction. Vertical and horizontal trace fossils are rarely found within this interval. Vertical tubes (skolithos?) generally occur in layers less than 5 cm thick. Horizontal feeding traces (psammichnites sp.) are also found on the top surfaces of some beds. Multi-story, cross-bedded sandstones, similar to those beneath the Copeland Coal Zone, erosionally truncate the Magoffin Member (Fig. 8). Each sandstone bed is 1 to 5 meters thick. Erosional bounding surfaces separate each sandstone. Pockets of matrix supported pebbles, coal spars, or heavy minerals occur at the base of many of these beds (Aitken and Flint, 1995).

The thickness of the Magoffin Member (from base of limestone or top of Copeland Coal Zone to incised sandstones) is highly variable (Fig. 9). Within the study area, three depocenters are recognizable. Four of the five measured rhythmite outcrops (C, D, E, and G) are located within the northern depocenter. The upper Magoffin Member is sandier where it is thick and muddier where it is thin (Figs. 8 and 10).

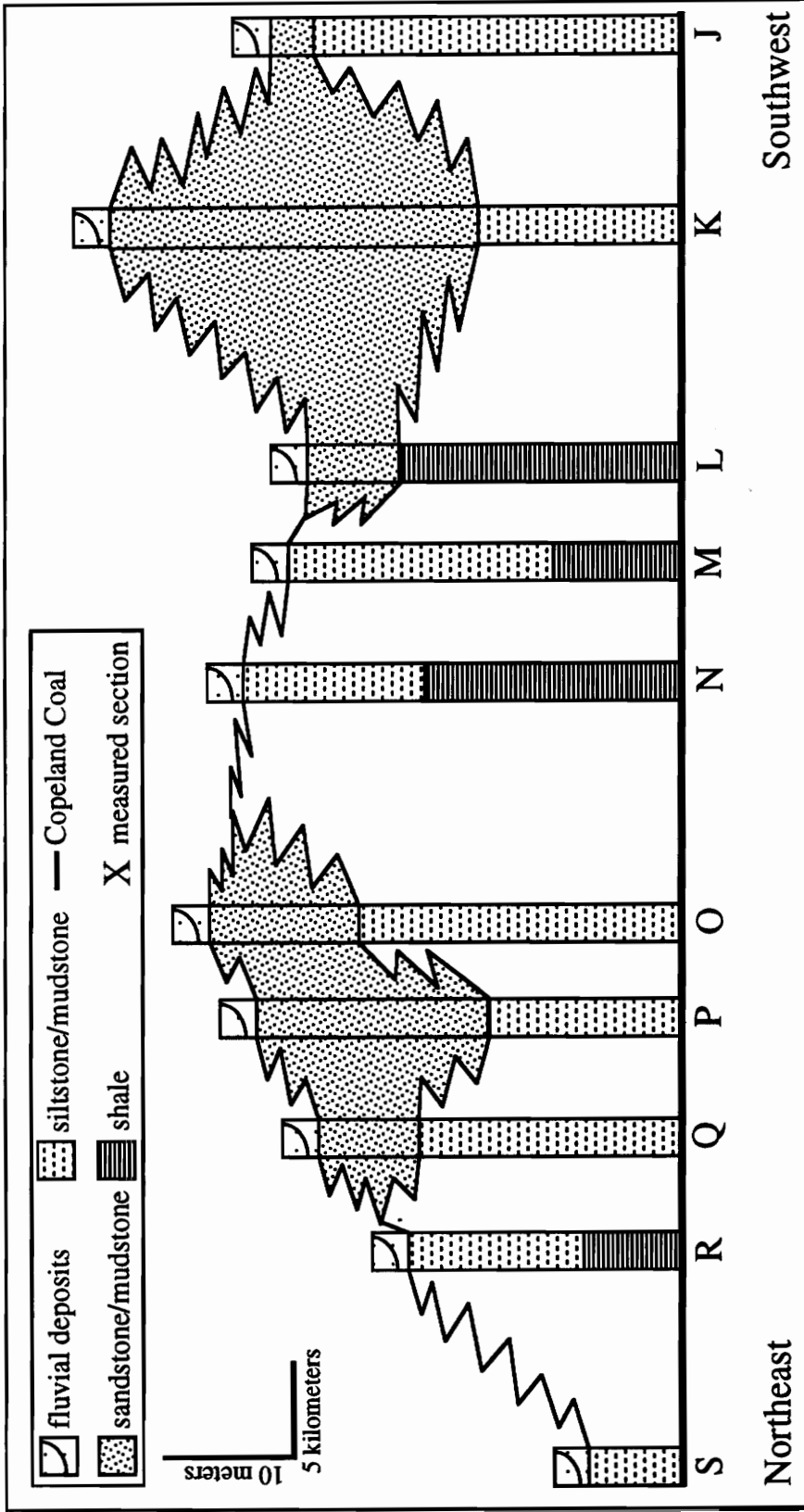
Figure 10 presents a cross-section of the Magoffin Member using two different data. In Figure 10A, the datum is the overlying paleovalley incision surface. This version of the cross-section is consistent with the presentation of Figure 8. The overlying paleovalley incision surface (as opposed to the underlying Copeland Coal) was chosen as the datum in Figure 8 because some of the measured sections (locations E and G) did not extend down to the Copeland Coal. In Figure 10B, the Copeland Coal is the datum. This presents a more realistic interpretation of this data because it depicts the depocenter as mounds instead of basins.



**FIG. 9.**—Isopach map of the Magoffin Member in the study area, showing three depocenters. Most measured Magoffin sections are located within the northernmost depocenter (locations C through G). Line A-G corresponds with Figure 8. Line J-S corresponds with Figure 10.



**FIG. 10A.**—Cross-section (northeast to southwest) through Magoffin Member, based upon sub-surface data. Sections extend from the underlying Copeland Coal to the overlying incised-valley succession. Where it is thickest, a thick succession of interlaminated mudstones and sandstones is developed at the top of the Magoffin Member. No information concerning the rhythmic packages is available for these successions. Datum is overlying paleovalley incision.



**FIG. 10B.**—Cross-section (northeast to southwest) through Magoffin Member, based upon sub-surface data. Sections extend from the underlying Copeland Coal to the overlying incised-valley succession. Where it is thickest, a thick succession of interlaminated mudstones and sandstones is developed at the top of the Magoffin Member. No information concerning the rhythmic packages is available for these successions. Datum is underlying Copeland Coal.

### *Depositional Setting and Sequence Stratigraphy*

The Magoffin Member is a progradational succession that probably represents prodeltaic (basal fossiliferous zone) to delta-front/distributary-mouth-bar (upper rhythmic unit) deposition. The interval from the base of the underlying multi-story sandstones to the base of the overlying multi-story sandstones records the deposition of one fourth-order Milankovitch cycle (400,000 year cycle).

The underlying sandstones are interpreted as stacked fluvial channel deposits. They comprise the majority of a Transgressive Systems Tract, recording a relative rise in sealevel. The lower basal limestone and overlying dark shale represents a condensed section (Bennington, 1996) related to maximum flooding of the depositional interface. Where the dark gray shale becomes lighter in color marks the onset of a relative fall in sealevel.

The section overlying the basal fossiliferous zone has been interpreted as a marine shelf deposit on the basis of its lithological relationships and fossil content (Aitken and Flint, 1995). The tool-marked beds are probably deltaic turbidite deposits. The large concretions are thought to have formed by early diagenetic precipitation of calcite and siderite. They can be used to distinguish marine to brackish from non-marine water deposits (Chesnut, 1981). The upper, non-fossiliferous section has been interpreted as a series of coalesced distributary mouth bars based on lateral facies geometries, the presence of vertical escape burrows and the rhythmic nature of these deposits (Aitken and Flint, 1995) which are herein interpreted as displaying cyclicity consistent with known tidal periodicities. The coalesced distributary-mouth-bar interpretation is consistent with Magoffin thickness variations depicted in Figures 8 and 10, where each area of increased accumulation represents one depocenter. The inclined beds indicate the presence of large-scale clinoforms that prograded towards the

northwest. The Magoffin Member, above the dark shale, probably comprises a Highstand Systems Tract and records a relative fall in sealevel.

The erosional contact between the Magoffin Member and the overlying fluvial sandstones probably marks a fourth order sequence boundary and records the maximum fall in sealevel for this interval (Chesnut, 1989). The overlying thick sandstones are interpreted as stacked fluvial channel deposits that occupy an incised paleovalley (Aitken and Flint, 1995). They represent the base of an upper Transgressive Systems Tract, recording another rise in sealevel. These overlying sandstones also have been interpreted as the deposits of distributary channels (Cobb et al., 1981) and shallow anastomosing streams (Rice et al., 1980).

#### THE BETSIE SHALE AND KENDRICK SHALE MEMBERS

Similar to the Magoffin Member, both the Betsie Shale and Kendrick Shale Members consist of generally coarsening-upward successions of interstratified mudstones, siltstones, and sandstones. At the base, both of these members consist of a thin shaley unit that coarsens-upward into a thick unit of interstratified mudstones and siltstones. The interstratified mudstones and siltstones unit grades-upward into a thick interval of rhythmically-bedded mudstone and sandstone. Within the upper 20 m of each member, a record of tidal cyclicity is manifested by a systematic thickening and thinning of mudstone-draped sandstones. As with the Magoffin Member, multi-story, cross-bedded fluvial sandstones erosionally truncate both the Betsie Shale and Kendrick Shale Members. The Betsie Shale and Kendrick Shale Members are both progradational successions, and like the Magoffin Member, probably represent prodeltaic to delta-front deposition.

## TIDAL CYCLICITY

Four orders of cyclicity, representing semi-diurnal, diurnal, semi-monthly, and monthly tidal periodicities are recognized within the upper 20 m of the Magoffin Member (Fig. 11). Preservation of these cycles is particularly evident within the northern depocenter (locations C, D, E, and G) where sand-sized sediments and thick semi-diurnal rhythmite couplets (up to approximately 20 cm) are present. Outside the northern depocenter (location A), tidal cycles are less obvious. The presence of finer-grained sediments and thinner, more laterally discontinuous semi-diurnal couplets makes it difficult to identify semi-monthly and monthly tidal packages.

Four orders of cyclicity, representing semi-diurnal through monthly tidal periodicities also are recognized within the upper 20 meters of the Betsie Shale Member. Three orders of cyclicity, representing semi-diurnal, diurnal, and semi-monthly tidal periodicities are recognized within the upper 20 meters of the Kendrick Shale Member. Unlike the Magoffin and Betsie Shale Members, no monthly cycle is preserved within the Kendrick Shale rhythmites.

### *Sandstone/Mudstone Couplets*

Fining-upward sandstone/mudstone couplets record individual tidal events within the Magoffin, Betsie Shale, and Kendrick Shale Members (Fig. 12; Table 1). The lower portion of each couplet is comprised of a thick layer of predominantly sub-angular, fine sand-sized quartz grains with minor amounts of coaly plant fragments and micas. Typically, the sandstone intervals are internally stratified, with coal fragments defining abundant thin (less than 0.5 mm), laterally discontinuous parallel laminae. Both thick (greater than 5 cm) and thin (less than 1 cm) couplets display internal stratification. The upper portion of each couplet is comprised of a thin dark layer

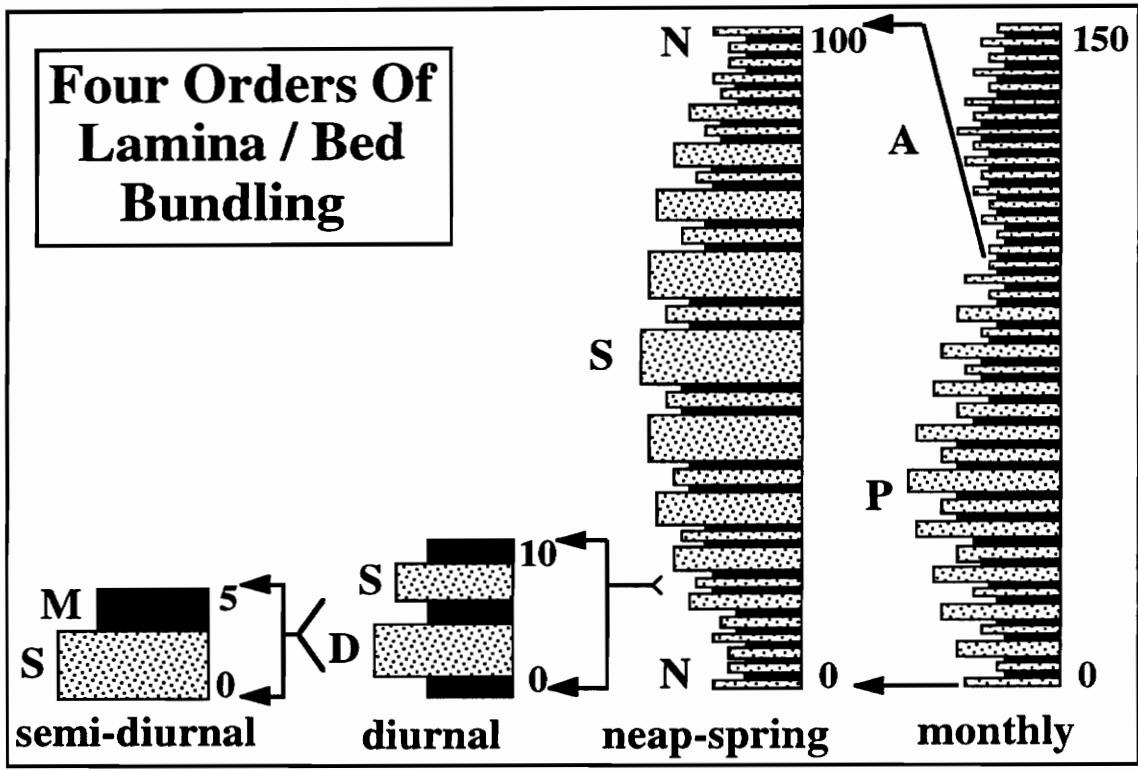
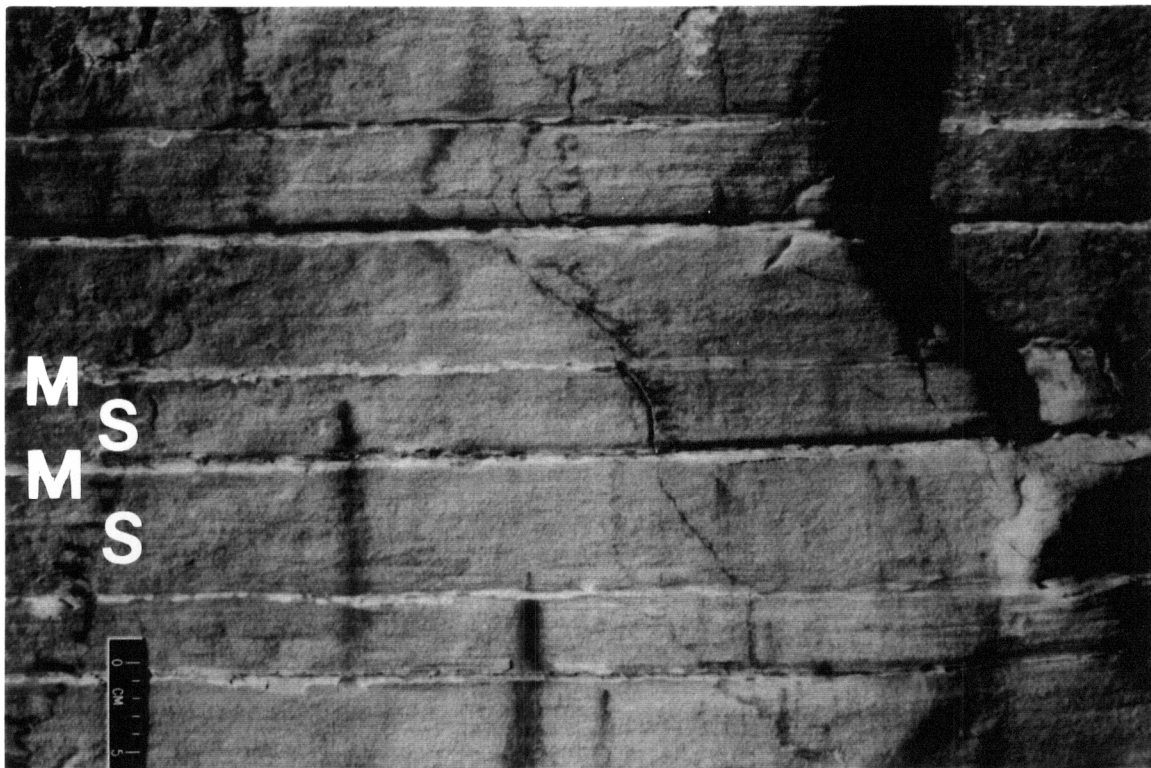


FIG. 11.—Idealized diagram of the hierarchy of cycles found within the Magoffin Member. Typical thicknesses are given in centimeters.



**FIG. 12.**— Photograph of typical semi-diurnal sandstone/mudstone couplet within the Magoffin Member. Relatively thick sandstones (S) were deposited during tidal flows. Thin mudstones (M) were deposited during subsequent slackwater periods. Photograph taken at location C.

**Table 1.--Description of Breathitt Group Rhythmite Intervals**

Unit	Recorded Flow	Accumulation Rates	Semi-diurnal Cycle	Diurnal Cycle	Semi-monthly Cycle	Monthly Cycle
Magoffin Member	Ebb	Typically: 1-7 cm/day Maximum: 30 cm/day	1 fining-upward sandstone/mudstone couplet	2 semi-diurnal couplets displaying thick/thin alternation	up to 28 couplets bundled into thickening and thinning packages	Paired thick/thin semi-monthly bundles Up to 56 couplets
Betsie Shale Member	Ebb	Typically: 1-4 cm/day Maximum: 16 cm/day	1 fining-upward sandstone/mudstone couplet	2 semi-diurnal couplets displaying thick/thin alternation	up to 28 couplets bundled into thickening and thinning packages	Paired thick/thin semi-monthly bundles Up to 56 couplets
Kendrick Shale Member	Predominantly Ebb Some Flood	Typically: 1-4 cm/day Maximum: 13 cm/day	1 to 2 fining-upward sandstone/mudstone couplets	2-4 semi-diurnal couplets displaying thick/thin alternation	up to 40 couplets bundled into thickening and thinning packages	None apparent

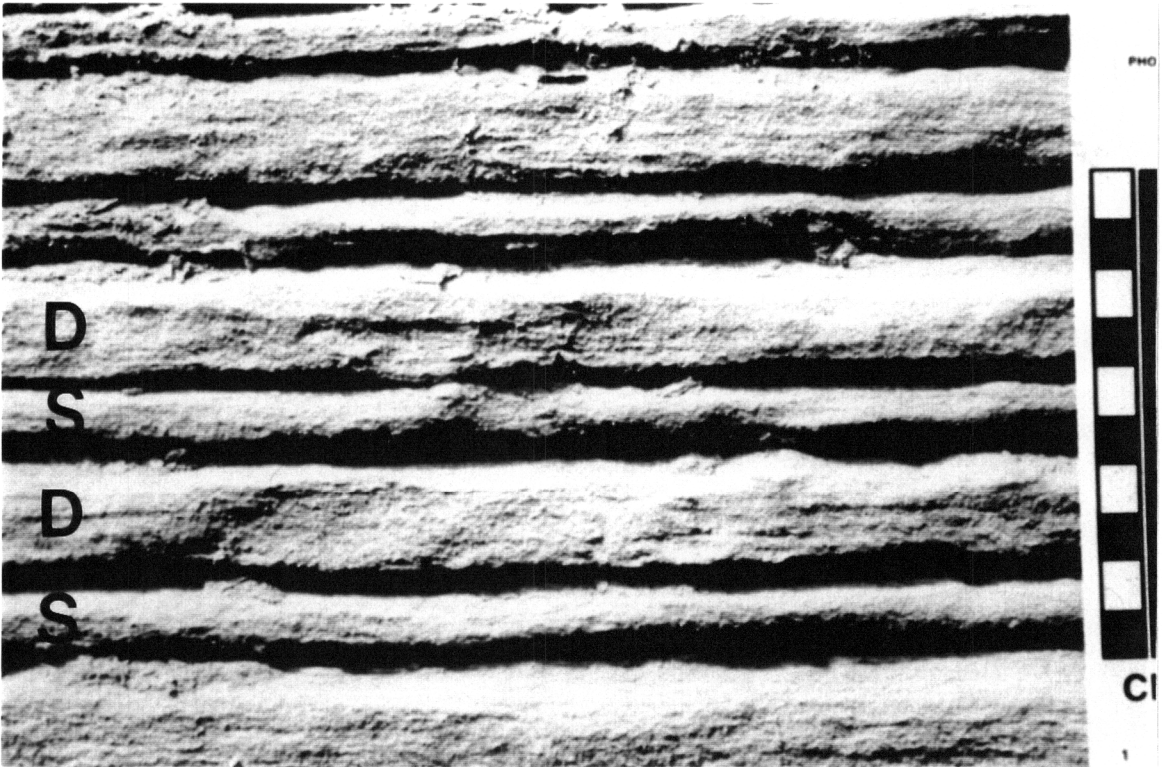
consisting of coaly plant fragments, clays, and micas. These couplets generally occur as laterally continuous layers with little to no evidence of wave reworking and only minor bioturbation. They are interpreted to have been deposited under the influence of tides.

Within the Magoffin Member, couplets range in thickness from less than 0.5 cm to greater than 20 cm. Within the Betsie Shale Member, couplets range in thickness from less than 0.5 cm to greater than 10 cm. Within the Kendrick Shale Member, couplets range in thickness from less than 0.5 cm to slightly greater than 5 cm. Rare climbing ripples, indicating a generally westward paleoflow direction, are developed at the base of a few sandstone layers within the Magoffin and Kendrick Shale Members. The top of the Kendrick Shale rhythmite interval is bioturbated.

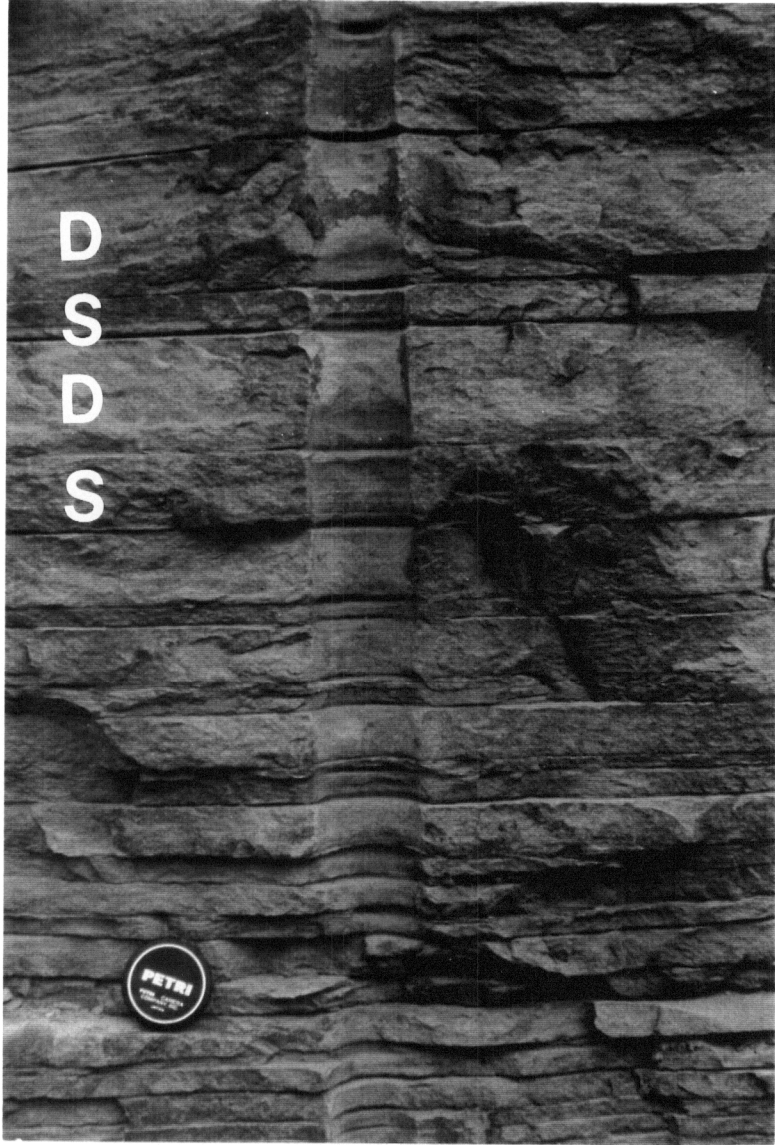
#### *Paired Sandstone/Mudstone Couplets*

Throughout most of the rhythmite interval within the Magoffin, Betsie Shale and Kendrick Shale Members, couplets are typically developed as alternating thick/thin pairs (Table 1). This relationship can be seen in outcrop (Fig. 13) and on bar graphs of measured couplet thicknesses (Figs. 14 and 15). These thick/thin pairs of couplets are interpreted to reflect deposition by both the dominant and subordinate daily tidal events.

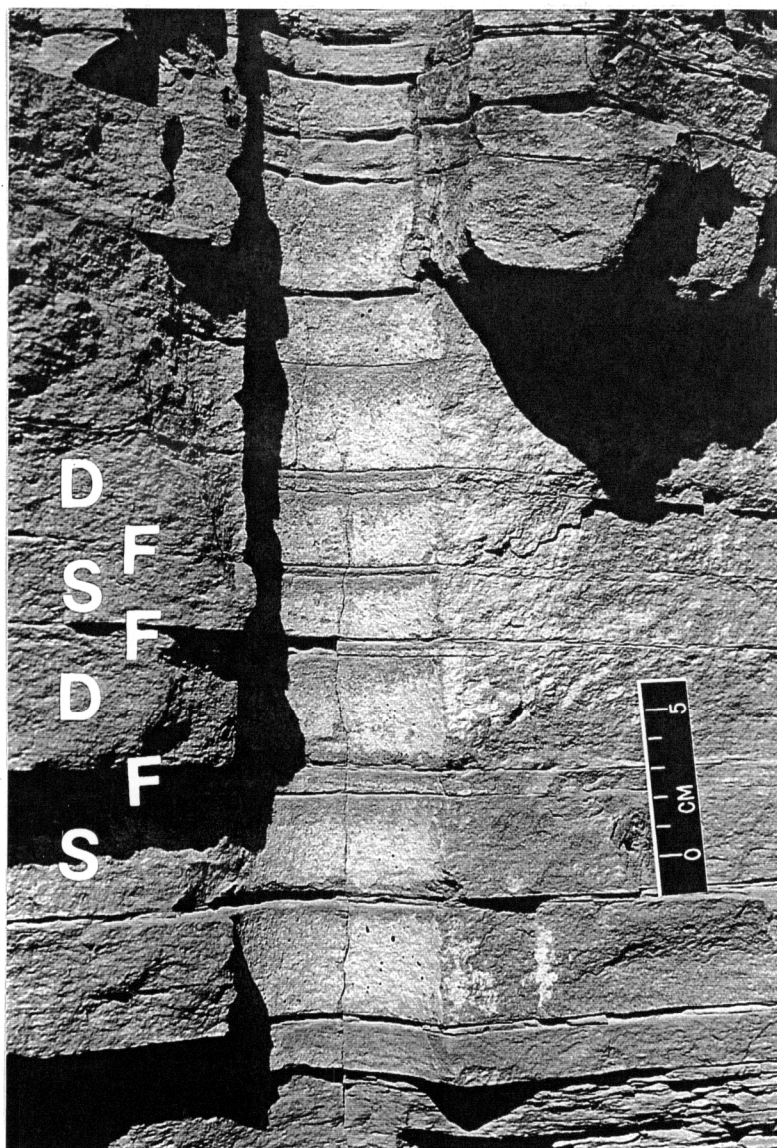
Within the Kendrick Shale rhythmites, extremely thin couplets (usually less than 1 cm thick) occasionally occur between the thick/thin couplet pairs (Figs. 13C and 15B). These thin couplets are interpreted to record subordinate tidal flow directions (ebb or flood). They are highlighted in red on the bar graph of measured rhythmite thicknesses (Fig. 15B).



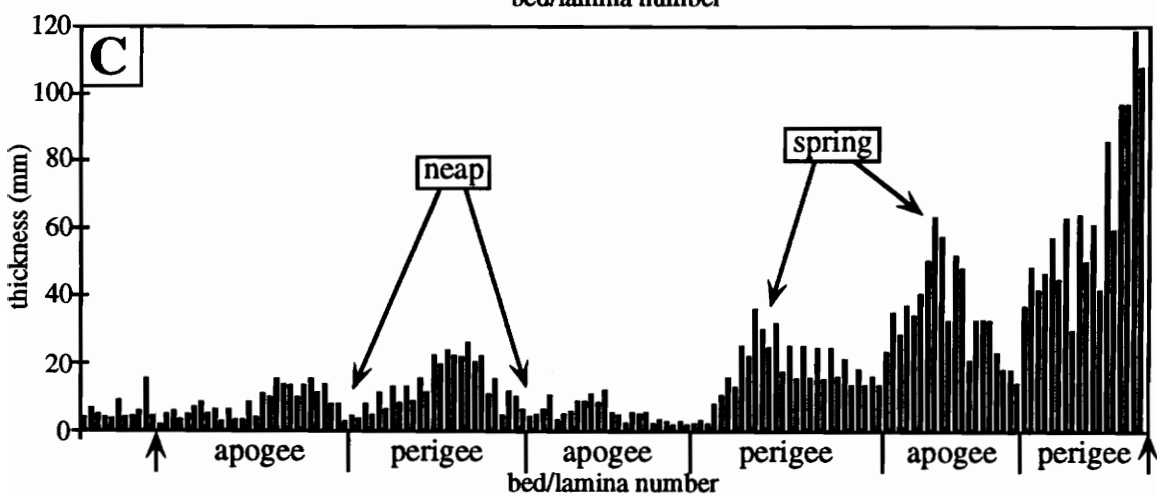
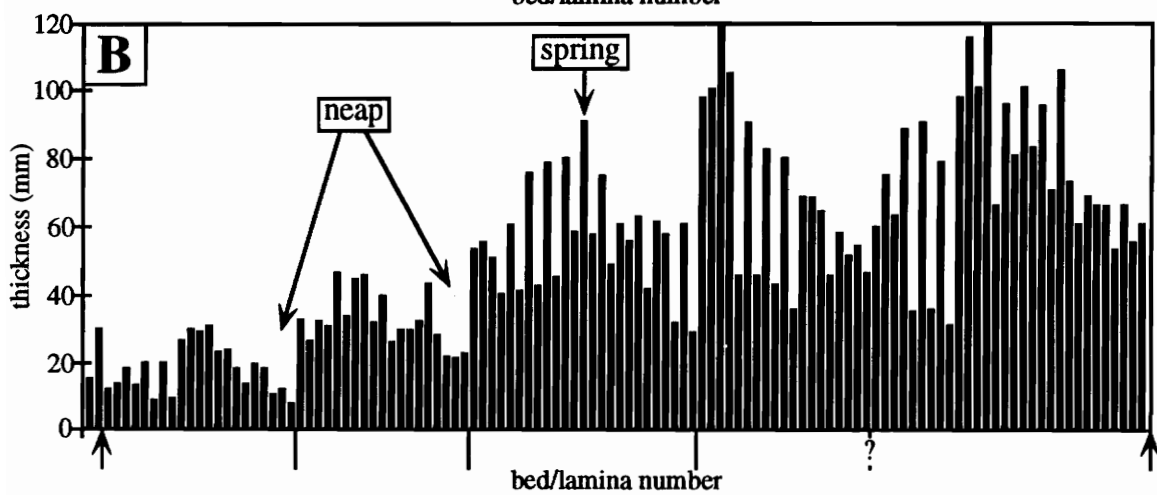
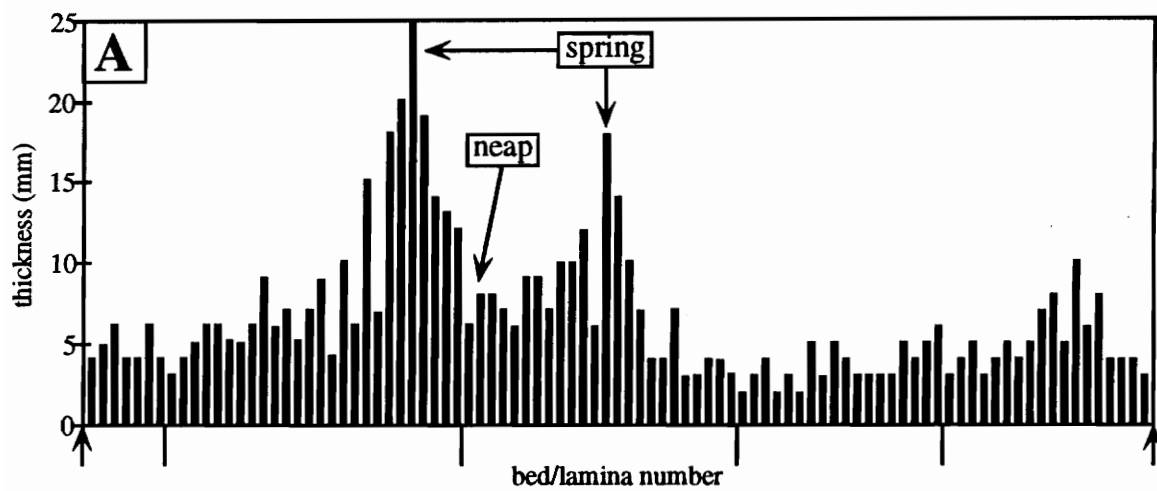
**FIG. 13A.**—Photograph of thick/thin daily tidal deposits within the Magoffin Member. This cyclicity records both the dominant (thick; D) and subordinate (thin; S) daily tides within a semi-diurnal tidal setting. Photograph taken at location D.

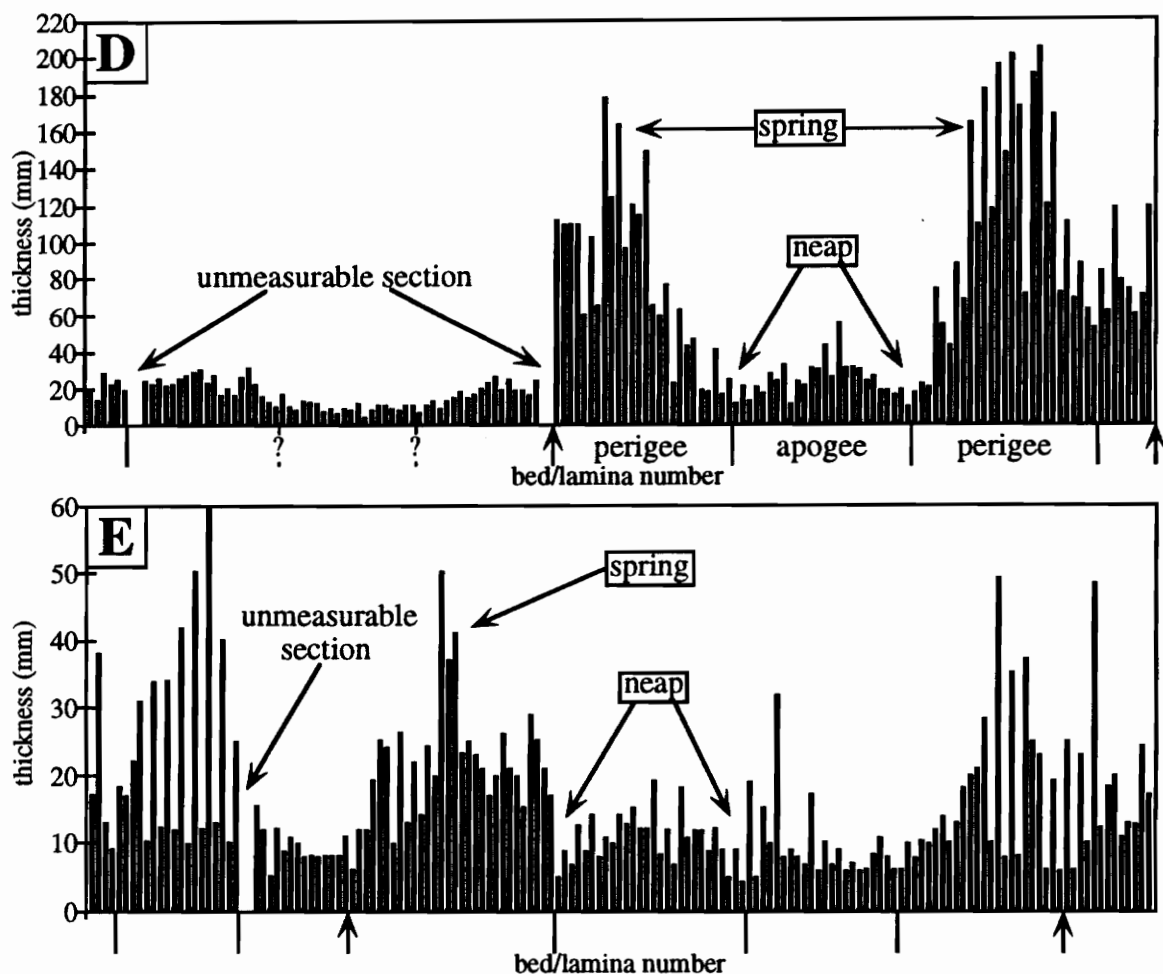


**FIG. 13B.**—Photograph of semi-diurnal sandstone/mudstone couplets from the Betsie Shale Member. Both the dominant (thick; D) and subordinate (thin; S) daily tides are recorded.

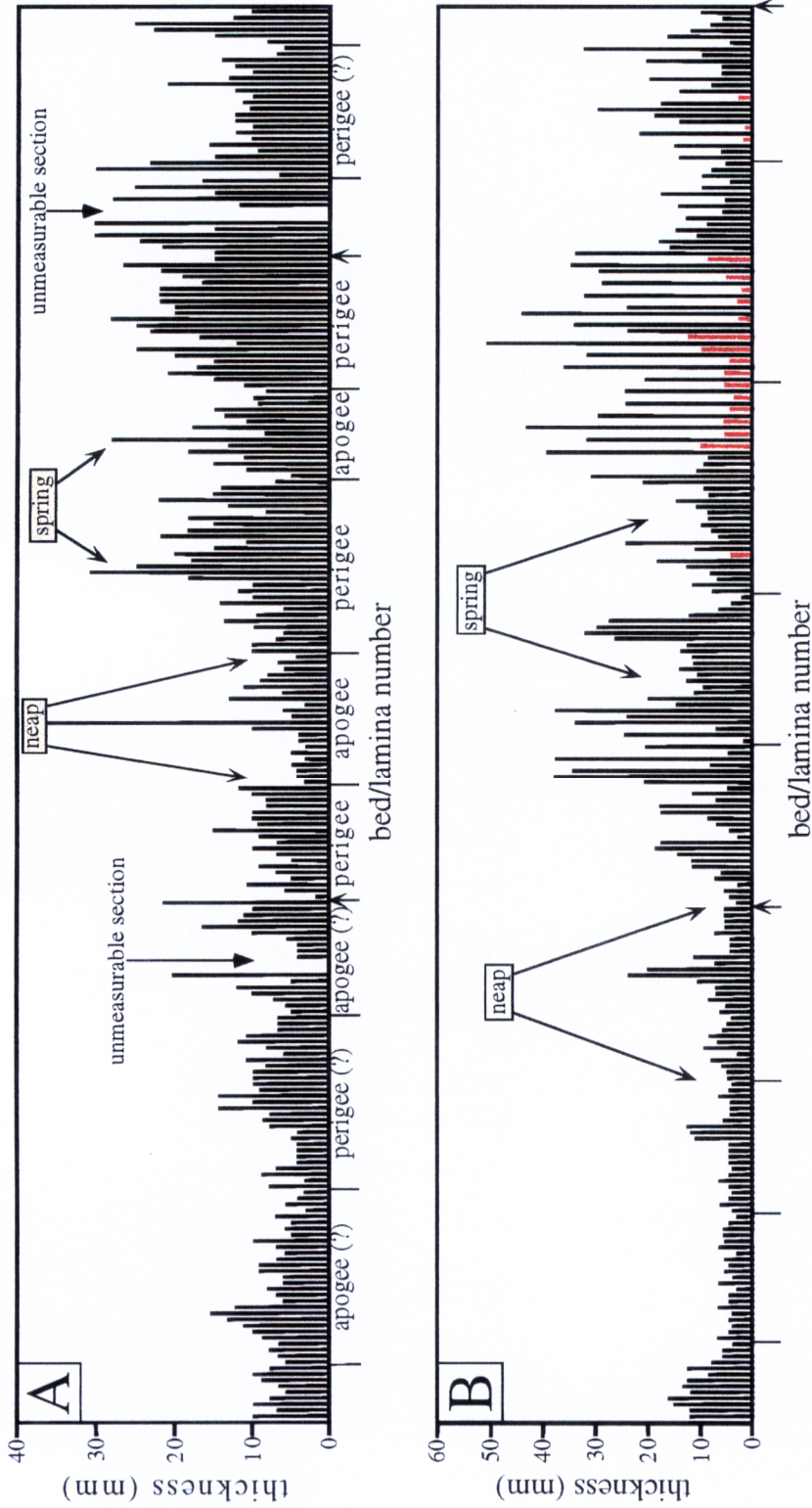


**FIG. 13C.**—Photograph of semi-diurnal sandstone/mudstone couplets from the Kendrick Shale Member. Both the dominant (thick; D) and subordinate (thin; S) daily tides are recorded. Note the thin, flood-tidal-flow deposits (F) between the thicker, dominant ebb-tidal-flow deposits (D and S).





**FIG. 14.**—Bar graphs of measured rhythmite thicknesses within the Magoffin Member (refer to Figure 1 for locations). Bar graph A is from location A; bar graph B is from location C; bar graph C is from location D; bar graph D is from location E; bar graph E is from location G. Semi-monthly (neap-spring-neap) cycles are marked by tick marks along the x-axes. Monthly (perigee-apogee) cycles, where discernible, are marked along the x-axes. Also, note the daily thick/thin pairs within these intervals. Arrows along the x-axes indicate intervals used for harmonic analyses (Fig. 18).



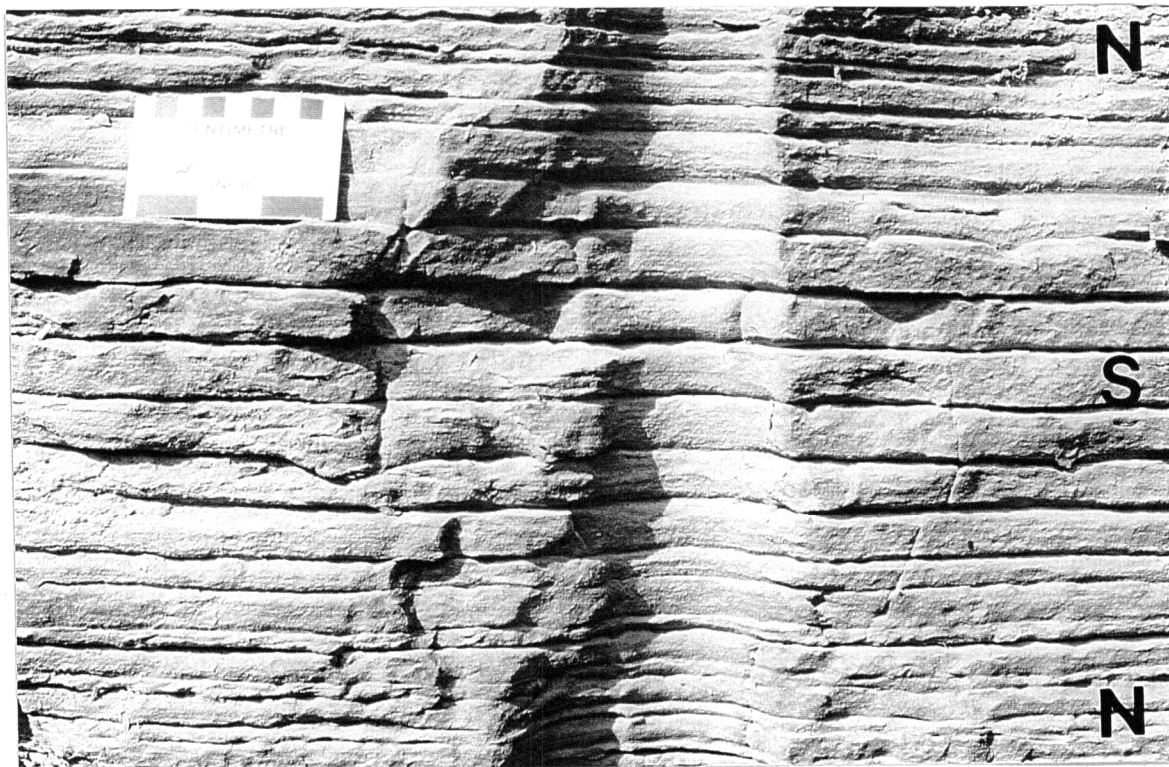
**FIG. 15.**—Bar graph of measured rhythmite thicknesses (refer to Figure 1 for locations). Bar graph A is from the Beisic Shale Member; bar graph B is from the Kendrick Shale Member. Semi-monthly (neap-spring-neap) cycles are marked by tick marks along the x-axes. Monthly (perigee-apogee) cycles, where discernible, are marked along the x-axes. Also, note the daily thick/thin pairs within these intervals. Arrows along the x-axes indicate intervals used for harmonic analyses (Fig. 24). Red bars note flood deposits in bar graph B.

### *Bundled Sandstone/Mudstone Couplets*

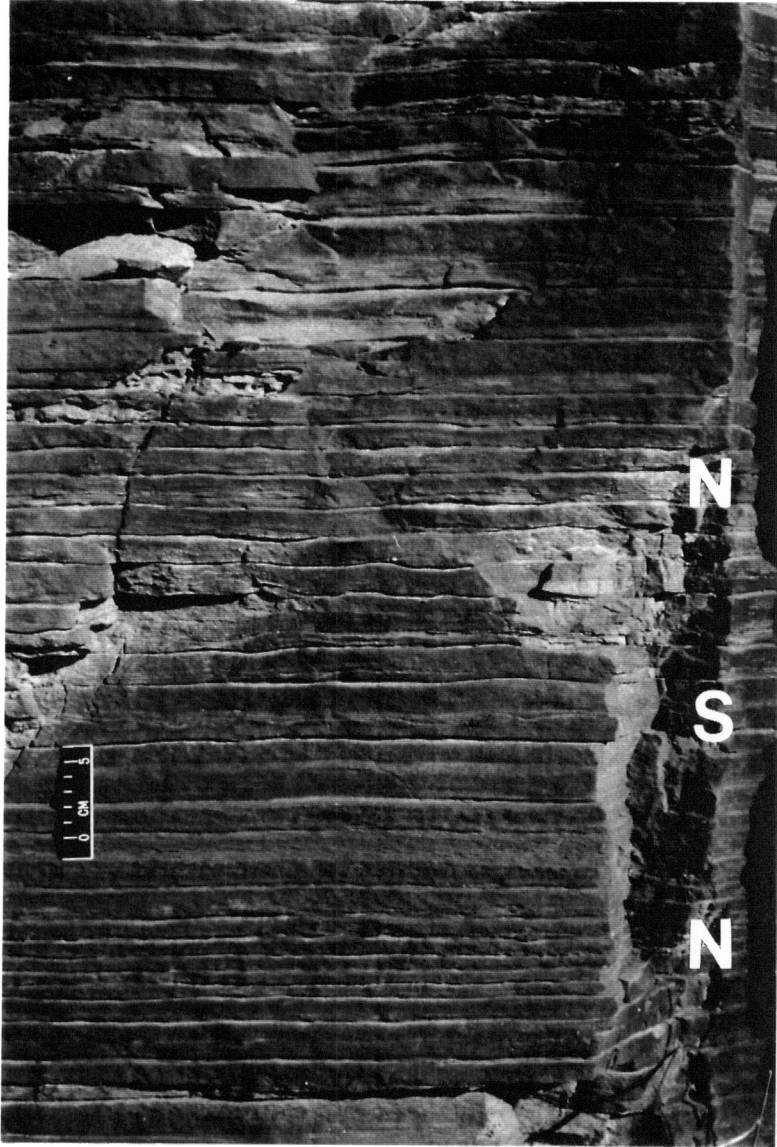
Within the Magoffin and Betsie Shale Members, semi-diurnal couplets are arranged in thickening and thinning cycles consisting of up to 28 couplets (Table 1). Within most of the Kendrick Shale Member, semi-diurnal couplets are arranged in cycles of up to 28 couplets, but in part of this interval, up to 40 couplets can be identified in each thick-thin-thick package. Each cycle within all three intervals rarely contains fewer than 20 sandstone/mudstone couplets. Cycles within the Magoffin Member are typically 20 to 100 cm thick while cycles in the Betsie Shale and Kendrick Shale Members are typically 10 to 60 cm thick. Bundles in all three sections are apparent in outcrop (Fig. 16) and on bar graphs of measured rhythmite thicknesses (Figs. 14 and 15). These packages are interpreted as semi-monthly (neap-spring-neap) tidal cycles. The presence of a maximum of 20 to 28 couplets per neap-spring-neap cycle indicates the preservation of a record of nearly every ebb or flood tidal event during the two weeks of deposition.

### *Paired Couplet Bundles*

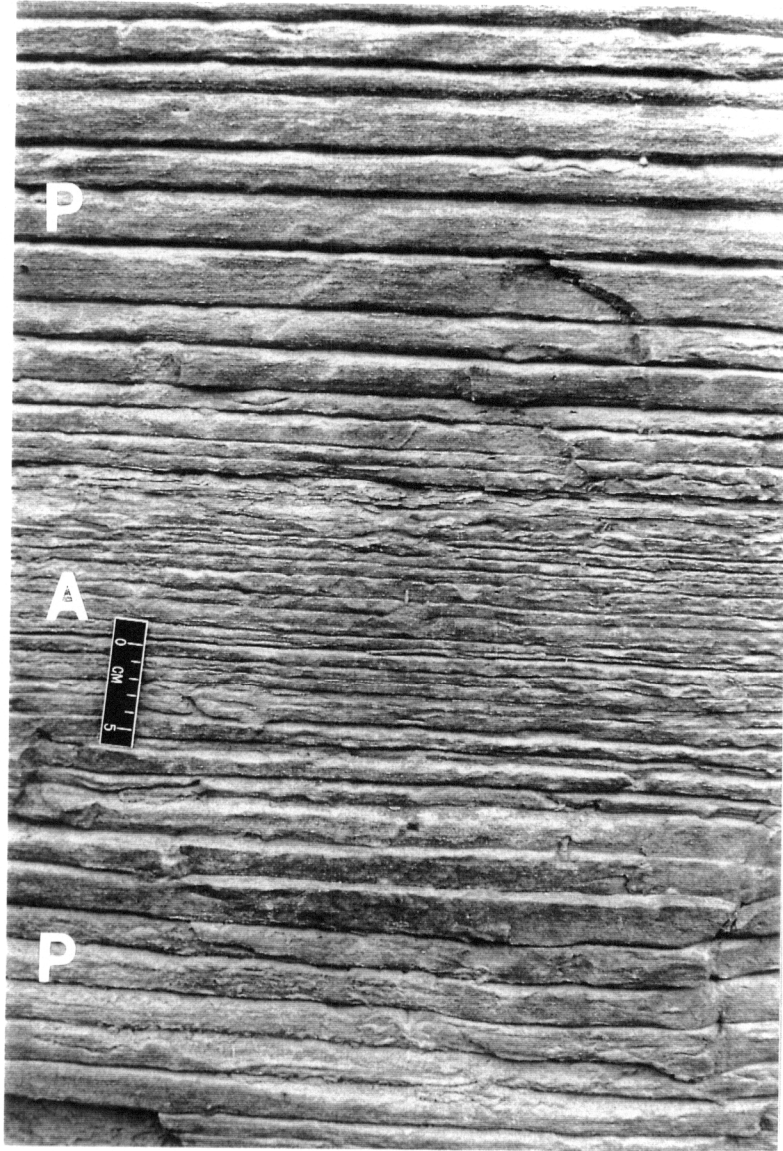
Successive neap-spring-neap cycles commonly display a thick/thin relationship within the Magoffin and Betsie Shale Members (Table 1). The thicker semi-monthly packages usually contain more abundant, coarser, and thicker couplets than the thinner semi-monthly packages. For the Magoffin Member, this pairing of fortnightly deposits is apparent in outcrop (Fig. 17) and on bar graphs of measured couplet thicknesses (Fig. 14). For The Betsie Shale Member, this pairing of fortnightly deposits is weakly developed and is most apparent on the bar graph of measured couplet thicknesses (Fig. 15A). This thick/thin relationship reflects the anomalistic monthly periodicity of the moon.



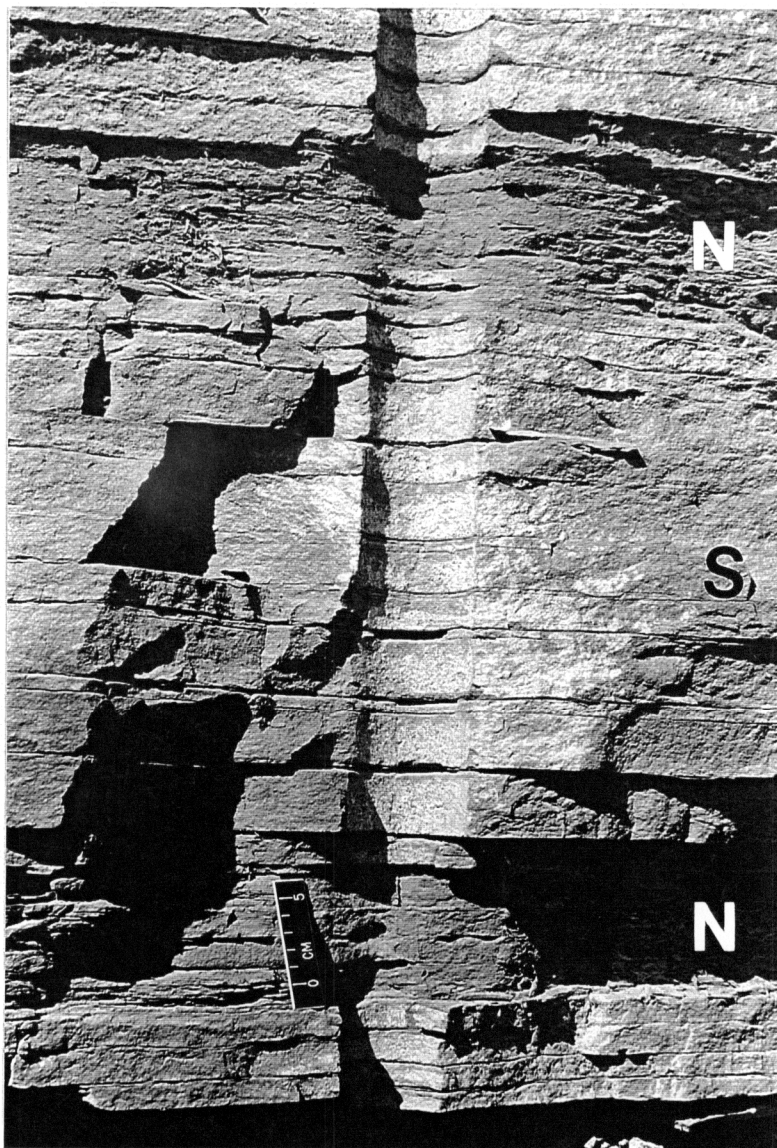
**FIG. 16A.**—Photograph of semi-monthly, neap-spring-neap cyclicality within the Magoffin Member. Note the systematic thickening and thinning of strata. Neap (N) and spring (S) deposits are marked. Photograph taken at location D.



**FIG. 16B.**—Photograph of semi-monthly neap-spring-neap cyclicity within the Betsie Shale Member. Note the systematic thickening and thinning of strata. Neap (N) and spring (S) deposits are marked.



**FIG. 17.**—Photograph of monthly cyclicality within the Magoffin Member. Thin apogean (A) deposits are shown between much thicker perigean (P) deposits. Photograph taken at location D.



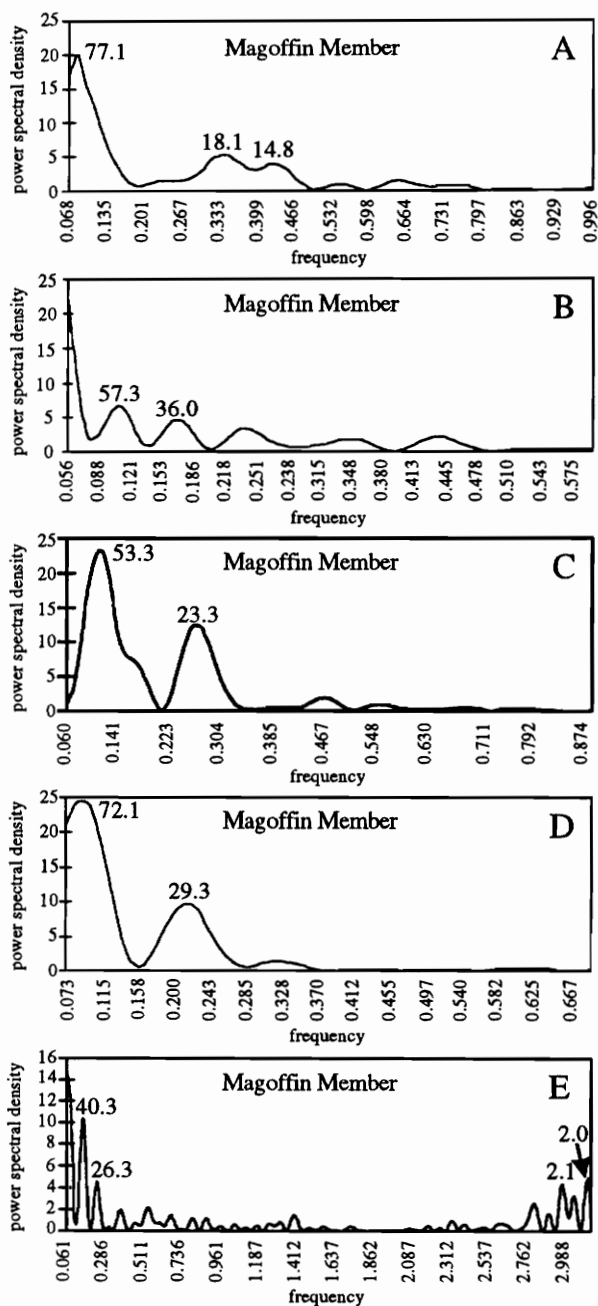
**FIG. 16C.**—Photograph of semi-monthly neap-spring-neap cyclicity within the Kendrick Shale Member. Note the systematic thickening and thinning of strata. Neap (N) and spring (S) deposits are marked.

### *Harmonic Analysis*

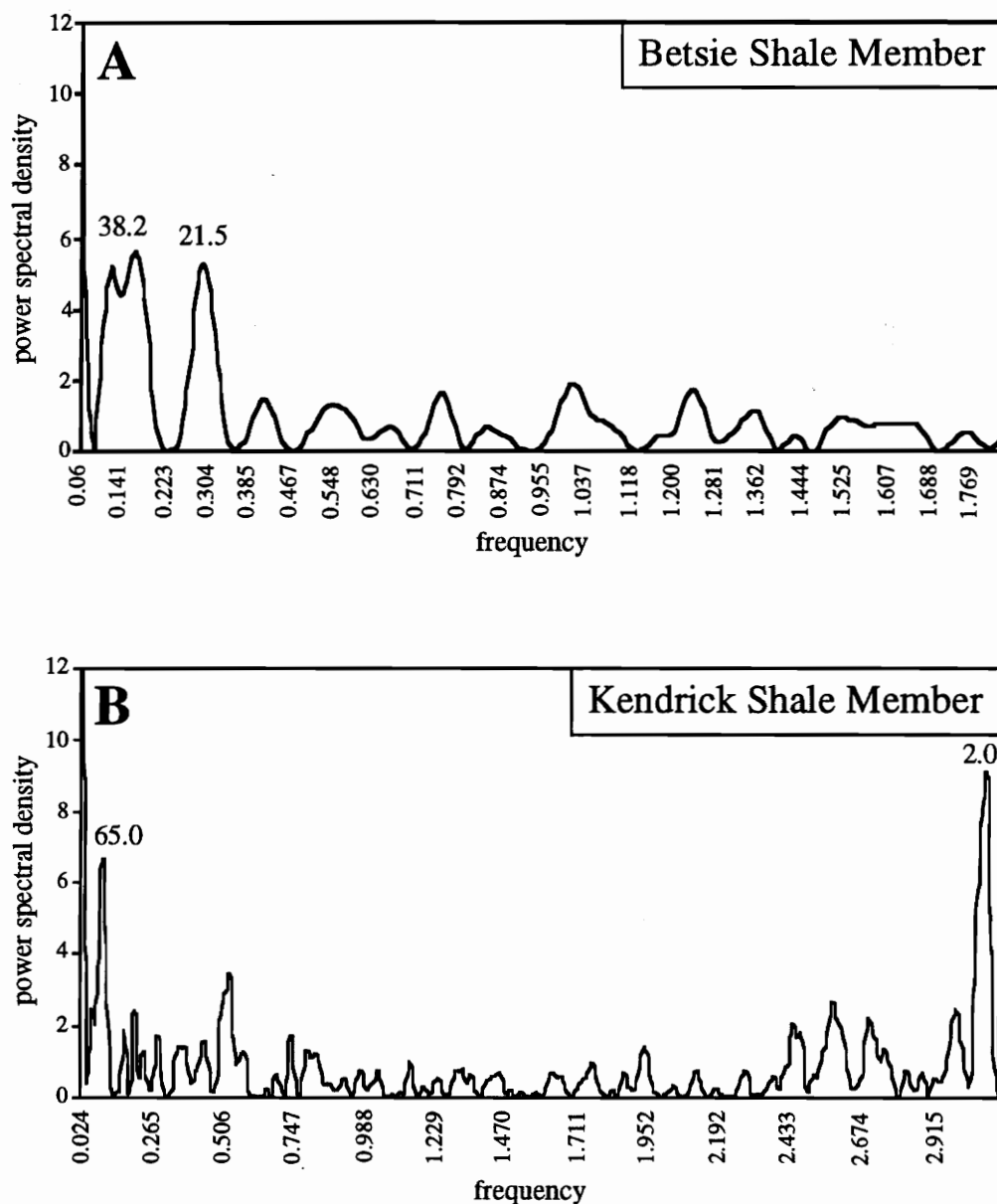
Harmonic analyses were performed on the data sets to confirm tidal cyclicity. For the Magoffin Member, analyses were performed at all measured rhythmite sections (Fig. 18). Location A shows significant peaks that indicate cycles containing 77.1 laminae per cycle, 18.1 laminae per cycle, and 14.8 laminae per cycle (Fig. 18A). Location C shows significant peaks that indicate cycles containing 57.3 laminae per cycle and 36.0 laminae per cycle (Fig. 18B). Location D shows significant peaks that indicate cycles containing 53.3 laminae per cycle and 23.3 laminae per cycle (Fig. 18C). Location E shows significant peaks that indicate cycles containing 72.1 laminae per cycle and 29.3 laminae per cycle (Fig. 18D). Location G shows significant peaks that indicate cycles containing 40.3 laminae per cycle, 26.3 laminae per cycle, 2.1 laminae per cycle, and 2.0 laminae per cycle (Fig. 18E).

For the Betsie Shale and Kendrick Shale Members, harmonic analyses also were performed (Fig. 19). Analysis of the Betsie Shale Member (location H) shows significant peaks that indicate cycles containing 38.2 laminae per cycle and 21.5 laminae per cycle (Fig. 19A). Analysis of the Kendrick Shale Member (location I), shows significant peaks that indicate cycles containing 65.0 laminae per cycle and 2.0 laminae per cycle (Fig. 19B).

Ideally, peaks would indicate cycles containing 2.0 laminae per cycle (daily cyclicity), 28.0 laminae per cycle (semi-monthly cyclicity), and 56.0 laminae per cycle (monthly cyclicity) for each measured outcrop. However, no peak indicates cycles containing the exact number of expected laminae per cycle. All of these outcrops preserve incomplete records of tidal activity. The farther an outcrop is located from the central zone of the depocenter (Magoffin Member), the more skewed are the indicated



**FIG. 18.**—Power spectral plots of rhythmite intervals from the Magoffin Member (refer to Figure 1 for locations). Plot A is from location A; plot B is from location C; plot C is from location D; plot D is from location E; plot E is from location G. Plots B, C and possibly A, D, and E show peaks suggestive of tidal processes related to monthly cyclicality. Plots B, C, D, E, and possibly A show peaks suggestive of tidal processes related to semi-monthly (neap-spring-neap) cyclicality. Plot E shows peaks suggestive of tidal processes related to semi-diurnal cyclicality.



**FIG. 19.**—Power spectral plots of rhythmite intervals (refer to Figure 1 for locations). Plot A is for the Betsie Shale Member. Plot B is for the Kendrick Shale Member. Plot A shows peaks suggestive of monthly (weakly preserved) and semi-monthly tidal periodicities. Plot B shows peaks suggestive of semi-monthly and diurnal/semi-diurnal tidal periodicities.

cycles. It also is possible that the shortness of the data sets (less than 4 months long) is affecting these analyses.

Location D is located in the thickest region of the northern depocenter. The harmonic analysis (Fig. 18C) indicates that it has cycles containing 23.3 and 53.3 laminae per cycle. These values are close to the expected values of 28.0 and 56.0 laminae per cycle. Therefore, these can be assumed to represent semi-monthly and monthly cyclicity and confirm initial conclusions based upon bar graph and outcrop analyses.

Location A is located outside the northern depocenter. The harmonic analysis (Fig. 18A) indicates that it has cycles containing 77.1, 18.1, and 14.8 laminae per cycle. These values are not in agreement with the expected values of 56.0, 28.0, and 2.0 laminae per cycle. It is possible that the 18.1 peak or the 14.8 peak represents a poorly preserved semi-monthly cycle. It is also possible that the 77.1 peak represents a poorly preserved monthly cycle, but it is more probable that the 77.1 peak is simply a function of the extremely short data set for location A and does not represent any true cyclicity recorded by this interval.

The Kendrick Shale Member has been interpreted as a sequence of both ebb and flood tidal deposits. Therefore, there should be peaks indicating 2.0 laminae per cycle (semi-diurnal cyclicity), 4.0 laminae per cycle (diurnal cyclicity), 56.0 laminae per cycle (semi-monthly cyclicity) and 112.0 laminae per cycle (monthly cyclicity). The harmonic analysis for the Kendrick Shale Member (Fig. 19B) shows peaks at 65.0 laminae per cycle and 2.0 laminae per cycle. The 2.0 peak probably represents the semi-diurnal tidal cycle and the 65.0 peak probably represents the semi-monthly tidal cycle. As with the analyses on the Magoffin rhythmites, these peaks do not exactly match the expected values due to an incomplete record of tidal activity.

## DISCUSSION

This study increases the understanding of the Magoffin Member and of Mid-Pennsylvanian tidal rhythmite development in the central Appalachian Basin. This is the first study to document the lateral changes within one tidal rhythmite sequence of the Breathitt Group. This study is also the first to develop contour maps of the Magoffin Member to help determine why the rhythmites are so anomalously thick within the study area. Sedimentation within major fourth-order sequences are also considered in this study which may help to develop a better understanding of cyclothem development in the central Appalachian Basin. Combined with pre-existing work on other rhythmite intervals, this study increases our understanding of how the earth-moon-sun rotational system works and how it has changed throughout time.

### *Ebb/Flood Dominance*

Neap-spring-neap bundles within the Magoffin and Betsie Shale Members, contain a maximum of 28 couplets, indicating that only one direction of tidal flow, either ebb or flood, is recorded. It is possible that some of these 28 couplets record flood tidal flows if incomplete records (fewer than 28 couplets per neap-spring-neap bundle) of ebb tidal activity are preserved. However, the flow direction recorded by most of these rhythmite couplets can be assumed to be to the northwest based upon the paleoflow data (tool marks and climbing ripples) from the Magoffin Member, and the rhythmite bundling patterns of both members. There is no evidence indicating that flow to the southeast is recorded within these intervals.

The northwestern paleoflow direction is consistent with reported Middle Breathitt fluvial flow (Englund and Thomas, 1989). Since sediment transport for the rhythmite interval and fluvial flow was to the northwest during the time of deposition,

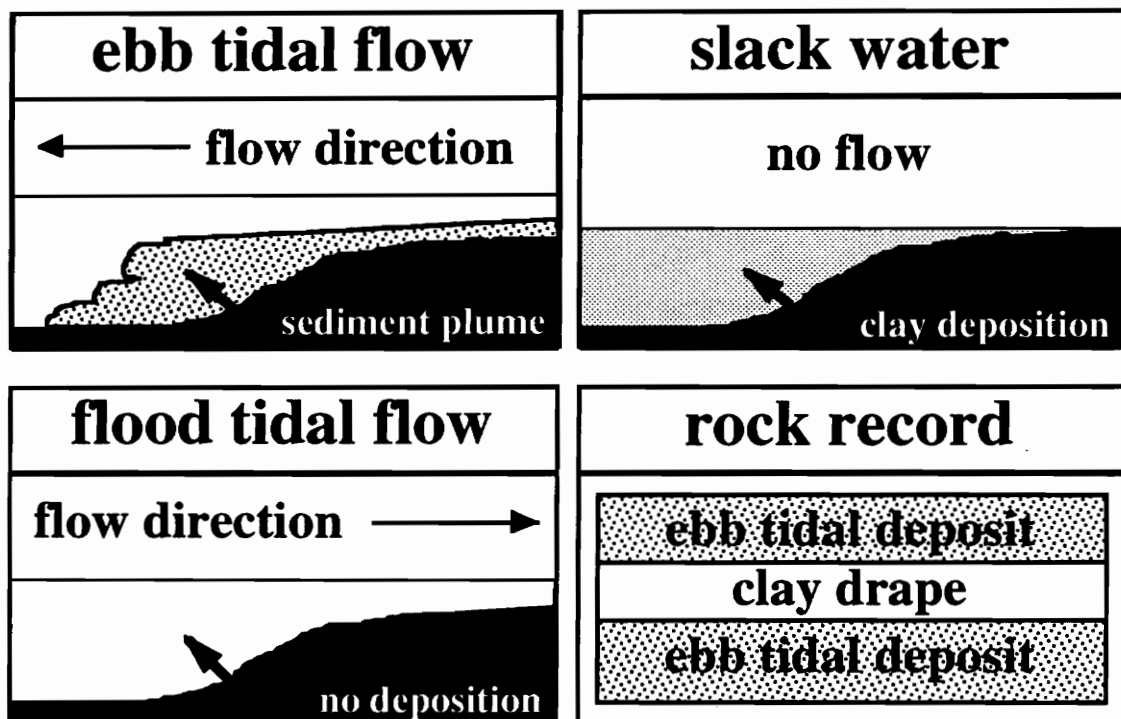
the rhythmite interval can be assumed to record predominantly ebb tidal flow.

Therefore, the Magoffin and Betsie Shale rhythmites are interpreted to be a series of sandstone beds deposited during ebb tidal flows separated by thin mudstone drapes that were deposited during subsequent slackwater periods (Fig. 20).

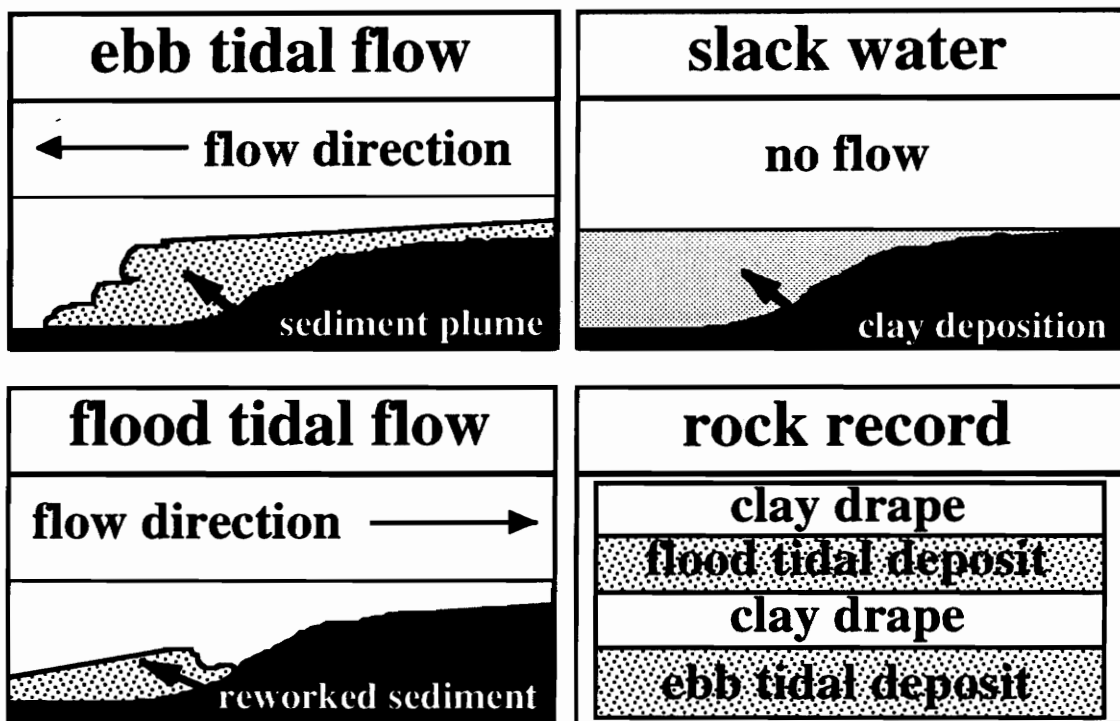
Neap-spring-neap bundles within the Kendrick Shale contain more than the expected 28 couplets. These semi-monthly packages contain up to 40 beds/laminae, providing a rare record of both ebb and flood tidal preservation within the Breathitt Group (Fig. 21). Based upon paleoflow data (climbing ripples), ebb tidal flow was west to northwest and flood tidal flow was east to southeast.

#### *Internal Stratifications*

The origin of the common parallel laminations within the lower portion of many of the sandstone layers (see semi-diurnal section above) is enigmatic. It is feasible that they simply represent amalgamated rhythmite layers. However, based upon their widespread occurrence, ubiquitous nature (occurrence in rhythmites ranging in thickness from less than 1 cm to greater than 15 cm), and lateral continuity, combined with higher-order bundling patterns (semi-monthly and monthly), it is unlikely that more than a small percentage of these internal laminations represent amalgamated layers. It is more likely that these internal stratifications indicate that deposition occurred predominantly under upper flow regime tractional conditions or under lower flow regime plane-bed conditions with high suspension fallout (cf. Collinson and Thompson, 1989; Dalrymple, 1992). Unsteady flow is indicated by the presence of coal fragments along these laminae. The rare, climbing ripples indicate periodic lower flow regime conditions (cf. Dalrymple, 1992).



**FIG. 20.**—The Magoffin and Betsie Shale rhythmites record ebb tidal activity. During ebb tidal flows, sediment was carried across the basin in the form of large sediment plumes. During subsequent slack water periods, flow energy was reduced allowing for the deposition of clay-sized particles. During flood tidal flows, no deposition occurred.



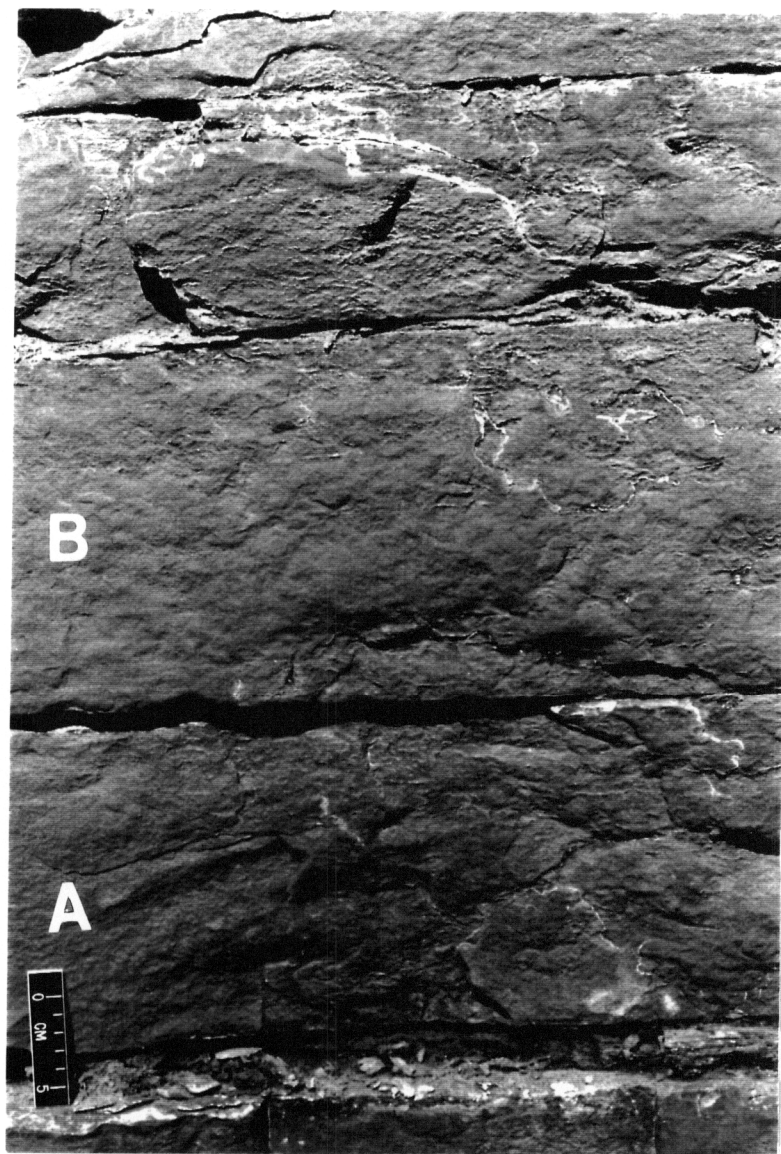
**FIG. 21.**—The Kendrick Shale rhythmites record both ebb and flood tidal activity. During ebb tidal flows, sediment was carried across the basin in the form of large sediment plumes. During subsequent slack water periods, flow energy was reduced allowing for the deposition of clay-sized particles. During strong flood tidal flows, thin layers of reworked sediments were deposited.

### *Sedimentation Rates*

Within the study area, sedimentation rates for the Magoffin rhythmites typically ranged from 20 to 100 cm per neap-spring-neap event. However, where the Magoffin Member is the thickest and the most proximal deltaic facies are preserved, sedimentation rates were probably at a maximum and reached over 30 cm per day (Fig. 22). Figure 9D (location E) records individual rhythmite couplets that are up to 20 cm in thickness. Rhythmite bundling patterns for these thicker beds are comparable to what is observed in the thinner beds. Pairs of couplets display a thick-thin relationship, indicative of a diurnal tidal cycle. Neap-spring-neap bundles contain close to 28 couplets and there is evidence that a monthly tidal cyclicity is recorded. It is possible that some of these beds may represent amalgamated layers but based upon rhythmite bundling patterns, it is unlikely that this is the case for more than a small percentage of the thicker beds. Other Magoffin rhythmite sections (location C, D, and G) do not record individual couplet thicknesses as great as those recorded at location E because of erosion at the sequence boundary and/or difficulty in measuring sections at the tops of benches.

Based upon initial interpretations, sedimentation rates for the Betsie Shale and Kendrick Shale rhythmites typically ranged from 10 to 60 cm per neap-spring-neap event. Sedimentation rates for the Betsie Shale rhythmites reached up to 16 cm per day; sedimentation rates for the Kendrick Shale rhythmites reached up to 13.0 cm per day. Similar to the Magoffin rhythmites, it is likely that these elevated sedimentation rates are related to the lithologies and overall thickness of each marine unit.

Within the Breathitt Group, thick packages (greater than 10 m) of tidal rhythmites only occur within widespread marine members. These marine members consist of a relatively condensed transgressive unit (less than 5 m) that grades upward



**FIG. 22.**—Photograph of thick Magoffin rhythmite beds. Depositional rates for Magoffin rhythmites typically ranged from 20 to 100 cm per neap-spring-neap cycle, but exceeded 30 cm per day in areas where the Magoffin Member is thickest and where the most proximal deltaic facies are preserved. Beds A and B in this photograph, taken at location E, represent a dominant/subordinate diurnal deposit that is over 30 cm thick.

into a relatively thick regressive unit (up to 60 m). The rhythmite packages are located within the upper 10 to 15 meters of the regressive units. Based upon the marine fauna, Bennington (1996) noted that there is a distinct fall in sealevel recorded by the dark gray shale located at the base of the Magoffin Member. This fall in sealevel would have resulted in the lowering of baselevel. Holland and Pickup (1976) and Schumm et al. (1987) demonstrated that lowering baselevel can increase depositional gradients which can result in the supply of large volumes of sediment downstream. Therefore, the extremely high sedimentation rates recorded by the Magoffin rhythmites is probably due to this lowering of baselevel.

The Magoffin Member and its underlying stacked fluvial channels have been interpreted as one fourth-order Milankovitch cycle. This interval is comprised of a lower transgressive unit and an upper regressive unit. It represents 400,000 years of deposition and is approximately 100 meters-thick within the study area. However, within this thesis, it has been demonstrated that 15 m of this interval (the rhythmites) were deposited within 4 months. This means that 15% of this fourth-order sequence was deposited in less than one tenth of a percent of the available time.

This fourth-order sequence probably represents an Appalachian equivalent of the Midcontinent Pennsylvanian cyclothems (e.g., Heckel, 1984). The rapid sedimentation rates reported within this thesis could affect some previously held notions about the rates of cyclothem development.

### *Rhythmite Development*

The thickest and most complete rhythmite cycles are developed where the Magoffin Member is thickest and where the interlaminated sandstone/mudstone interval is best preserved (Figs. 8 and 10). At locations C and D where the Magoffin Member is

greater than 40 m thick (Fig. 9) tidal cycles are easily recognizable (Figs. 14C and 14D). Harmonic analyses of the rhythmites at locations C and D are highly suggestive of semi-monthly (a 36.0 peak for location C and a 23.3 peak for location D) and monthly (a 57.3 peak for location C and a 53.3 peak for location D) tidal periodicities. The only measured outcrop that lies outside the northernmost depocenter is location A (Fig. 9) where the Magoffin Member is only 20 m thick. At this location, no interlaminated sandstone/mudstone interval is present and it is difficult to identify complete tidal packages on the bar graph of measured couplet thicknesses (Fig. 14A). Spectral analyses for the rhythmites at location A show peaks that are less consistent with known tidal periodicities (Fig. 18A) than do the spectral analyses for locations C (Fig. 18B) and D (Fig. 18C). The peaks on Figure 18A are suggestive of tidal processes possibly related to monthly and semi-monthly tidal periodicities, but the short data set makes it difficult to draw any firm conclusions about the cycles preserved at this location.

Due to a lack of data, it is difficult to comment on rhythmite development within the Betsie Shale and Kendrick Shale Members. However, it is likely that rhythmite development for these two members is similar to that of the Magoffin Member since all three are lithologically similar.

#### *Modern and Ancient Analogs*

The most notable modern analogs for the Breathitt Group rhythmites are the Bay of Fundy and the Oosterschelde tidal basin, southwest Netherlands. The Bay of Fundy contains a thick rhythmite package displaying semi-diurnal, diurnal, and semi-monthly cycles (Dalrymple et al., 1991). It has estimated depositional rates of up to 7m/yr on its upper tidal flats. The Oosterschelde tidal basin in the Netherlands contains sediments

that are approximately 400 years old (Yang and Nio, 1989). Semi-diurnal, diurnal, and semi-monthly tidal cycles are reported in cross-bedded sands. In the Oosterschelde tidal basin, individual semi-diurnal sandstone/mudstone couplets range in thickness from less than 5 cm up to 70 cm (Yang and Nio, 1991). The upper limit of these values is 3 times greater than the maximum values reported for the Breathitt Group rhythmites.

Most reported ancient rhythmite successions contain individual couplets that range in thickness from less than 1 mm up to a few centimeters. These values are an order of magnitude lower than the values reported for the Breathitt Group. However, a few notable exceptions of thicker rhythmites are reported in the literature. Lanier et al. (1993) identified couplets that ranged in thickness from less than 1 mm up to 12.5 cm from the Pennsylvanian Tanganoxie sandstone of the Douglas Group (Kansas). These rhythmites occur within a transgressive package and display well-developed semi-monthly cyclicity. Kvale and Archer (1991) reported couplets from the Pennsylvanian Abbott Formation of Illinois that range in thickness from less than 2 cm up to 22 cm. These display well-developed diurnal and semi-monthly cyclicity.

The above rhythmite packages occur within retrogradational successions. Rhythmites have also been identified from progradational settings, such as the Pennsylvanian Brazil Formation of Indiana (Kvale and Archer, 1990) and the Mississippian Pride Shale of West Virginia (Miller and Eriksson, 1997). However, depositional rates for these progradational packages are much lower than depositional rates recorded by the Breathitt Group rhythmites. The Brazil Formation records depositional rates that range from 1 cm/yr to 1 m/yr and displays well-developed semi-monthly cyclicity. The Pride Shale records average depositional rates of 10 cm/yr but

reached over 60 cm/yr. These rhythmites record diurnal, semi-monthly, monthly, annual, and 18.6-year nodal cycles.

## CONCLUSIONS

The Magoffin Member is comprised of a coarsening-upward succession of interlaminated sandstones, siltstones, and mudstones. Within the study area, it is interpreted to be a laterally extensive prodeltaic to delta-front/distributary-mouth-bar deposit that contains tidally influenced rhythmites within its upper 20 m. These rhythmites display several orders of cm- to dm-scale cycles that are consistent with known semi-diurnal, diurnal, semi-monthly, and monthly tidal periodicities. Based upon paleocurrent data and rhythmite bundling patterns, it is probable that deposition of sand occurred entirely in response to ebb tidal flow. The upper 20 m of the Magoffin Member appears to provide a near complete record of short term (up to 4 months) ebb tidal activity for the mid-Pennsylvanian central Appalachian Basin. Tidal bundling patterns within these deposits are suggestive of a semi-diurnal tidal setting where semi-monthly and monthly cycles were forced by synodic and anomalistic lunar periodicities. Tidal cycles indicate that the rhythmite interval accumulated at rates of 1 to 7 cm per semi-monthly (neap-spring-neap) event. However, accumulation rates exceeded 30 cm per day for short periods (less than 1 week) in areas where the Magoffin Member is thickest and the most proximal deltaic facies are preserved. These rates compare favorably with other ancient and modern tidal rhythmite deposits. Within the study area, the most complete tidal cycles in the Magoffin Member appear to correlate with the overall thickness of this unit. In areas where the Magoffin Member is thickest, interlaminated sandstone/mudstone deposits comprise the upper portion of the interval

and tidal cycles are better developed than in areas where the Magoffin Member is thinner and is mainly comprised of interlaminated siltstone/mudstone deposits.

The Betsie Shale and the Kendrick Shale Members of the Breathitt Group are also comprised of coarsening-upward successions of interlaminated sandstones, siltstones, and mudstones. The Betsie Shale Member is similar to the Magoffin Member and displays a hierarchy of cycles consistent with known semi-diurnal, diurnal, semi-monthly, and monthly tidal periodicities. Sedimentation rates for the Betsie Shale rhythmites typically ranged from 1 to 4 cm per day but reached rates of up to 16 cm per day. The Kendrick Shale Member displays a hierarchy of cycles consistent with known semi-diurnal, diurnal, and semi-monthly tidal periodicities. Assuming a semi-diurnal tidal setting, the Kendrick Shale rhythmites contain more than the expected 28 couplets per neap-spring-neap event. Each semi-monthly bundle contains up to 40 individual couplets, providing a rare record of both ebb and flood tidal preservation. Sedimentation rates for the Kendrick Shale rhythmites typically ranged from 1 to 4 cm per day but reached rates of up to 12.5 cm per day.

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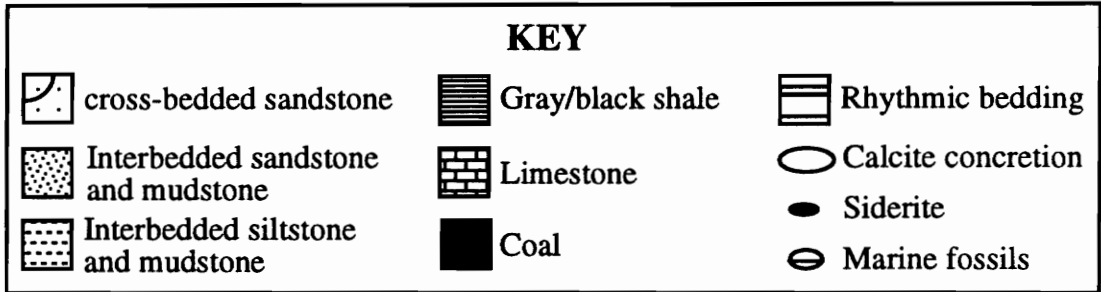
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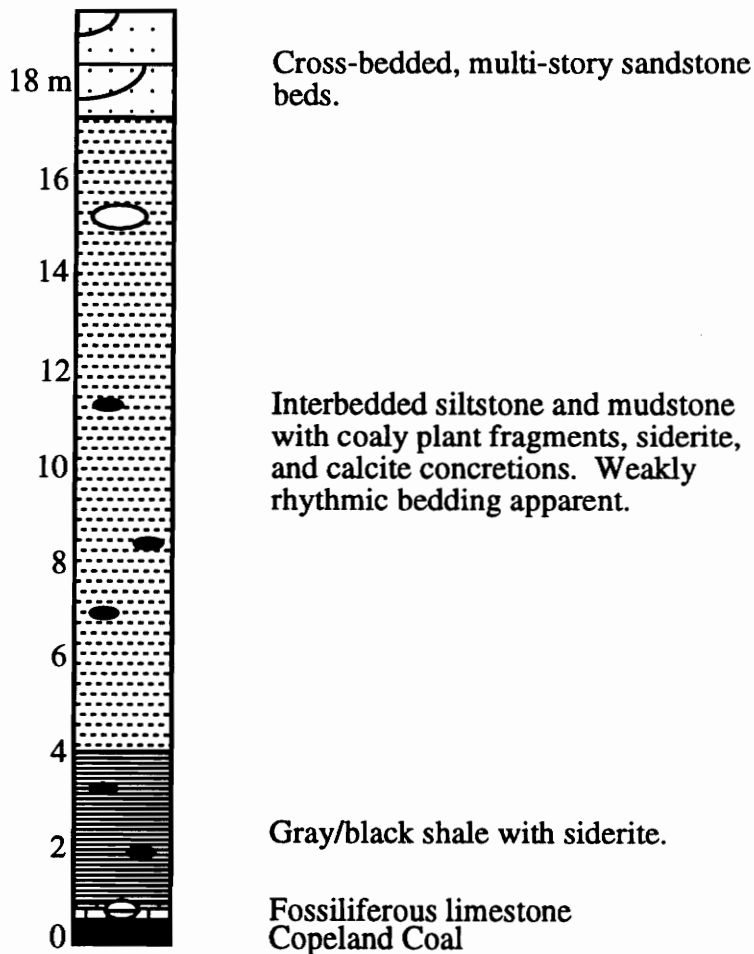
APPENDIX A: MEASURED SECTIONS

Outcrop locations along KY 80 are reported in miles. Measured outcrop thicknesses are reported in meters.



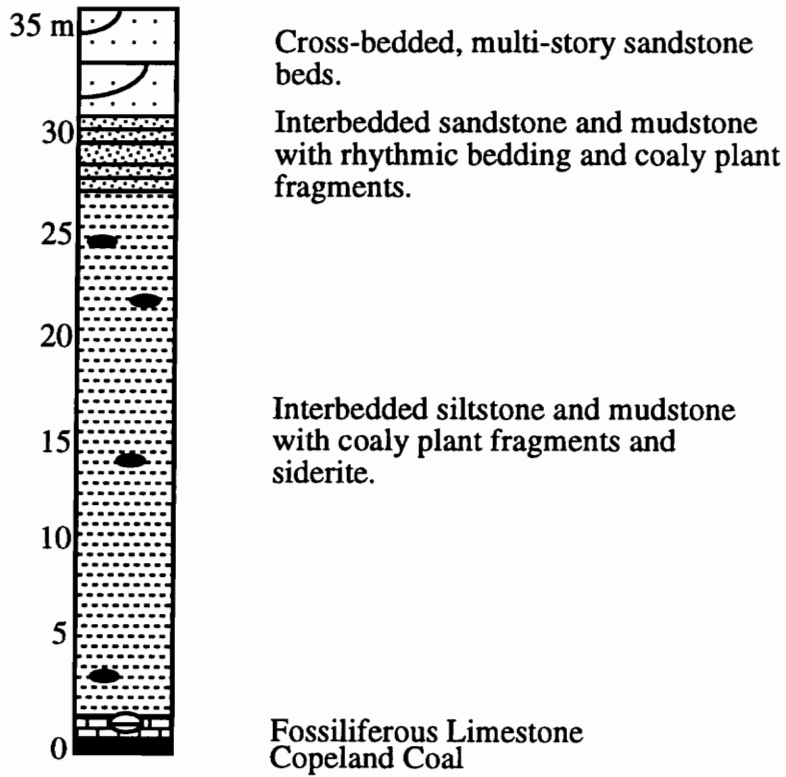
Location A

Located on the northern and southern sides of KY 80, 6.9 miles west of the junction between KY 80 and KY 160.



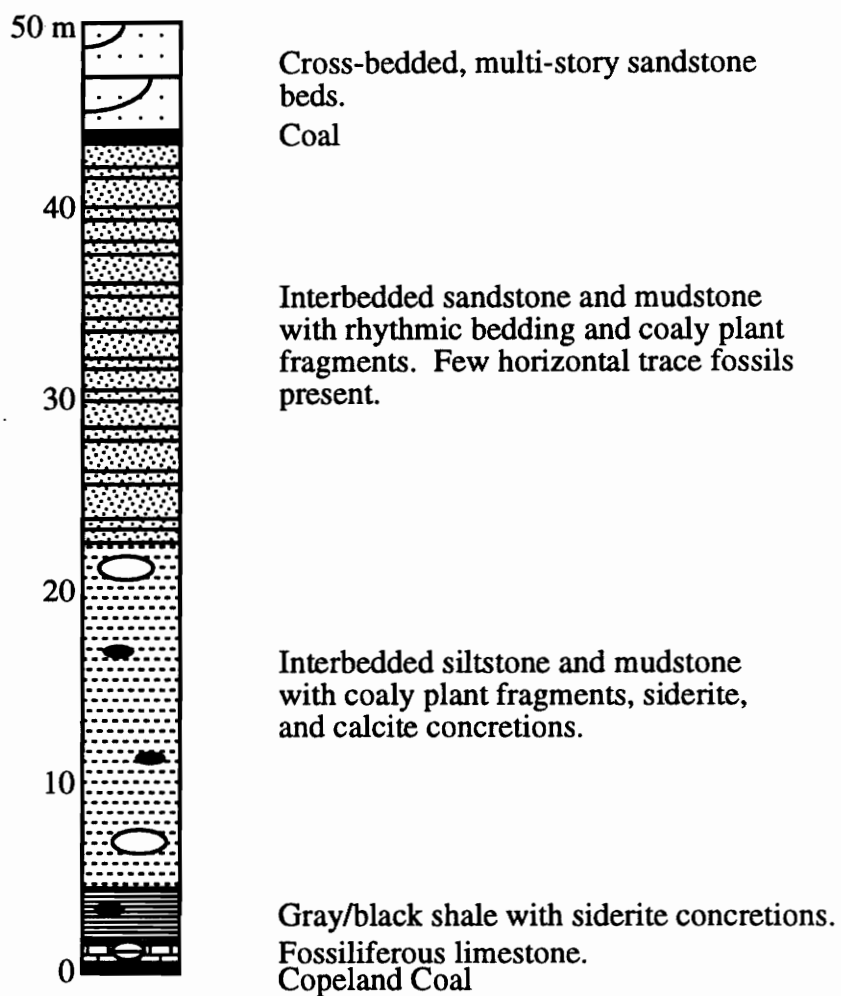
*Location B*

Located on the southern side of KY 80, 4.6 miles west of the junction between KY 80 and KY 160.



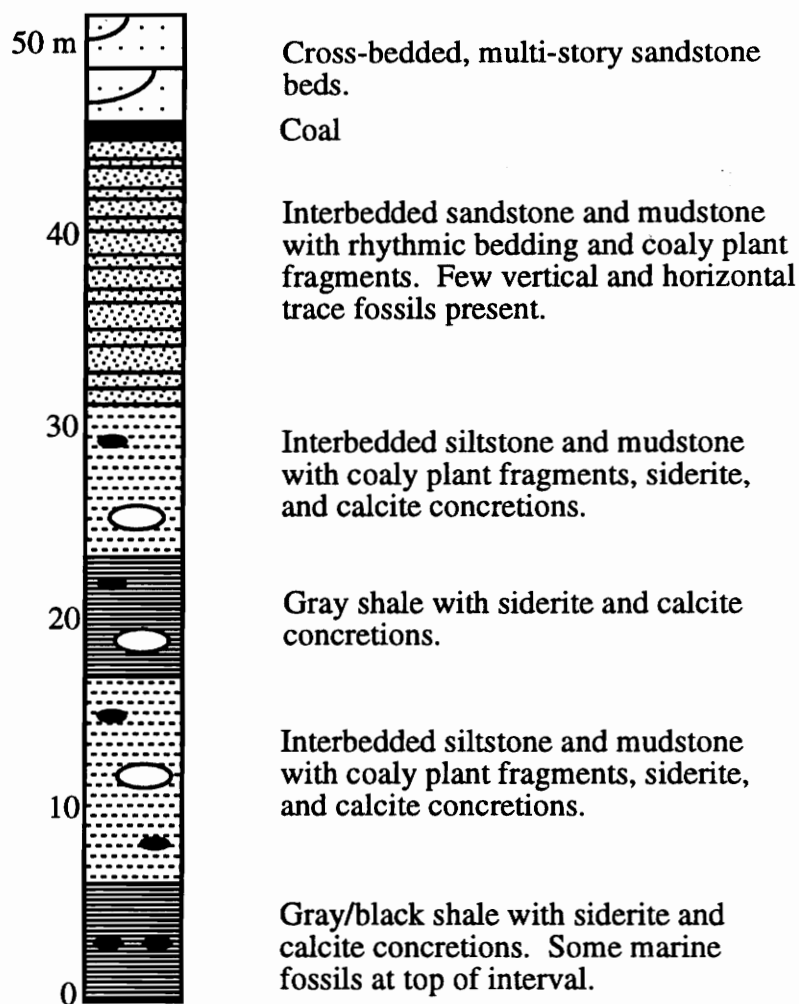
*Location C*

Located on the northern side of KY 80, 3.4 miles west of the junction between KY 80 and KY 160.



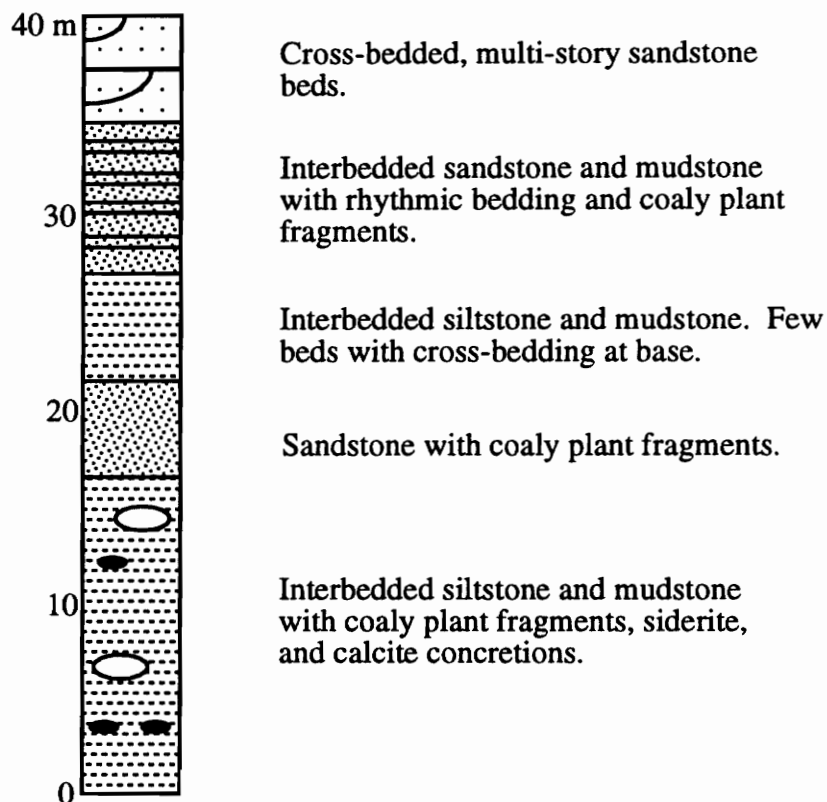
*Location D*

Located on the northern and southern sides of KY 80, 2.8 miles west of the junction between KY 80 and KY 160.



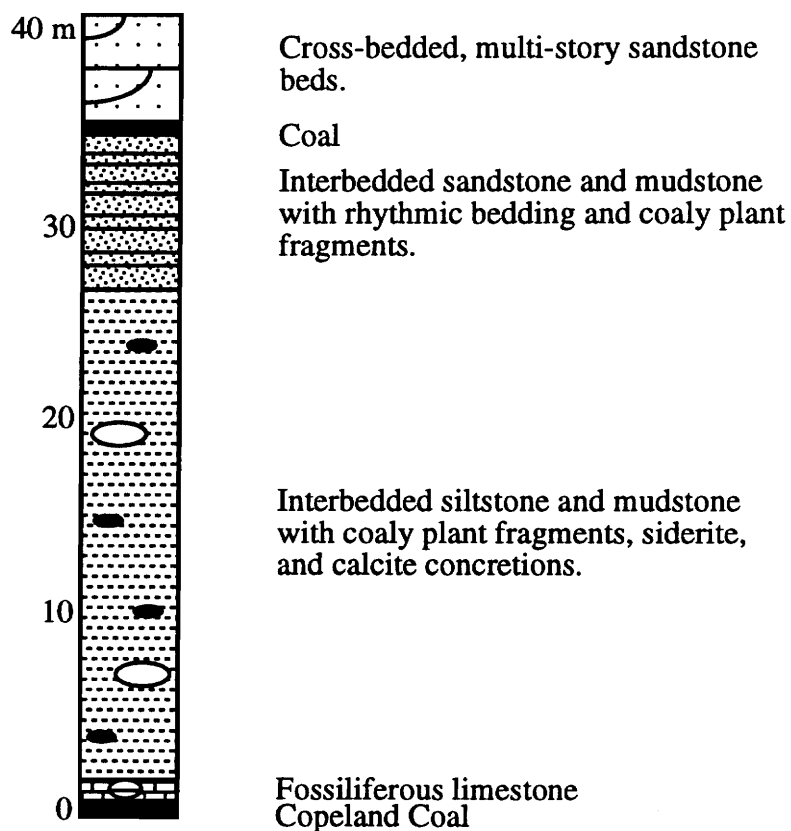
*Location E*

Located on the northern and southern sides of KY 80, 0.3 miles west of the junction between KY 80 and KY 160.



*Location F*

Locate on the northern and southern sides of KY 80, 1.4 miles east of the junction between KY 80 and KY 160.





## APPENDIX B: RHYTHMITE THICKNESS MEASUREMENTS

Data corresponding to bar graphs (Figures 14 and 19). Measurements are reported in millimeters. Data extend from the base of the rhythmite interval to the top of the rhythmite interval for each location. Unmeasurable sections within the rhythmite intervals are noted by ---.

*Location A; Bar Graph 14A*

4	9	3
5	7	4
6	10	5
4	10	4
4	12	5
6	6	7
4	18	8
3	14	5
4	10	10
5	7	6
6	4	8
6	4	4
5	7	4
5	3	4
6	3	3
9	4	
6	4	
7	3	
5	2	
7	3	
9	4	
4	2	
10	3	
6	2	
15	5	
7	3	
18	5	
20	4	
25	3	
19	3	
14	3	
13	3	
12	5	
6	4	
8	5	
8	6	
7	3	
6	4	
9	5	

*Location C; Bar Graph 14B*

14	42	120
29	78	65
11	45	95
13	79	80
17	58	100
12	90	83
19	57	95
8	74	70
19	48	105
8	60	72
26	55	60
29	62	68
28	41	65
30	61	65
22	57	53
23	31	65
17	60	55
13	28	60
18	97	
17	99	
10	119	
11	104	
7	45	
32	90	
26	45	
32	82	
30	42	
46	79	
33	35	
44	68	
45	68	
31	64	
39	45	
25	58	
29	51	
29	54	
31	46	
42	59	
27	74	
21	63	
21	88	
22	34	
53	90	
55	35	
50	78	
40	30	
60	97	
41	115	
75	100	

*Location D; Bar Graph 14C*

4	16	36	41
7	12	30	85
5	22	25	59
4	20	32	96
4	24	17	96
9	23	25	118
4	22	15	107
5	26	25	
6	21	15	
15	22	24	
4	11	15	
1	15	24	
5	5	16	
6	12	21	
3	10	13	
5	6	18	
7	4	13	
8	5	15	
5	6	14	
6	10	22	
2	3	34	
6	5	28	
3	5	36	
3	9	33	
8	8	40	
4	11	50	
11	8	62	
10	12	57	
15	5	32	
14	4	51	
14	2	47	
10	5	21	
14	5	32	
15	5	32	
11	1	32	
14	3	23	
8	2	17	
8	1	14	
3	2	36	
4	1	48	
4	1	41	
8	3	46	
5	2	57	
11	8	44	
6	10	62	
13	16	29	
8	13	63	
13	25	49	
9	22	60	

*Location E; Bar Graph 14D*

19	10	17	83
14	13	27	62
29	10	24	118
22	13	32	78
25	15	12	73
20	18	24	60
—	15	22	70
—	17	31	119
24	20	30	
22	23	43	
26	27	26	
21	19	55	
22	25	31	
25	19	32	
28	19	30	
29	17	24	
30	24	27	
23	—	19	
27	—	19	
16	111	16	
19	109	19	
17	110	11	
26	109	17	
32	60	22	
23	102	21	
16	65	73	
13	178	56	
10	124	43	
16	164	88	
10	97	68	
8	120	164	
14	115	109	
13	148	181	
12	65	118	
8	60	195	
9	76	148	
7	23	200	
9	63	172	
9	44	71	
12	47	190	
5	19	203	
8	18	120	
10	41	168	
11	17	72	
9	24	110	
9	12	69	
11	21	88	
10	13	63	
7	20	53	

*Location G ; Bar Graph 14E*

17	24	15	12
38	20	10	18
13	50	32	20
9	37	8	11
18	41	9	13
17	23	8	13
22	25	7	24
31	23	17	17
10	21	6	
34	17	10	
12	20	7	
34	26	9	
12	21	6	
42	20	7	
10	15	6	
50	29	6	
12	25	8	
60	21	11	
13	17	8	
40	5	6	
10	9	6	
25	7	10	
--	13	8	
--	9	10	
15	14	10	
12	8	12	
5	1	14	
12	10	10	
9	14	13	
11	13	18	
10	15	20	
8	12	21	
8	12	28	
8	19	10	
8	8	49	
8	12	8	
8	7	35	
11	18	8	
6	11	37	
12	12	25	
12	12	23	
19	9	6	
25	12	19	
24	9	6	
10	5	25	
26	9	6	
13	4	23	
22	19	10	
14	5	48	

*Location H; Bar Graph 19A*

10	9	9	15	15
7	8	10	18	30
10	14	10	8	---
8	10	8	13	---
6	14	8	22	12
7	9	10	10	27
9	10	12	9	15
10	10	3	7	25
8	10	4	5	17
6	8	4	11	6
7	11	5	15	30
8	6	3	11	23
7	8	5	18	15
9	12	3	13	9
10	11	4	28	16
11	7	4	8	10
13	7	10	18	12
15	7	37	11	10
12	5	5	13	12
6	6	6	15	12
7	8	3	9	10
8	10	13	10	11
6	12	6	8	10
6	5	11	11	12
9	20	9	15	21
9	---	8	21	13
7	---	6	17	10
6	4	7	15	12
7	4	4	20	14
10	4	10	25	7
5	6	10	12	6
6	10	6	17	8
5	16	10	23	15
7	12	13	25	23
3	11	9	28	25
6	10	6	20	
4	21	14	20	
3	2	10	22	
8	6	12	22	
3	11	10	22	
9	5	18	17	
7	7	31	19	
4	9	25	22	
4	5	17	27	
4	7	20	15	
4	10	15	15	
5	7	11	22	
4	9	22	25	
8	15	18	30	

*Location I; Bar Graph 19B*

12	6	7	8	11
12	4	9	10	15
15	4	18	9	9
16	4	18	9	13
12	7	7	11	6
14	5	12	15	15
13	4	5	9	5
9	5	21	10	18
13	5	38	22	10
8	6	35	32	4
6	8	8	11	10
6	3	38	10	8
4	9	5	9	5
7	7	21	40	15
5	8	2	10	6
4	6	25	32	16
5	5	7	6	2
4	4	34	44	22
7	6	24	6	1
5	5	38	30	14
5	8	15	5	19
3	7	20	25	30
7	7	12	4	18
4	10	10	25	3
6	23	13	6	14
5	20	11	21	8
6	7	14	6	20
3	11	12	37	6
7	4	12	5	6
6	4	14	32	21
6	4	13	10	10
6	7	27	51	33
5	5	33	13	4
3	5	30	25	17
4	5	28	35	12
7	5	12	3	8
5	4	6	45	6
4	5	4	25	10
5	6	2	3	
7	3	7	32	
5	7	12	2	
4	6	7	29	
5	12	8	5	
5	12	13	30	
5	15	19	35	
5	19	4	9	
11	18	11	34	
12	3	25	16	
13	5	7	18	

## APPENDIX C: SEDIMENTATION RATES

*Location A*

Minimum daily rate: 0.5 cm  
 Average daily rate: 1.4 cm  
 Maximum daily rate: 4.5 cm

Minimum semi-monthly rate: 6.5 cm  
 Average semi-monthly rate: 16.3 cm  
 Maximum semi-monthly rate: 24.6 cm

*Location C*

Minimum daily rate: 1.8 cm  
 Average daily rate: 10.7 cm  
 Maximum daily rate: 22.3 cm

Minimum semi-monthly rate: 35.8 cm  
 Average semi-monthly rate: 116.7 cm  
 Maximum semi-monthly rate: 217.9 cm

*Location D*

Minimum daily rate: 0.3 cm  
 Average daily rate: 4.2 cm  
 Maximum daily rate: 22.5 cm

Minimum semi-monthly rate: 12.2 cm  
 Average semi-monthly rate: 36.9 cm  
 Maximum semi-monthly rate: 113.7 cm

*Location E*

Minimum daily rate: 1.6 cm  
 Average daily rate: 8.9 cm  
 Maximum daily rate: 39.3 cm

Minimum semi-monthly rate: 20.0 cm  
 Average semi-monthly rate: 102.7 cm  
 Maximum semi-monthly rate: 288.2 cm

*Location G*

Minimum daily rate: 1.2 cm  
 Average daily rate: 3.5 cm  
 Maximum daily rate: 8.7 cm

Minimum semi-monthly rate: 22.0 cm  
 Average semi-monthly rate: 43.1 cm  
 Maximum semi-monthly rate: 65.8 cm

*Location H*

Minimum daily rate: 0.7 cm  
 Average daily rate: 2.7 cm  
 Maximum daily rate: 16.0 cm

Minimum semi-monthly rate: 16.0 cm  
 Average semi-monthly rate: 25.5 cm  
 Maximum semi-monthly rate: 60.9 cm

*Location I*

Minimum daily rate: 0.6 cm  
 Average daily rate: 2.5 cm  
 Maximum daily rate: 12.4 cm

Minimum semi-monthly rate: 10.9 cm  
 Average semi-monthly rate: 31.2 cm  
 Maximum semi-monthly rate: 60.0 cm

## APPENDIX D: LOCATIONS OF MEASURED SUB-SURFACE DATA POINTS

Location-Fig. 23 (page 87)	Quadrangle Name	Borehole Number (KY Geological Survey)	Thickness (m)
1	Tiptop	1	18.6
2	Tiptop	30	16.5
3	Tiptop	36	5.2
4	Tiptop	63	15.5
5	David	3	19.2
6	David	25	19.2
7	David	89	1.2
8	David	99	12.8
9	Martin	7	29.9
10	Martin	30	26.8
11	Martin	36	14.9
12	Martin	37	8.5
13	Harold	22	14.6
14	Harold	33	19.8
15	Harold	34	11.6
16	Harold	35	7.3
17	Harold	36	12.8
18	Harold	69	2.7
19	Noble	154	47.9
20	Noble	159	25.0
21	Vest	23	20.7
22	Vest	150	23.5
23	Vest	154	19.8
24	Vest	158	23.2
25	Vest	176	26.2
26	Handshoe	11	34.8
27	Handshoe	24	36.6
28	Handshoe	28	22.3
29	Handshoe	43	38.4
30	Handshoe	48	23.2
31	Handshoe	67	31.4
32	Handshoe	76	40.5
33	Handshoe	146	36.2
34	Wayland	1	22.6
35	Wayland	3	33.5
36	Wayland	25	24.4
37	Wayland	33	25.0
38	Wayland	37	20.7

Location- <u>Fig. 23</u> (page 87)	<u>Quadrangle Name</u>	<u>Borehole Number</u> (KY Geological Survey)	<u>Thickness (m)</u>
39	McDowell	16	33.8(?)
40	McDowell	17	17.1
41	Hazard North	186	32.9
42	Carrie	7	30.2
43	Carrie	75	22.3
44	Carrie	92	29.3
45	Hindman	9	31.7
46	Hindman	26	34.1
47	Hindman	61	31.7
48	Hindman	74	34.8
49	Kite	10	18.3
50	Kite	12	24.1
51	Kite	13	24.4
52	Kite	36	40.5
53	Hyden East	4	26.8
54	Hyden East	10	46.6
55	Hyden East	15	24.7
56	Hazard South	2	31.7
57	Hazard South	22	34.1
58	Hazard South	28	38.0
59	Hazard South	57	46.6
60	Vicco	1	51.2
61	Blackey	44	26.2
62	Blackey	46	23.2
63	Cutshin	1	27.1
64	Cutshin	13	30.2
65	Cutshin	15	29.0
66	Cutshin	39	25.3
67	Cutshin	49	40.5
68	Cutshin	63	34.1
69	Leatherwood	9	34.5
70	Leatherwood	36	30.5
71	Leatherwood	41	32.9
72	Leatherwood	49	33.8
73	Tilford	11	36.6

<u>Location-Fig. 23</u> <u>(page 87)</u>	<u>Quadrangle Name</u>	<u>Borehole Number</u> <u>(KY Geological Survey)</u>	<u>Thickness (m)</u>
74	Tilford	14	40.2
75	Tilford	20	61.0
76	Bledsoe	11	31.7
77	Bledsoe	13	30.8
78	Bledsoe	20	31.7
79	Bledsoe	33	29.6
80	Bledsoe	58	34.1

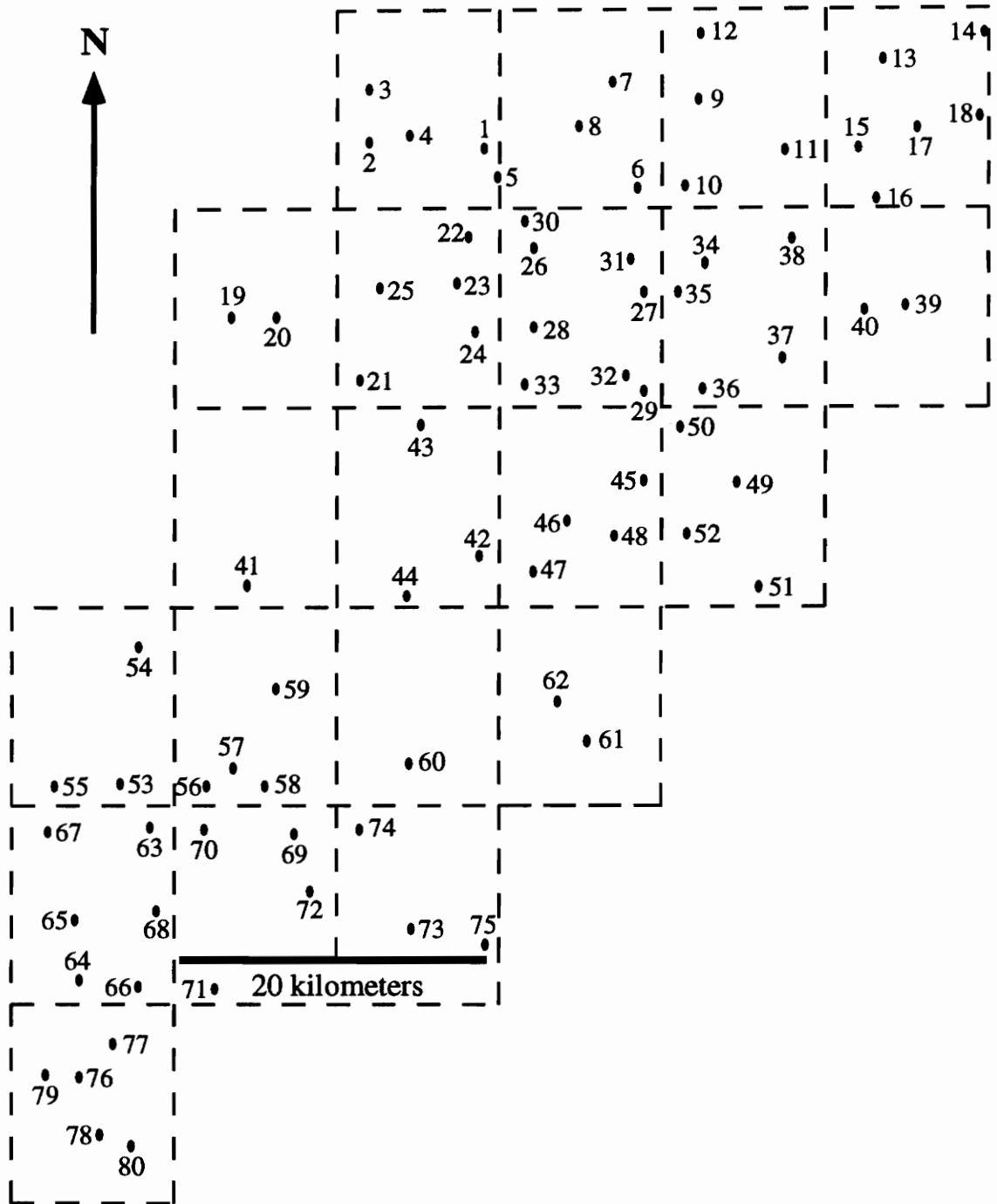


FIG. 23.—Location map of measured sub-surface data points.

## VITA

Rhonda M. Adkins was born in Radford, Virginia on August 30, 1970. She received her Bachelor of Science degree in 1993 at Virginia Tech, Blacksburg, Virginia. She enrolled in the graduate program of the Department of Geological Sciences, at Virginia Tech, in August 1994. After completion of the Master of Science degree, R. M. Adkins will be employed as an exploration geologist with Texaco, Inc. in New Orleans, Louisiana.

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