[AMERICAN JOURNAL OF SCIENCE, VOL. 287, NOVEMBER, 1987, P. 893-926]

AN EPEIRIC SHELF-TO-BASIN TRANSITION: BEDFORD-BEREA SEQUENCE, NORTHEASTERN KENTUCKY AND SOUTH-CENTRAL OHIO

JACK C. PASHIN and FRANK R. ETTENSOHN
Department of Geological Sciences, University of Kentucky, Lexington, Kentucky, 40506

ABSTRACT. Paleoenvironmental analysis of the Devonian-Mississippian Bedford-Berea sequence of northeastern Kentucky and south-central Ohio was based upon field investigation of stratigraphic, lithologic, and paleontologic attributes. The Bedford-Berea sequence in this area represents progradation from a storm-dominated shelf into an oxygen-deficient basin. The shelf-to-basin transition is shown to be unusually abrupt for an epeiric sea floor; the nature of this transition and a concomitant proliferation of lithofacies are probably related to structurally controlled sea-floor topography. Basinal environments were characterized by anaerobic, pelagic sedimentation, and shelf environments by storm-related silt deposition. Lower-slope environments were dominated by dysaerobic mud deposition which was episodically interrupted by influxes of turbiditic silt. Upper-slope environments, which included an apparent shelf-break complex with hummocky topography, were apparently dominated by storm-related silt deposition. Basement faulting is inferred to have influenced facies distribution and the sea-floor topography of the Bedford-Berea shelf–slope–basin system.

INTRODUCTION

In northeastern Kentucky and south-central Ohio, the black to greenish-gray shales and gray to greenish-gray siltstones of the Bedford and Berea formations separate the black, fissile shales of the underlying Cleveland Member of the Ohio Shale from the very similar, overlying Sunbury Shale (fig. 1) . The Bedford Shale can be traced southward from northeastern Ohio into Bath County, east-central Kentucky, where it passes into black shale with sparse interbeds of greenish-gray shale, all of which are presently mapped in the New Albany Shale (McDowell and Weir, 1977; fig. 1). We realize that the name New Albany should be restricted to the Illinois Basin (deWitt, 1981; Ettensohn and Elam, 1983, 1985) and is probably inappropriate for any part of the Appalachian Basin. Nonetheless, the New Albany was mapped in the southern parts of our study area, and to maintain conformity with the geologic quadrangle maps (Weir, 1976; Weir and McDowell, 1976; McDowell and Weir, 1977; McDowell, 1978), which most geologists in the area use, we continue to use the term New Albany as it is used on the maps. Though both the Bedford and Berea are distinct lithostratigraphic units, they and equivalent strata in the New Albany Shale are parts of a single depositional continuum as noted by Ettensohn and Elam (1985). Hence, we refer to them collectively as the Bedford-Berea sequence.

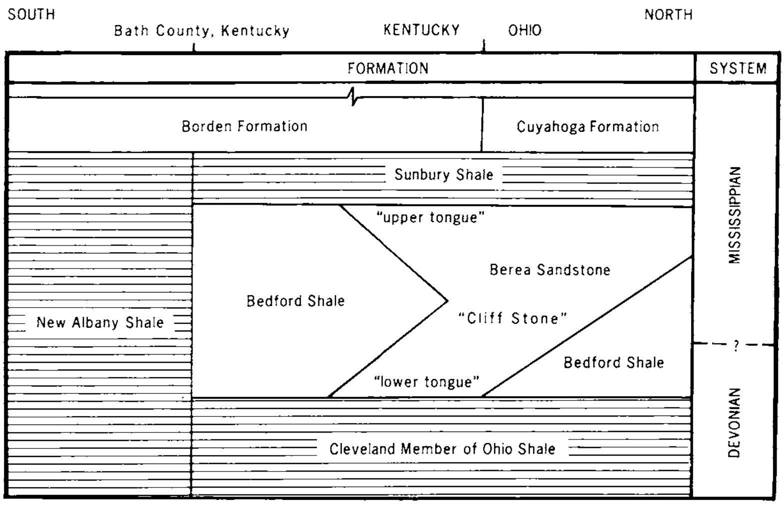

Fig. 1. Generalized Late Devonian-Early Mississippian stratigraphy, northeastern Kentucky and south-central Ohio. Black shale units shaded; lighter colored shale and siltstone units unshaded.

The precise ages of the Bedford and Berea formations have long been a subject of controversy (see Hyde, 1953). This controversy stems from a lack of biostratigraphic evidence for the placement of the Devonian-Mississippian boundary in the Appalachian Basin (Hyde, 1953; deWitt, 1970). Recently, however, deWitt (1970) suggested that the Bedford-Berea sequence is Mississippian in age, with the possible exception of the basal few centimeters of the sequence, which may be of latest Devonian age (fig. 1). This interpretation is supported by recent finds of Devonian ammonoids near the base of the Bedford (House, Gordon, and Hlavin, 1986).

The Bedford and Berea formations were named by Newberry (1870) for exposures near Cleveland, Ohio, and Morse and Foerste (1909a, 1912) were first to trace these formations into Kentucky. Most early work in the study area, however, centered on delineating the lithologic and paleontologic characteristics of these formations (Morse and Foerste, 1909a, b, 1912; Hyde, 1911, 1953; Butts, 1922; Stockdale, 1939; McFarlan, 1943; Hoover, 1960). These workers found that the Berea Sandstone does not occur south of Lewis County, Ky., and that lithologies typical of the Bedford Shale are not present south of Powell County, Ky. (fig. 2), except for lenses of Bedford-type shale only centimeters thick.

During the U. S. Geological Survey-Kentucky Geological Survey cooperative mapping program, Morris and Pierce (1967) found that the Berea Sandstone (actually a siltstone formation which was mapped as sandstone in Kentucky) could be divided into two distinct tongues in

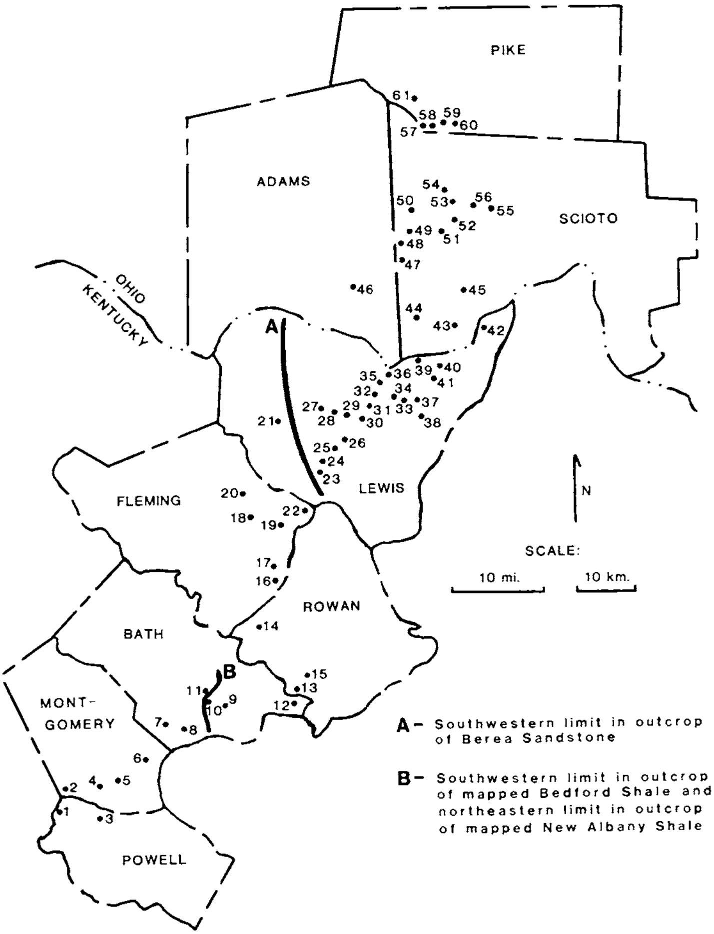

Fig. 2. Map of field area showing distribution of study sites and outcrop distribution of units studied.

north-central Lewis County, Ky. These two tongues will be referred to as the "upper tongue" and "lower tongue" (fig. 1); the "lower tongue" lies upon the Cleveland Shale at many places. The "upper tongue" is separated from the "lower tongue" by an eastward-thinning wedge of Bedford Shale, which pinches out in the eastern half of Lewis County, Ky. In the eastern portion of the county, the Berea Sandstone makes up almost the entire Bedford-Berea sequence and forms the "Cliff Stone" of Hyde (1953).

Another major advance in Bedford-Berea stratigraphy was made by VanBeuren (ms), Elam (ms), Kepferle, Potter, and Pryor (1981), and Ettensohn and Elam (1983, 1985) who, using artificial gamma-ray logs (see Ettensohn, Fulton, and Kepferle, 1979), identified black shales equivalent to the Bedford-Berea in the Ohio, New Albany, and Chattanooga shales as far south as Cumberland County, south-central Kentucky. These workers found that the Bedford-Berea is present as an interval of black shale of reduced radioactivity separating the more radioactive Cleveland and Sunbury black-shale equivalents, and that the Bedford-Berea does not truly pinch out in east-central Kentucky but merely passes laterally into coeval black shales.

Previous work.—Aside from being first to trace the Bedford-Berea into Kentucky, Morse and Foerste (1909b) also were first to describe the Bedford fauna from Kentucky. The fauna is a thin-shelled, brachiopod-mollusc fauna from a Bedford-type layer now mapped within the New Albany Shale; a similar fauna was described earlier from the Bedford Shale of Ohio by Herrick (1888). As already indicated, most early work in the study area centered on delineating lithologic and paleontologic attributes (Morse and Foerste, 1909a, b, 1912; Hyde, 1911, 1953; Butts, 1922; Stockdale, 1939; Hoover, 1960). For example, Hyde (1911) studied the wave ripples that are so prevalent in the two formations and noted a persistent linearity and parallelism of the ripple crests. He found that nearly all the ripple crests trend from N 40 W to N 55 W in central Ohio, whereas farther southward, ripple crests gradually swing to a more east-west orientation, such that in Lewis County, Ky, ripple crests range in orientation from N 60 W to N 70 W. Hyde, however, was unable to explain these changes in ripple orientation, but Potter and others (1983) related them to changes in the orientation of paleoslope.

A now classic treatment of the Bedford-Berea sequence (Pepper, deWitt, and Demarest, 1954) represents the culmination of an extensive 11-yr mapping program conducted by the U. S. Geological Survey. This pioneering work advanced major ideas on environmental interpretation as well as on regional paleogeography. Pepper, deWitt, and Demarest (1954) interpreted the two formations as fluvio-deltaic, barrier-bar, and offshore, marine deposits. They also characterized northeastern Kentucky and south-central Ohio as an area of offshore silt, which was derived from several fluvio-deltaic sources that lay to the east during Bedford-Berea deposition.

Walls (1975) identified three distinctive lithofacies in the subsurface and confirmed the presence of the Virginia-Carolina Delta (see Pepper, deWitt, and Demarest, 1954). The Virginia-Carolina Delta evidently prograded northwestwardly into West Virginia and easternmost Kentucky during Bedford-Berea deposition.

Rothman (ms) studied the Berea of south-central Ohio and northeasternmost Kentucky by means of outcrop and thin-section analysis. His analysis showed that the Berea in these areas is composed largely of coarse-grained, slightly calcareous siltstone, and that in most outcrop sections, the grain size coarsens upward weakly. Rothman was first to interpret the Berea of northeastern Kentucky and south-central Ohio as a regressive, siliciclastic, shelf deposit.

In addition to identifying black shales equivalent to the Bedford-Berea, Elam (ms) constructed an isopachous map of the Bedford-Berea sequence based on approx 9400 geophysical and driller's logs. He also presented evidence that the Bedford-Berea sequence represents a regressive clastic wedge that prograded into a sediment-deficient, euxinic basin. Applying the findings of Byers (1977) to the Bedford-Berea, Elam further suggested that black, fissile shales rich in organic matter generally represent anaerobic conditions, whereas lighter colored, less-fissile shales poor in organic matter generally represent dysaerobic conditions. In a detailed investigation of the relationship of the Bedford-Berea sequence to density stratification, Ettensohn and Elam (1985) mapped the apparent intersection of the paleopycnocline with the sea bottom in eastern Kentucky. Ettensohn and Elam (1985) were reluctant to assign any Bedford-Berea sediments to the aerobic zone but suggested that the Berea represents at least locally aerobic conditions.

Potter and others (1983) studied Berea exposures throughout the Bedford-Berea outcrop belt as well as in several cores. They found that all the Berea siltstones exposed between central Ohio and northeastern Kentucky probably were deposited in storm-dominated shelf environments, and their core study showed that rocks representing such environments apparently are widespread in the subsurface.

Objectives.—The Bedford and Berea formations have produced oil and gas for many years (Pepper, deWitt, and Demarest, 1954), and overlying and underlying black shales are currently being investigated as possible oil-shale and uranium resources (Ettensohn and Elam, 1983). Yet, despite great economic potential, the paleoenvironmental aspects of the Bedford-Berea sequence have received only limited attention since the classic work of Pepper, deWitt, and Demarest (1954). Only in recent years have direct inquiries been made into the nature of the Bedford-Berea of northeastern Kentucky and south-central Ohio (Rothman, ms; Elam, ms; Potter and others, 1983; Ettensohn and Elam, 1983, 1985).

Elam (ms) and Ettensohn and Elam (1983, 1985) concentrated on the relationship of the Bedford-Berea sequence to oxygen-deficient waters, whereas Rothman (ms) and Potter and others (1983) focused on the sedimentology and depositional environments of the Berea. These studies have elucidated much about conditions on the Bedford-Berea shelf and in the adjacent basin, but relatively little is known about the shelf-to-basin transition. Consequently, a comprehensive, up-to-date paleoenvironmental analysis of the Bedford-Berea sequence in northeastern Kentucky and south-central Ohio is lacking. Bedford-Berea strata representing shelf-to-basinal environments are well exposed in northeastern Kentucky and south-central Ohio, offering an excellent opportunity to investigate paleoenvironmental aspects of the sequence. Hence, the major objectives of this study were to interpret the depositional environments of the Bedford-Berea sequence of northeastern Kentucky and south-central Ohio through outcrop investigation of its lithologic, stratigraphic, and paleontologic attributes and to evaluate possible regional controls affecting the shelf-to-basin transition.

Procedures.—The study area (fig. 2) is situated on the west-central margin of the Appalachian Basin. Field work was conducted along the Knobs outcrop belt from Powell County, Ky, to Pike County, Ohio, where Bedford-Berea strata are well exposed. Previous studies of the Bedford-Berea outcrop belt (Morse and Foerste, 1909a, 1912; Stockdale, 1939; Hyde, 1953; Ohio Geol. Soc. and the Geol. Soc. of Kentucky, 1968; Coogan and others, 1981; Elam, ms; Potter and others, 1983), as well as geologic quadrangle maps compiled during the U. S. Geological Survey-Kentucky Geological Survey cooperative mapping program, served as guides for exposure selection and correlation. In order to collect data suitable for paleoenvironmental analysis and to determine the areal extent of the various Bedford-Berea lithologies, outcrops at 61 loc. (fig. 2) were measured, sampled, and described in terms of lithology, grain size, color, primary sedimentary structures, fossil content, and bioturbation using standard field techniques. Bedding thicknesses described in this paper are in accordance with the classification of Ingram (1954). Detailed measured sections as well as exact locations for the examined outcrops are provided in Pashin (ms).

BEDFORD-BEREA LITHOLOGIES AND LITHOFACIES

Black shales.—Black shales were first included in the Bedford-Berea sequence by Elam (ms), who recognized the Bedford-Berea equivalent as an interval of shale with reduced radioactivity separating more radioactive Cleveland and Sunbury equivalents. Bedford-Berea black-shale equivalents generally are black, silty, highly fissile, and brittle; however, laminae of silty, grayish-black to dark greenish-gray shale locally are common. Bedford-Berea black-shale equivalents tend to have many more lighter colored laminae and are less pyritic than Cleveland and Sunbury black shales (Elam, ms), but discrimination of Bedford-Berea black-shale equivalents from those equivalent to the Cleveland and Sunbury can only be verified through use of gamma-ray profiles. As mappable units, black-shale equivalents cannot be separated as distinct lithologies. Hence, to the north, these shales are mapped with the Ohio, and to the south, with the New Albany.

Lingula, an inarticulate brachiopod, is the only common megafossil present in Bedford-Berea black-shale equivalents. In addition to *Lingula,* occasional specimens of *Orbiculoidea,* another inarticulate brachiopod, are found in some greenish-gray laminae. Moreover, it is not uncommon to find burrows that descend from greenish-gray laminae into black shale; they are commonly filled with greenish-gray sediment. Microfossils such as conodonts and the alga *Tasmanites* also are locally abundant.

Even though thin layers and lenses of greenish-gray Bedford Shale lithology are present in Bedford-Berea black-shale equivalents, they are too thin and too local to be mapped as Bedford Shale, and hence only the

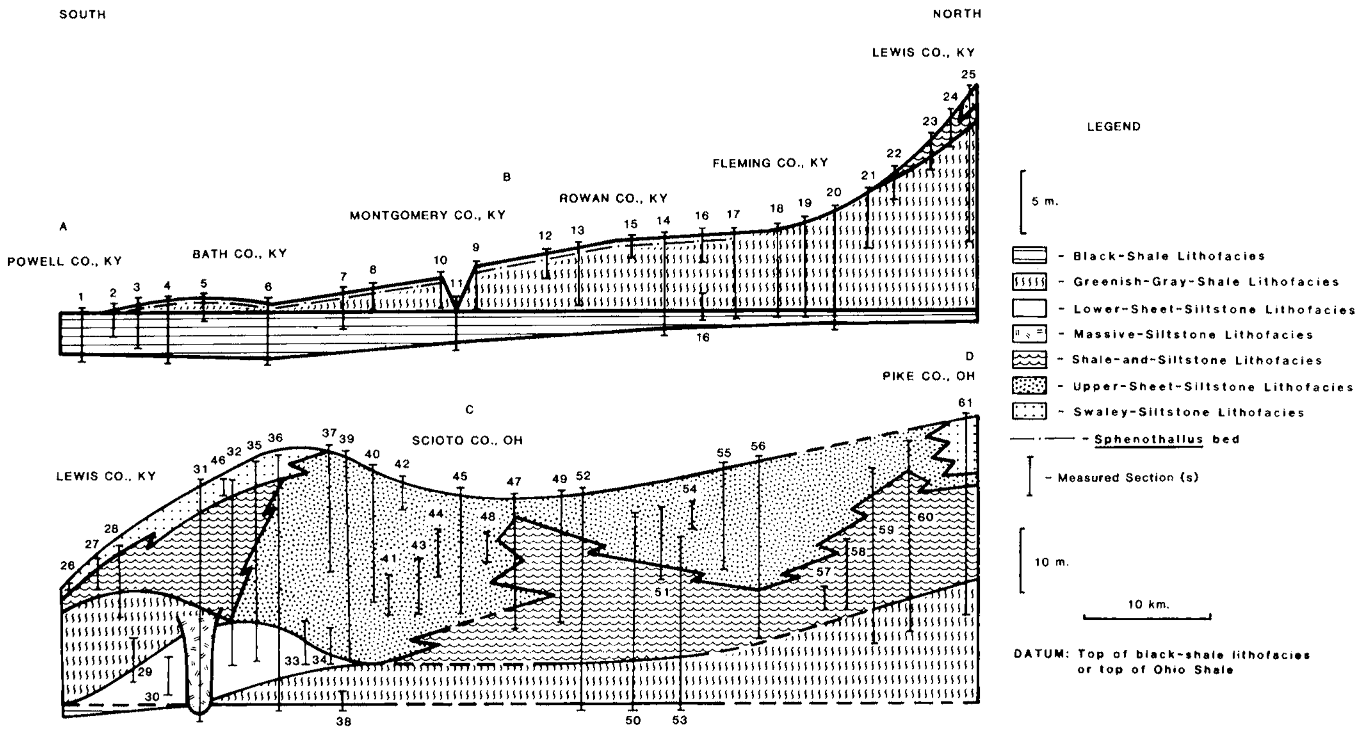

Fig. 3. Schematic cross section showing relationships among Bedford-Berea lithofacies in the field area. Line of cross section shown in figure 4.

dominant black shales can be mapped. We designate parts of the Bedford-Berea sequence in which black shales dominate over other lithologies as the black-shale lithofacies. Based upon data in Elam (ms) and Ettensohn and Elam (1983, 1985), the black-shale lithofacies is present at the base of the Bedford-Berea sequence (fig. 3) and comprises the entire Bedford-Berea sequence south of the field area (figs. 3 and 4). This lithofacies comprises most of the sequence as far north as Bath County, Ky., and reaches a maximum thickness of approx 4 m (fig. 3). From Lewis County, Ky, northward, however, the black-shale lithofacies apparently becomes volumetrically insignificant (fig. 3).

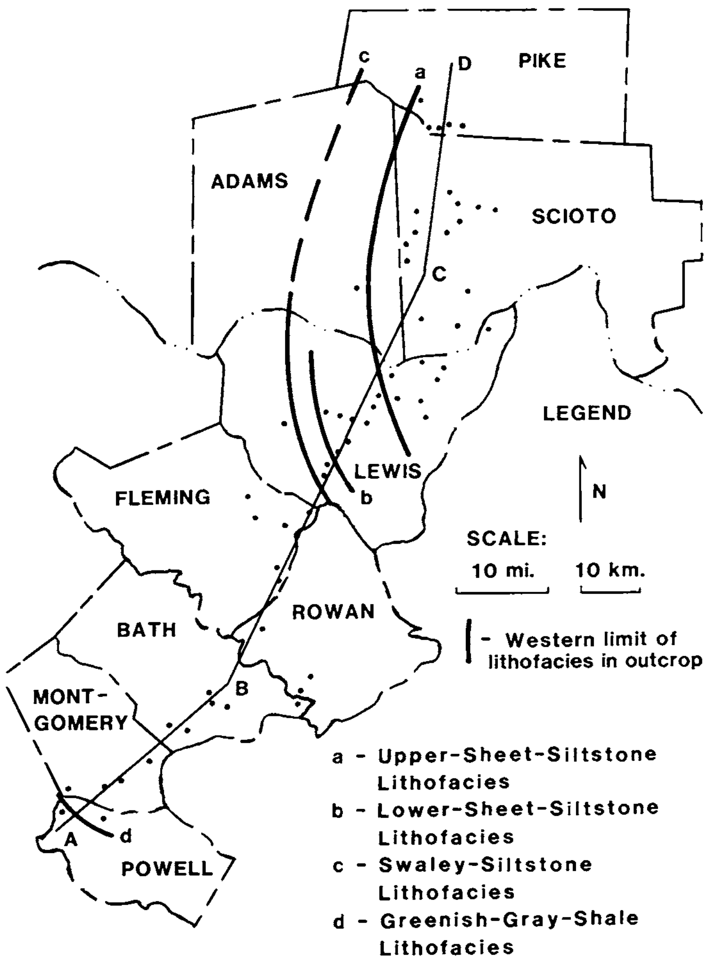

Fig. 4. Map of field area showing distribution of Bedford-Berea lithofacies and position of cross section in figure 3.

Greenish-gray shales.—Bedford-Berea shales are most commonly dark greenish-gray, but colors vary from grayish-black to greenish-gray or bluish-gray. For the sake of convenience, these shales will be referred to as greenish-gray. Greenish-gray shales occur throughout virtually all the Bedford-Berea sequence, are commonly silty, and have an irregular, platy fissility (fig. 5A). Additionally, these shales are commonly calcareous and contain flecks and nodules of pyrite.

The Bedford fauna, dominated by *Orbiculoidea, Lingula,* and nuculoid bivalves, is present in thicker greenish-gray shales that directly overlie or intertongue with black shales. *Parallelodon irvinensis* (Foerste), a modioliform, suspension-feeding bivalve, and a few articulate brachiopods (chonetids, *Rhipidomella, Schuchertella*) are also common in the greenish-gray shales. Body fossils found in the greenish-gray shales are all complete specimens. Phosphatic shells are well preserved, whereas calcareous shells are preserved as casts and impressions or are locally pyritized.

The greenish-gray shales are extremely bioturbated, as indicated by their irregular fissility. Horizontal burrows (fodinichnia) predominate in these shales. However, vertical burrows (fodinichnia) also commonly descend from greenish-gray shales into underlying black shales.

Although greenish-gray shales occur throughout the Bedford-Berea sequence, the greenish-gray-shale lithofacies is present only where greenish gray shales predominate over other lithologies. Siltstones contained within the greenish-gray-shale lithofacies lack wave ripples. In the field area, this lithofacies begins in the south at Indian Fields (loc. 2), where it is represented by the *Sphenothallus* bed, a silty subfacies of the greenish-gray-shale lithofacies. The greenish-gray-shale lithofacies thickens northward to a maximum thickness of approx 13 m in Lewis County, Ky., where it meets more silty lithofacies (fig. 3). In the northernmost portion of the study area, the greenish-gray-shale lithofacies is present only at the base of the Bedford-Berea sequence (fig. 3).

Sphenothallus bed.—An unusual, thin bed of medium bluish-gray, shaly siltstone, which contains phosphate nodules, glauconite, burrows (fodinichnia), and the Bedford fauna is present in the southern portion of the field area. In fact, Morse and Foerste (1909b) described the Bedford fauna from this bed at Indian Fields, Ky. (loc. 2). A probable annelid dwelling tube, *Sphenothallus bicarinatus* (Girty), is especially characteristic of this bed. In the northern part of its distribution, the bed occurs as a grayish-black, shaly siltstone that is burrowed, contains phosphate, and apparently lacks body fossils. We informally designate this layer the *Sphenothallus* bed.

The *Sphenothallus* bed is present in both the Bedford and New Albany formations and is present at most localities south of Fleming County, Ky. (fig. 3). Scintillometer profiles of several cores (Elam, ms) clearly demonstrate that the bed was deposited near the very top of the Bedford-Berea sequence, only centimeters below black shales equivalent to the Sunbury, and generally several meters above black shales equivalent to the Cleveland. The *Sphenothallus* bed is included as a subfacies of the greenish-gray-shale lithofacies.

Unrippled siltstones.—Unrippled siltstones (those lacking wave ripples) are light greenish-gray to medium-gray, generally well sorted, and vary in thickness from laminae to thick beds. Grain sizes range from silt to very fine sand and tend to increase with increasing bed thickness, although as Rothman (ms) noted, sandstones are rare in the Berea of northeastern Kentucky and south-central Ohio. Laminated and thinly bedded siltstones tend to be tabular and have relatively great lateral continuity, and the more thinly bedded siltstones can be wavy or lenticular (fig. 5A). The thicker siltstone beds also tend to be tabular and have relatively great lateral continuity and commonly exhibit flow rolls (fig. 5B), load casts, and flame structures.

Bioturbation of the laminated and thinly bedded siltstones effectively obliterated internal sedimentary structures. Locally, however, bioturbation was minimal, and internal structures, including horizontal laminae and current-ripple laminae, can be discerned. Laminated and thinly bedded, unrippled siltstones are especially characteristic of the greenish-gray-shale lithofacies but are not the dominant lithology. Such siltstones tend to become thicker, coarser grained, and more numerous both upward in section and to the north, where the greenish-gray-shale lithofacies adjoins more sandy lithofacies (fig. 3).

The thicker siltstones have sharp basal contacts, bioturbated upper contacts, and as previously mentioned, flow rolls, load casts, and flame structures. These strata seldom show internal sedimentary structures, but at Holly Branch (loc. 29, fig. 2), individual siltstone beds exhibit the following ascending succession: (1) a structureless basal interval containing sparse shale clasts, (2) an interval of horizontal laminae, (3) an interval of convolute laminae with flame structures (fig. 5C), and (4) a gradational, typically burrowed top.

The thicker, unrippled siltstones are characteristic of only the lower-sheet-siltstone lithofacies, which is composed of at least 33 percent unrippled, medium- to thick-bedded siltstones. The remainder of the lower-sheet-siltstone lithofacies is composed of lithologies typical of the greenish-gray-shale and black-shale lithofacies. The lower-sheet-siltstone lithofacies is exposed only at a few localities in Lewis County, Ky. (fig. 4), where it underlies a northeastwardly thinning tongue of the greenish-gray-shale lithofacies (fig. 3) and comprises most of the "lower tongue" (fig. 1). The lower-sheet-siltstone lithofacies also contains interbedded black shales in the southern part of its distribution and rises in the section such that, less than 15 km north of the Walnut Grove Church (loc. 31; fig. 2), the lithofacies rests upon approx 7 m of the greenish-gray-shale lithofacies and underlies rippled siltstones (fig. 3).

Rippled siltstones.—Rippled siltstones are those containing wave ripples. They comprise much of the Bedford-Berea sequence in northeastern Kentucky and south-central Ohio and probably are the most typical or classic Bedford-Berea lithology (see Hyde, 1911, 1953; Pep-

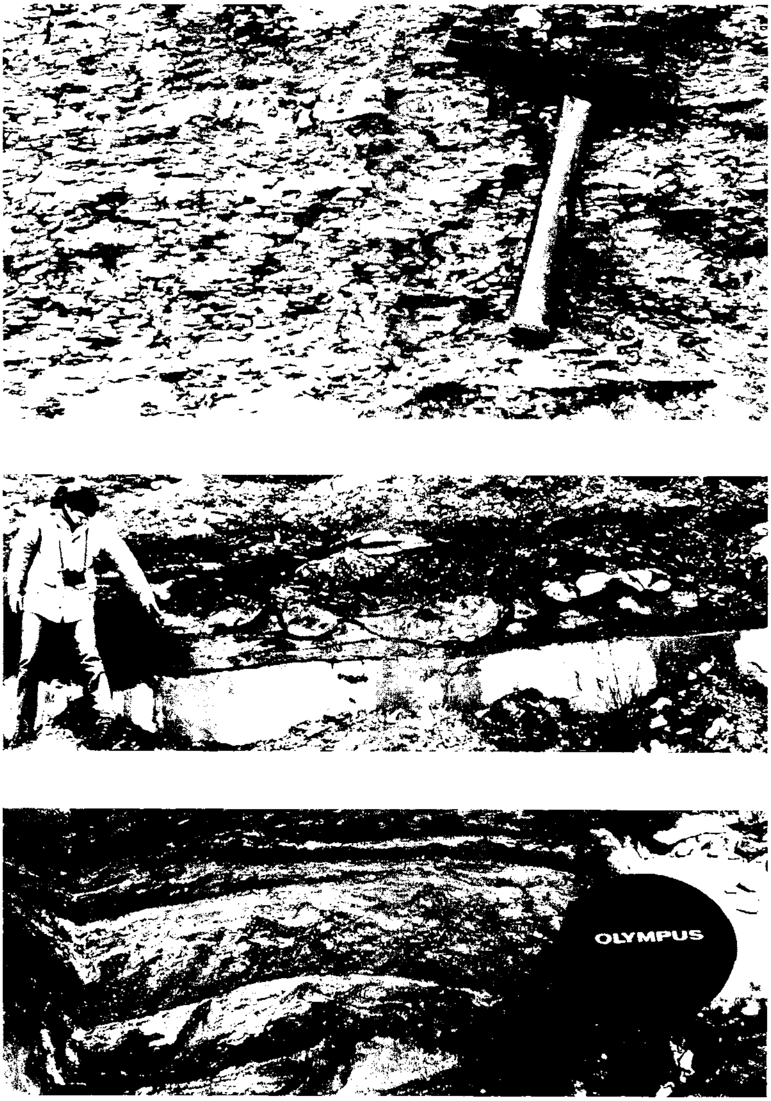

Fig. 5. (A) Dark greenish-gray shale containing laminae and thin beds of bioturbated siltstone; Bedford Shale, loc. 14. Note irregular, platy fissility. (B) Ball-and-pillow structures (flow rolls); "lower tongue" of Berea Sandstone, loc. 29. (C) Convolute laminae (flame structures) in laminated siltstone; "lower tongue" of Berea Sandstone, loc. 29.

per, deWitt, and Demarest, 1954). The rippled siltstones are similar to the unrippled strata in terms of color, grain size, thickness, and bedding. The major differences between rippled and unrippled beds, however, are the presence of wave ripples on bedtops and the sequence of internal sedimentary structures.

Although wave ripples are easily distinguished in outcrop, other internal structures seldom are visible. At a few localities (especially the Garrison Quarry, loc. 40; fig. 2), however, the internal nature of the thicker, rippled beds is apparent, and they contain in upward succession: (1) a structureless basal interval with a sharp basal contact (fig. 6A), (2) a hummocky-stratified interval (fig. 6A) that grades vertically into (3) an interval of horizontal laminae (fig. 6B), and (4) an interval of wave-ripple cross laminae (fig. 6B). Locally, sparse, greenish-gray shale clasts and finely comminuted plant debris occur in these sequences. Additionally, large tool marks as much as 7 cm wide and small channels approx 1 to 3 m wide are locally present at the bases of these beds. In most sections, hummocky stratification is of extremely variable wavelength and amplitude; however, both wavelength and amplitude tend to increase upsection. Locally, flow rolls are absent, and large-scale, synformal, bowl-shaped bedforms (fig. 6C) termed swaley stratification (see Leckie and Walker, 1982) are more common than hummocky stratification. At such localities, beds commonly have gently undulating tops or are broadly lensoid.

The bases of thinner rippled siltstones (fig. 6D) commonly exhibit casts of burrows, and most exhibit an internal, horizontally laminated interval capped by an interval of wave-ripple cross laminae. In many exposures, thinner rippled siltstones have been bioturbated to the extent that internal laminae are not recognizable. Rippled siltstones have bioturbation features that consist largely of feeding burrows (fodinichnia) and tracks and trails (repichnia).

The top few centimeters of the Berea generally are highly bioturbated and typically contain flecks and nodules of phosphate, pyrite, and marcasite. The rhynchonellid brachiopod, *Camerotoechia,* and inarticulate brachiopods have been reported from this interval in Ohio by Hyde (1953) and Coogan and others (1981). This interval usually is overlain by a thin bed of greenish-gray shale which in turn is overlain by the black Sunbury Shale.

Three lithofacies contain rippled siltstones but are differentiated from each other based on the presence of other lithologies, the nature of bedding, bedforms, and stratigraphic position. In the shale-and-siltstone lithofacies, at least two-thirds of the facies is dominated by laminated and thin-bedded siltstones intercalated with laminae and thin beds of greenish-gray shale; virtually all the siltstones are rippled (fig. 6D). The shale-and-siltstone lithofacies is restricted to the Bedford Shale and grades into the greenish-gray-shale, upper-sheet-siltstone, and swaley-siltstone lithofacies (fig. 3). The lithofacies first appears in southernmost Lewis County, Ky., and is widespread throughout the northern half of

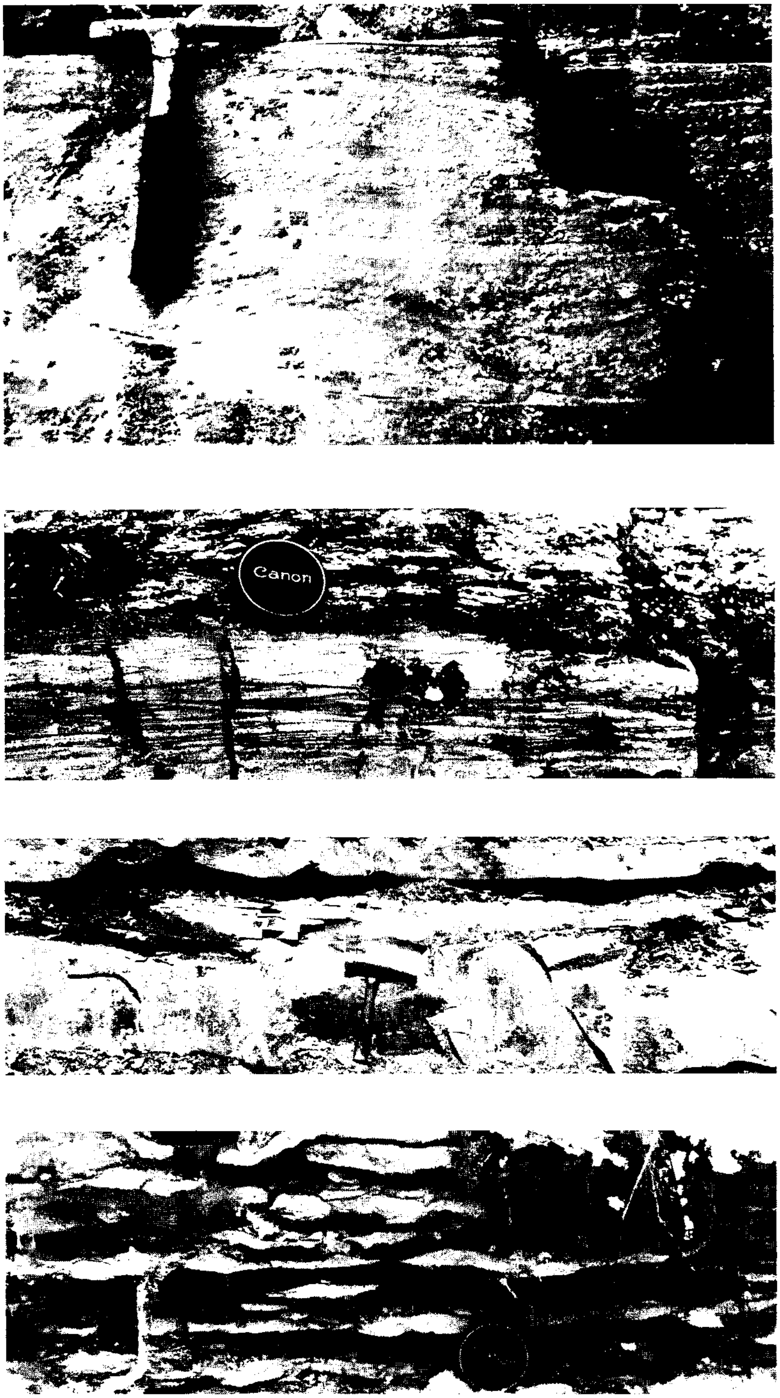

Fig. 6. (A) Hummocky-stratified siltstone overlying structureless interval; "Cliff Stone" (Berea), loc. 40. (B) Wave-ripple cross-laminated siltstone (below lens cap); "Cliff Stone" (Berea), loc. 40. Note horizontal laminae below cross-laminated interval. (C) Swaley-stratified siltstone; "upper tongue" of Berea Sandstone, loc. 61. (D) Thinly bedded siltstones interbedded with shale; Bedford Shale, loc. 27. Note bioturbated wave ripples.

the field area; it reaches a maximum thickness of approx 28 m in northwestern Scioto County, Ohio (fig. 3).

The upper-sheet-siltstone lithofacies contains at least 33 percent rippled, medium- to thick-bedded, tabular siltstones which commonly exhibit flow rolls. These siltstones are intercalated with lithologies typical of the shale-and-siltstone lithofacies. Amalgamated siltstones are most common at the top of the upper-sheet-siltstone lithofacies; they commonly give the top of the lithofacies a slightly wavy appearance.

The upper-sheet-siltstone lithofacies is exposed only in eastern Lewis County, Ky., western Scioto County, Ohio, and in a portion of Pike County, Ohio (fig. 4). In these areas, the upper-sheet-siltstone lithofacies comprises the "Cliff Stone" of Hyde (1953) and forms most of the Bedford-Berea sequence. In north-central Lewis County, Ky., the upper-sheet-siltstone lithofacies is included in the upper portion of the "lower tongue." Here, the lithofacies lies directly upon the lower-sheet-siltstone lithofacies and underlies a northeastwardly thinning tongue of the shale-and-siltstone lithofacies (fig. 3). The upper-sheet-siltstone lithofacies generally rises stratigraphically in section northeastwardly and merges with the swaley-siltstone and shale-and-siltstone lithofacies (fig. 3).

The swaley-siltstone lithofacies is composed of at least 33 percent medium- to thick-bedded siltstones. The remainder of the facies is composed of lithologies typical of the shale-and-siltstone lithofacies. The siltstones of the swaley-siltstone lithofacies differ from those in the upper-sheet-siltstone lithofacies in that they lack flow rolls, contain swaley stratification (fig. 6C), and exhibit gently undulating tops or broadly lens-shaped beds. Swaley stratification is most common in close proximity to locations where the swaley-siltstone lithofacies passes into the upper-sheet-siltstone lithofacies, whereas the more lens-shaped beds are most common near places where the swaley-siltstone lithofacies passes laterally into the shale-and-siltstone lithofacies.

The swaley-siltstone lithofacies constitutes most of the "upper tongue" (fig. 1) and forms a belt around the "Cliff Stone" (upper-sheet-siltstone lithofacies; fig. 4); the apparent disjunct distribution of the swaley-siltstone lithofacies in figure 3 is simply an artifact of the way in which the cross section was constructed (figs. 3 and 4). The shale-and-siltstone and upper-sheet-siltstone lithofacies grade vertically and laterally into the swaley-siltstone lithofacies. Additionally, the swaley-siltstone lithofacies apparently passes laterally into the upper-sheet-siltstone lithofacies in Lewis County, Ky. and Scioto and Pike counties, Ohio (fig. 3). The swaley-siltstone lithofacies attains a maximum thickness of approx 8 m at Tener Mountain, Ohio (loc. 61), the northernmost exposure in the field area.

Massive siltstone.—A series of roadcuts on Kentucky State Route 59 near the Walnut Grove Church (see Ohio Geol. Soc. and the Geol. Soc. Kentucky, 1968; loc. 31) reveals a massive, gray, fine-grained siltstone at the position of the Bedford-Berea sequence (figs. 7, 8A) which is atypical

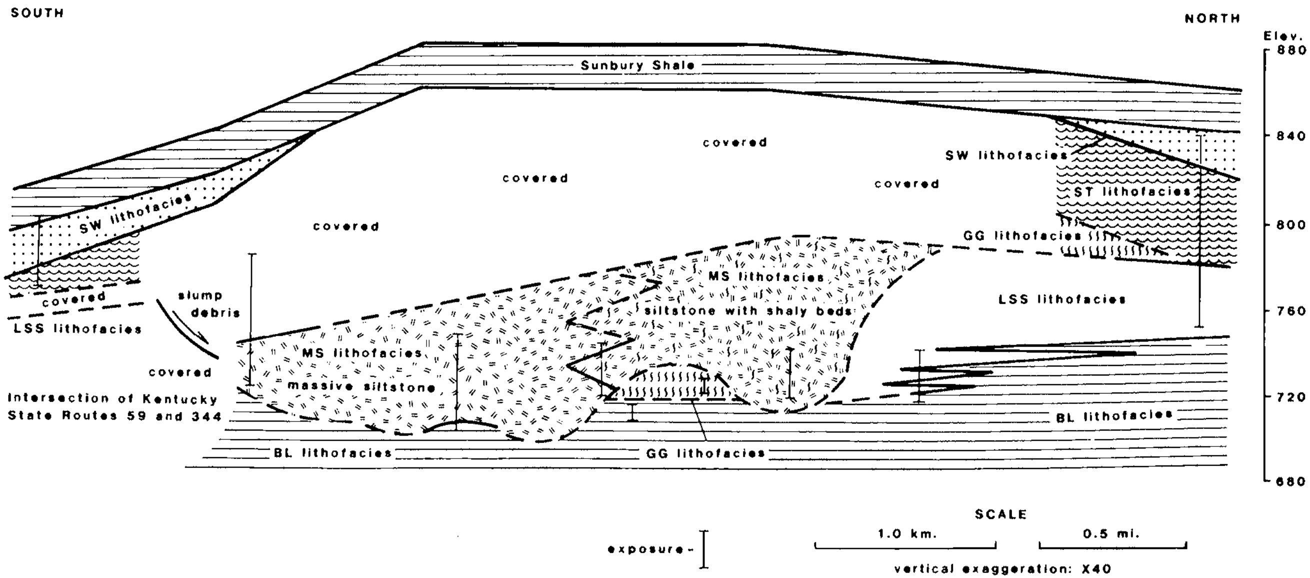

Fig. 7. Schematic cross section of Bedford-Berea sequence along Kentucky State Route 59 (loc. 31 and 32), Lewis County, Ky. Northernmost section at loc. 32; all other sections at loc. 31. Elevations in feet. BL = black shale, GG = greenish-gray shale, LSS = lower sheet siltstone, MS = massive siltstone, ST = shale and siltstone, SW = swaley siltstone.

Fig. 8. (A) Exposure of massive siltstone along Kentucky State Route 59; "lower tongue" of Berea Sandstone, loc. 31. (B) Isolated mass of black, silty shale in massive siltstone; "lower tongue" of Berea Sandstone, loc. 31. (C) Probable deformed cross-bedding in siltstone; "lower tongue" of Berea Sandstone, loc. 31.

of Bedford-Berea lithologies. At the intersection of State Route 59 with State Route 344 is a relatively thick exposure of the lower-sheet-siltstone lithofacies. Farther northward in the exposure (fig. 7), a variety of large-scale deformational features are present, including large, contorted blocks of siltstone, greenish-gray shale, and black, silty shale. The contorted blocks laterally truncate strata of the lower-sheet-siltstone lithofacies and overlie the massive siltstone. Many of the siltstone blocks adjacent to the lower-sheet-siltstone lithofacies dip toward the truncation surface. The massive siltstone is finer grained than adjacent lower-sheet-siltstone strata, is contorted, lies upon contorted black shales, and contains distorted clumps of black, silty shale (fig. 8B), greenish-gray shale, and siltstone. Laminae and crossbeds, some of which are deformed, also are present in the massive siltstone.

Farther north, the siltstone becomes both darker and more shaly and passes laterally into several discrete, thin-to-thick beds separated by silty, greenish-gray shale and shaly siltstone (fig. 7). Deformed crossbeds (fig. 8C) and flame structures were observed in some of these siltstones. Strata in the northernmost exposure at loc. 31 (fig. 7) show the thicker, unrippled siltstones of the lower-sheet-siltstone lithofacies intercalated with both black and greenish-gray shales.

The massive siltstone and associated deformational features exposed along Kentucky State Route 59 between the Walnut Grove Church and Vanceburg (loc. 31 and 32; figs. 3 and 7) are designated the massive-siltstone lithofacies. The lithofacies is restricted to the one roadcut sequence described above; thus, the massive-siltstone lithofacies is the most geographically restricted lithofacies in the field area (figs. 3 and 7).

INTERPRETATIONS

Black-shale lithofacies.—The black-shale lithofacies is interpreted in accordance with Ettensohn and Barron (1981), Elam (ms), Ettensohn (1984), and Ettensohn and Elam (1985) as having been deposited in anaerobic, basin-floor environments dominated by pelagic sediments rich in organic matter (fig. 9). However, the local presence of greenish-gray shale laminae in the lithofacies implies that these environments were periodically subject to dysaerobic conditions, suggesting proximity of the pycnocline and shelf-slope sedimentation. South of the field area, however, sediment-deficient, anaerobic environments apparently persisted, even at the apex of regression. Using a bathymetric model for deltaic clastic sequences proposed by Klein (1974), Ettensohn (1984) suggested that black shales equivalent to the Bedford-Berea were deposited in a basin at least 120 m deep (fig. 9).

Greenish-gray-shale lithofacies.—The color of the greenish-gray-shale lithofacies, as well as the presence of the taxonomically restricted, thin-shelled Bedford fauna, are typical of sediments deposited within the pycnocline as defined by Byers (1977). Also, Kammer (ms) noted that calcareous shells which have been pyritized or preserved as molds are typical of dysaerobic fossil assemblages. Siltstones similar to those in the greenish-gray-shale lithofacies have been documented in the distal portions of turbidite complexes (Walker, 1978; Nelson and others, 1978; Kumar and Slatt, 1984; Lundegard, Samuels, and Pryor, 1985) and have been referred to as "toe-of-slope turbidites" by Broadhead, Kepferle, and Potter (1982). Hence, the greenish-gray-shale lithofacies is interpreted as having been deposited in dysaerobic, offshore environments dominated by pelagic sedimentation and episodically interrupted by turbiditic influxes of silt (fig. 9).

The presence of phosphate and glauconite in the *Sphenothallus* bed implies that sedimentation rates were drastically reduced during deposition of the bed. A recent study of *Sphenothallus* tubes by Mason and Yochelson (1985) indicated that these enigmatic fossils were restricted to hard or firm substrates. The fauna, presence of phosphate, and the burrowed nature of the *Sphenothallus* bed suggest that this layer represents an offshore firmground that formed in the dysaerobic zone.

Lower-sheet-siltstone lithofacies.—The sharp bases, indistinct, bioturbated bed-tops, and vertical sequence of sedimentary structures in the thicker siltstones of the lower-sheet-siltstone lithofacies indicate rapid deposition from waning flows. These features are perhaps best explained in terms of the Bouma sequence for turbidites (Bouma, 1962), even though current-ripple laminae were never observed. A turbidite origin, moreover, satisfactorily explains the presence of these siltstones in offshore to marginally basinal environments (fig. 9), as indicated by interbedded lithologies characteristic of the black-shale and greenish-gray-shale lithofacies.

Strata in portions of the Borden and Cuyahoga formations (fig. 1), interpreted to be turbidites by Moore and Clarke (1970) and Kepferle (ms and 1977, 1978), are extremely similar to the lower-sheet-siltstone lithofacies in terms of lithology, bedding, and sedimentary structures, although flow rolls and load casts are much less common. Kepferle (ms and 1977, 1978) and Chaplin (1980) characterized the Borden-Cuyahoga turbidites as prodeltaic turbidite aprons, and Kepferle (ms and 1977, 1978) developed a thin-fan model for silt-rich, cratonic, prodelta turbidites, acknowledging the possibility of oversteepened slopes and syndepositional seismicity to explain the presence of turbidite packages within these formations. It should be pointed out, however, that the Berea examples are located far from the deltaic sources of Pepper, deWitt, and Demarest (1954) and thus appear to be more intimately related to nearby shelf sedimentation.

The facts that the lower-sheet-siltstone lithofacies in the southern part of its distribution rests upon and intertongues with the black-shale lithofacies and rises stratigraphically in section northward such that it rests upon several meters of the greenish-gray-shale lithofacies and coalesces with the upper-sheet-siltstone lithofacies (figs. 3 and 9) suggest that it was deposited low on a slope near the base of the pycnocline. The reasons for the extremely limited geographic extent of the lower-

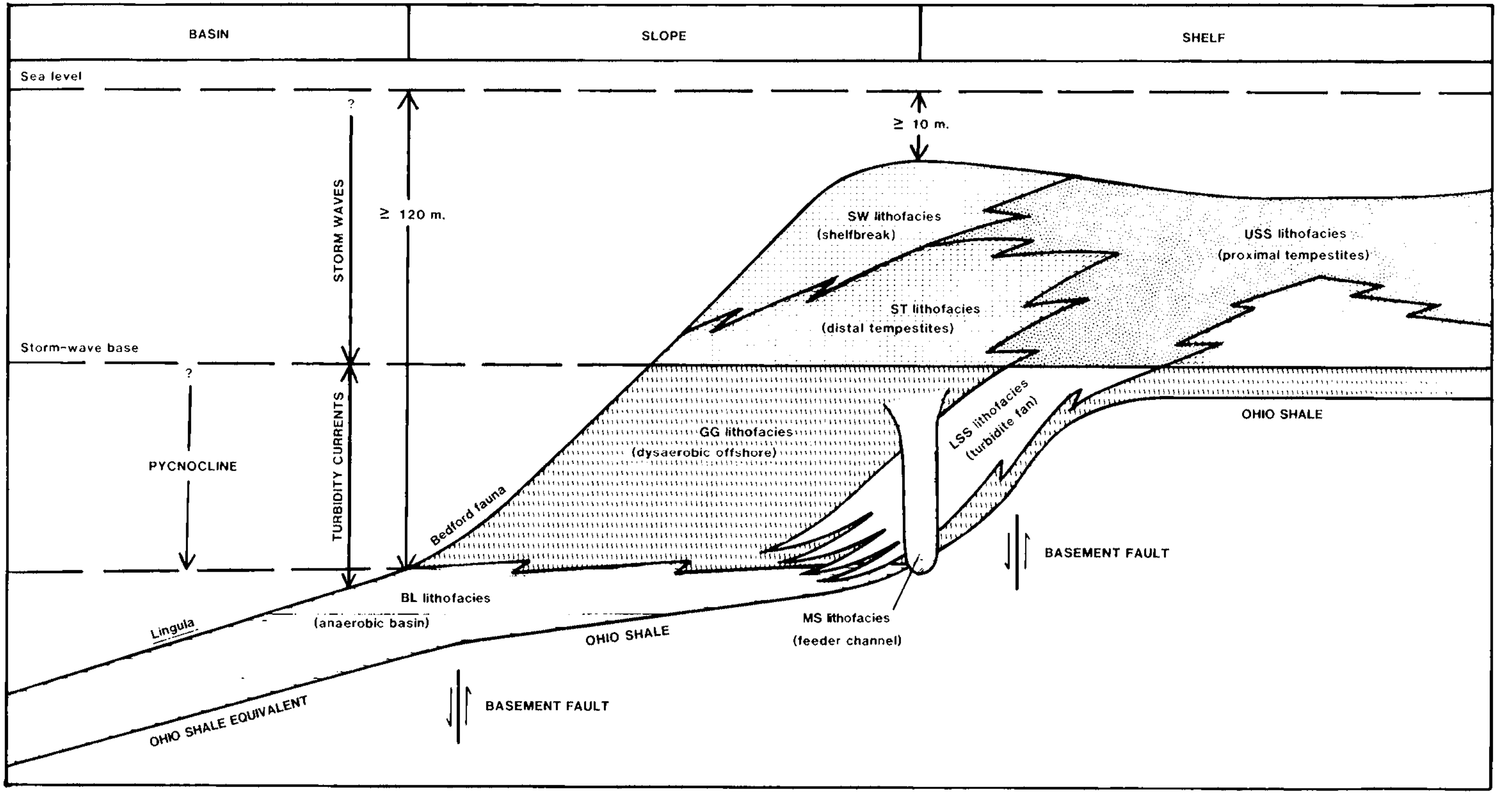

Fig. 9. Diagrammatic representation of interpreted environments in the Bedford-Berea sequence, northeastern Kentucky and south-central Ohio. BL = black shale, GG = greenish-gray shale, LSS = lower sheet siltstone, MS = massive siltstone, ST = shale and siltstone, USS = upper sheet siltstone, SW = swaley siltstone.

sheet-siltstone lithofacies, however, are unclear in the light of interpretations presently offered. Nevertheless, interpretation of the massive-siltstone lithofacies offers some insight into this problem.

Massive-siltstone lithofacies.—Lithologies in the massive-siltstone lithofacies were previously interpreted as probable channel fills (Morris and Pierce, 1967; Ohio Geol. Soc. and the Geol. Soc. Kentucky, 1968), and Morris and Pierce (1967) indicated that the channel had a north-south orientation. The deformed material overlying the massive siltstone is interpreted to be a slump feature, because several detached siltstone blocks dip toward relatively undeformed strata of the lower-sheet-siltstone lithofacies (see Laury, 1971). The massive siltstone apparently overlies the black-shale lithofacies with an erosional discontinuity and is interpreted to have cut through strata of the lower-sheet-siltstone lithofacies (fig. 9). Cross-bedding in the massive siltstone indicates that the channel conducted currents strong enough to produce dune bedforms.

Because the massive siltstone is finer grained than adjacent lower-sheet-siltstone strata, we suggest that the massive siltstone is more closely related to the turbiditic siltstones in the greenish-gray-shale lithofacies. However, because the massive-siltstone lithofacies occurs where the siltstones of the lower-sheet-sandstone lithofacies are relatively thick and numerous, it is possible that the channel transported the sediment deposited in the lower-sheet-siltstone lithofacies and later cut through lower-sheet-siltstone strata.

Intraformational debris in the massive-siltstone lithofacies is typical of turbidite feeder channels (von der Borch, Smit, and Grady, 1982; Chan, 1983; von der Borch and others, 1985). That slumping is apparently restricted to one end of the massive-siltstone lithofacies and that the massive siltstone passes laterally into more shaly strata away from the slump debris (fig. 7), suggesting an analogy with meandering channel deposits (see Laury, 1971), indicate a somewhat sinuous channel. The only other ancient, sinuous turbidite-feeder-channel fill known to us (see von der Borch and others, 1985) is quite different from the Berea example, because it is much coarser grained and deeply entrenched on both sides. Because channels provide either a point or line source for dispersal of sediments, it seems that a large portion of the lower-sheet-siltstone lithofacies may represent a turbidite apron or fan deposited near the base of a slope (fig. 9), and that many of the siltstones deposited in the greenish-gray-shale lithofacies represent a succeeding episode of toe-of-slope turbidite-fan sedimentation.

Shale-and-siltstone and upper-sheet-siltstone lithofacies.—The siltstones of the shale-and-siltstone and upper-sheet-siltstone lithofacies are typical of those recently recognized as extremely common, cyclic strata in the geologic record. Dott and Bourgeois (1979) drew an analogy between these strata and turbidites, because both commonly have sharp, erosional bases and burrowed tops, as well as a vertical sequence of sedimentary structures which indicates rapid deposition from waning flow. These strata differ from turbidites, however, in that they contain predominantly oscillation-related bedforms rather than unidirectional bedforms.

Goldring and Bridges (1973) first referred to these cyclic strata as "sublittoral sheet sandstones" and suggested that such sandstones and siltstones were deposited by storm waves operating as oscillatory surges acting either alone or in combination with tidal currents. They further realized that turbidity currents, rip currents, and tsunamis also may play a significant role in forming these cycles. Recently, Swift and others (1983) suggested that these cycles result from combined oscillatory and geostrophic flows. Marsaglia and Klein (1983) and Duke (1985) indicated that such strata form in response to major storms, such as hurricanes and intense winter storms; Duke (1985) included the Berea in a group of sediments most likely to have formed as a result of intense tropical storms.

In fact, a storm-wave origin has become so widely applied to sublittoral sheet sandstones that Seilacher (1982) referred to these cyclic strata as tempestites. Many workers have shown that tempestites form in the transition zone between fair-weather and storm wave bases (Hamblin and Walker, 1979; Bourgeois, 1980; Howard and Reineck, 1981; Dott and Bourgeois, 1982; Hunter and Clifton, 1982; Aigner and Reineck, 1982). Storm-wave base can be in excess of the minimum depth predicted for the black-shale lithofacies by Ettensohn (1984; for example, Komar, Neudeck, and Kulm, 1972), but fair-weather wave base commonly occurs between 10 and 70 m below sealevel (Hamblin and Walker, 1979; Bourgeois, 1980; Dott and Bourgeois, 1982; Hunter and Clifton, 1982; Aigner and Reineck, 1982). Most workers believe that the shales that commonly are interbedded with tempestites represent pelagic, fair-weather sedimentation.

Aigner and Reineck (1982) recognized proximality trends in tempestites currently forming in the Helgoland Bight of the North Sea. Proximal tempestites are thicker and contain higher energy structures than distal tempestites. Based on these criteria, the upper-sheet-siltstone lithofacies represents proximal tempestites, whereas the shale-and-siltstone lithofacies represents distal tempestites. Tempestites are widespread today in shelf environments (Howard and Reineck, 1981; Aigner and Reineck, 1982; Swift and others, 1983; Greenwood and Miller, 1985), and thus the shale-and-siltstone and upper-sheet-siltstone lithofacies are interpreted in accordance with Rothman (ms) and Potter and others (1983) as having been deposited in storm-wave-dominated shelf environments (fig. 9).

Many workers (for example, Hamblin and Walker, 1979; Bourgeois, 1980; Hunter and Clifton, 1982) have documented tempestites in close association with turbidites and have regarded storm-generated turbidity currents as a potentially major geological process. In the "lower tongue" of the Berea, tempestites of the upper-sheet-siltstone lithofacies directly overlie the turbidites of the lower-sheet-siltstone lithofacies (fig. 3). Hence, some of the turbidites probably are storm related. Traditional turbidite models (for example, Walker, 1978; Kepferle, ms and 1977, 1978) are not entirely applicable to the lower-sheet-siltstone lithofacies, because turbidity currents during mid-Bedford-Berea deposition probably transported sediment directly over a shelf edge instead of through a feeder channel. Moreover, many of the turbiditic siltstones in the greenish-gray-shale lithofacies also are probably storm related, because they pass both laterally and vertically into the shale-and-siltstone lithofacies (fig. 3). Figure 3 shows that the locus of silt deposition shifted northward in time, perhaps terminating the initial progradation represented by the "lower tongue" of the Berea (figs. 1 and 9).

Swaley-siltstone lithofacies.—Sedimentary structures in the swaley-siltstone lithofacies suggest a close relationship to tempestites of the shale-and-siltstone and upper-sheet-siltstone lithofacies. Presence of large-scale swaley stratification in the swaley-siltstone lithofacies implies that these strata were deposited by storm waves of higher amplitude and longer wavelength than those in the upper-sheet-siltstone lithofacies. The waviness or discontinuity of siltstones in this lithofacies suggests storm waves that were at least partially deficient in sediment.

Because the swaley-siltstone lithofacies passes laterally into the shale-and-siltstone lithofacies, as well as into the upper-sheet-siltstone lithofacies, and wholly overlies shalier strata (fig. 3), the swaley-siltstone lithofacies is interpreted to have been deposited at a break in slope where tempestite deposition gave way to deeper water sedimentation. The longer wavelength, higher amplitude bedforms in the swaley-siltstone lithofacies may reflect interaction of storm waves with a possible shelf break. Furthermore, the fact that the swaley-siltstone lithofacies forms a belt around the upper-sheet-siltstone lithofacies (fig. 4) indicates that progradation and regression facilitated distribution of silt from the area of the upper-sheet-siltstone lithofacies, thereby giving rise to renewed progradation in Lewis County, Ky. ("upper tongue" of the Berea; figs. 3 and 9).

To the best of our knowledge, no documented modern analogue for the swaley-siltstone lithofacies exists. The only major published accounts of swaley bedding (Leckie and Walker, 1982; McCrory and Walker, 1986) suggested that the structure develops in waters shallower than those where hummocky bedding forms, probably above fair-weather wave base. Bedford-Berea examples, however, are contained in waning-flow sequences capped by silty shale, suggesting deposition in the transition zone below fair-weather wave base. Nevertheless, the presence of swaley strata indicates that shelf-break sediments (swaley-siltstone lithofacies) probably were deposited in water shallower than that where most of the other associated shelf sediments (upper-sheet-siltstone lithofacies) were deposited. Therefore, we suggest that interaction of storm waves with the shelf break resulted in a concentration of silt, which apparently increased relief to the point that waters at the shelf break were shallower than those over adjacent portions of the shelf (fig. 9). Moreover, the Bedford-Berea shelf break probably was characterized by a slightly hummocky topography, whereas modern shelf breaks along continental margins have a highly irregular topography dissected by channels and sub-marine canyons (see Vanney and Stanley, 1983).

The thin, bioturbated, phosphate-marcasite layer at the very top of the Berea is interpreted to represent a sediment-deficient transition interval preceding return to transgressive, basinal, black-shale deposition. Presence of phosphate and prolific bioturbation reflect the absence of major sedimentation. Perhaps the phosphatic nature of this interval as well as its stratigraphic position near the top of the Bedford-Berea sequence indicate contemporaniety with the *Sphenothallus* bed.

DISCUSSION

Sea-floor topography.—Rich (1951) first suggested that epeiric sea-floor topography must have been quite different from that of continental margins (fig. 10). Hence, Walker (1971) and Woodrow and Isley (1983) were reluctant to apply traditional shelf models in interpreting the Devonian black-shale sequence of New York and Pennsylvania. Rich (1951) and Woodrow and Isley (1983) pointed out that epeiric sea-floor topography was not comparable to that of continental margins, because continental-margin topography is strongly influenced by the transition from continental crust to oceanic crust. Conversely, epeiric sea floors were developed wholly on continental crust, so the resultant topography was probably quite subdued relative to continental margins. In fact, Woodrow and Isley (1983) emphasized that the black-shale sequence of New York and Pennsylvania evidently represents a sea-floor topography that was largely the result of sedimentary processes rather than geophysical discontinuities.

Therefore, Woodrow and Isley (1983), following the lead of Rich (1951), proposed a topographic terminology for sea floors represented by the Devonian black-shale sequence of New York and Pennsylvania (fig. 10). The basin margin was characterized by sediments that are typical of modern shelf and deltaic environments. The basin floor was typified by anaerobic muds rich in organic matter, whereas the clinoform, which separated basin margin from basin floor, was characterized by shale and turbidites. Turbidity currents apparently flowed down the clinoform unconstrained by channels, so that turbidites were deposited as sheets rather than as fans. Furthermore, proximal turbidites were deposited near the top of the clinoform and passed "down-clino" into distal turbidites. The position of proximal turbidites on the clinoform contrasts sharply with the position of proximal turbidites along continental margins, because continental-margin turbidites commonly are deposited at the toe of the continental slope, or continental rise (fig. 10).

In the Bedford-Berea sequence of northeastern Kentucky and south-central Ohio, strata of the upper-sheet-siltstone and shale-and-

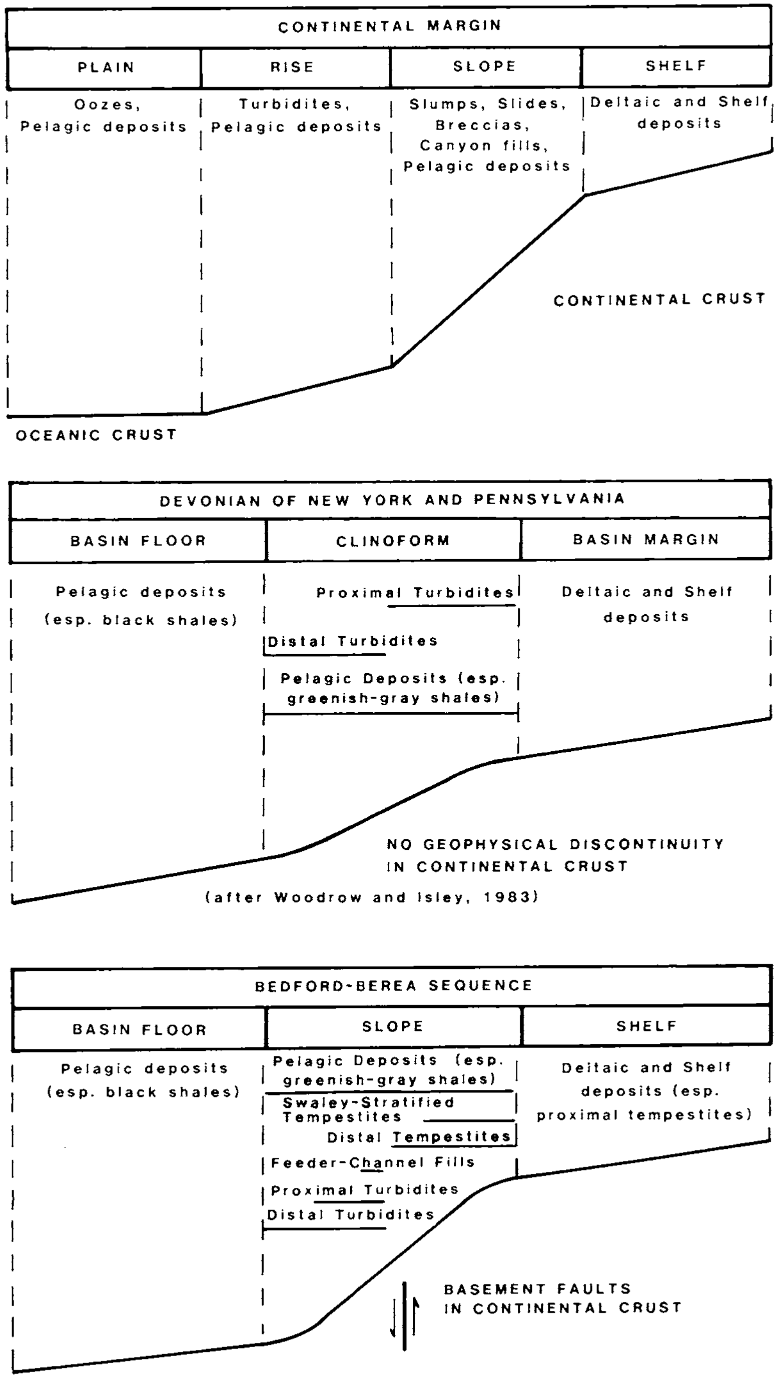

Fig. 10. Schematic diagram comparing sea-floor topographies of continental margins, the Devonian of New York and Pennsylvania, and the Bedford-Berea sequence of northeastern Kentucky and south-central Ohio (after Woodrow and Isley, 1983).

siltstone lithofacies are characteristic of sediments from a basin margin, and strata of the black-shale lithofacies are typical of sediments from a basin floor (see Woodrow and Isley, 1983). However, only some aspects of the remaining Bedford-Berea lithofacies are typical of a clinoform. The lack of widespread slumps, slides, and debris flows, as well as the prevalence of shaly and turbiditic sediments on the Bedford-Berea slope, are typical, whereas presence of tempestites (swaley-siltstone and shale-and-siltstone lithofacies), though not necessarily typical, simply indicates that storm-wave base intersected the sea floor at the slope during later Bedford-Berea deposition.

Other aspects of the Bedford-Berea lithofacies, however, are not well explained in terms of a clinoform. First, many of the turbidites in the Bedford-Berea sequence (parts of the lower-sheet-siltstone and greenish-gray-shale lithofacies) apparently were deposited at the base of a slope instead of near the top of a slope (fig. 10). Secondly, Bedford-Berea turbidite deposition probably was influenced by at least one major feeder channel (massive-siltstone lithofacies). Both these characteristics are poorly explained in terms of classical epeiric sedimentation models, suggesting a steeper paleoslope than that implied for a clinoform by Woodrow and Isley. The lack of widespread slumps and debris flows on the Bedford-Berea slope as well as the eventual coalescence of turbidite (lower-sheet-siltstone lithofacies) and shelf (upper-sheet-siltstone lithofacies) sediments (figs. 3 and 9) indicate that the Bedford-Berea slope was quite gentle in comparison with continental slopes and probably was only slightly oversteepened relative to a clinoform as suggested by Kepferle (ms) for thin-fan turbidite systems. For example, coalescence of shelf and deep-sea fan sediments is characteristic of only supermature continental margins (Dailly, 1983); coalescence of such sediments in the Bedford-Berea of Lewis County, Ky., seems to have happened relatively early in Bedford-Berea deposition.

The Bedford-Berea slope apparently widened greatly through time, because turbidites of the lower-sheet-siltstone lithofacies in north-central Lewis County, Ky., which intertongue with basinal shales of the black-shale lithofacies, pass eastward into shelf sediments of the upper-sheet-siltstone lithofacies across a distance of less than 15 km (figs. 3 and 9). On the other hand, strata of the greenish-gray-shale lithofacies grade southwardly into basinal shales in Powell County, Ky., and grade northwardly into distal tempestites and, ultimately, into shelf-break sediments of the swaley-siltstone lithofacies approx 80 km farther north in Lewis County, Ky. (figs. 3 and 9). Moreover, the fact that the swaley-siltstone lithofacies (shelf break) and the more distal portions of the lower-sheet-siltstone lithofacies (turbidite fan) are largely present at the same localities in Lewis County, Ky. (fig. 3), suggests that the Bedford-Berea slope must have migrated laterally through time. This implies that the base of slope early in Bedford-Berea deposition had become a shelf break during later Bedford-Berea deposition. Furthermore, the slope must have become relatively subdued during later

Bedford-Berea deposition, because proximal tempestites pass downslope into distal tempestites and, in turn, into distal turbidites much in the same manner as suggested for proximal and distal turbidites in the model of Woodrow and Isley (1983).

Structural implications.—Because the Bedford-Berea slope initially was steeper and narrower than is typical of epeiric sea floors, it seems reasonable that the slope was influenced by some type of geophysical discontinuity in the same manner that the transition from continental crust to oceanic crust influences continental slopes. Of course, because the Berea was deposited wholly on continental crust, any structure influencing sedimentation must have been of a much smaller magnitude than the continental-oceanic crustal transition. Since studies by Woodward (1961), Goble (ms), and Ammerman and Keller (1979) demonstrated that many existing surface faults in Kentucky (for example, the Kentucky River and Irvine-Paint Creek fault systems) are surface expressions of normal, basement faults active periodically throughout the Paleozoic, much data has accumulated supporting relationships between sedimentation and basement-related growth faulting in eastern Kentucky (Goble, ms; Ettensohn, ms; Dever and others, 1977; Ammerman and Keller, 1979; Haney, 1979).

Since Woodward's (1961) study, several normal, basement faults pertinent to the present discussion have been identified in eastern Kentucky. A major east-west-trending set of basement faults partially defines the boundaries of the Rome Trough and has surface expression in the Kentucky River fault system, the Irvine-Paint Creek fault system, and numerous smaller surface faults (see Ammerman and Keller, 1979). We refer to these collectively as the Rome Trough basement-fault system (fig. 11). Each constituent basement fault generally is downthrown to the south (Harris, 1975). A basement fault whose trend coincides closely with the axis of the Waverly Arch of Ettensohn (ms) and Dever and others (1977) was identified by Goble (ms), who showed that the fault affected Cambrian deposition and was downthrown to the west by the end of Cambrian time. This fault is referred to here as the Waverly Arch basement fault (fig. 11).

Sediments of the Bedford-Berea sequence offer an excellent opportunity to examine the relationship between sedimentation and basement-related growth faulting in eastern Kentucky. Sediments were evidently transported onto a rather wide shelf area (Potter and others, 1983) far removed from the fluvio-deltaic sources of Pepper, deWitt, and Demarest (1954) and Walls (1975). The shelf area lay in relatively shallow water, where storms were the major controls on deposition, whereas the basin floor was situated well below the influence of storm processes where anoxia and suspension sedimentation were the major depositional controls. Hence, if growth faulting affected sea-floor topography during Bedford-Berea deposition, shallower water sediments, such as the upper-sheet-siltstone lithofacies, would be expected to predominate on the upthrown fault blocks, whereas deeper water

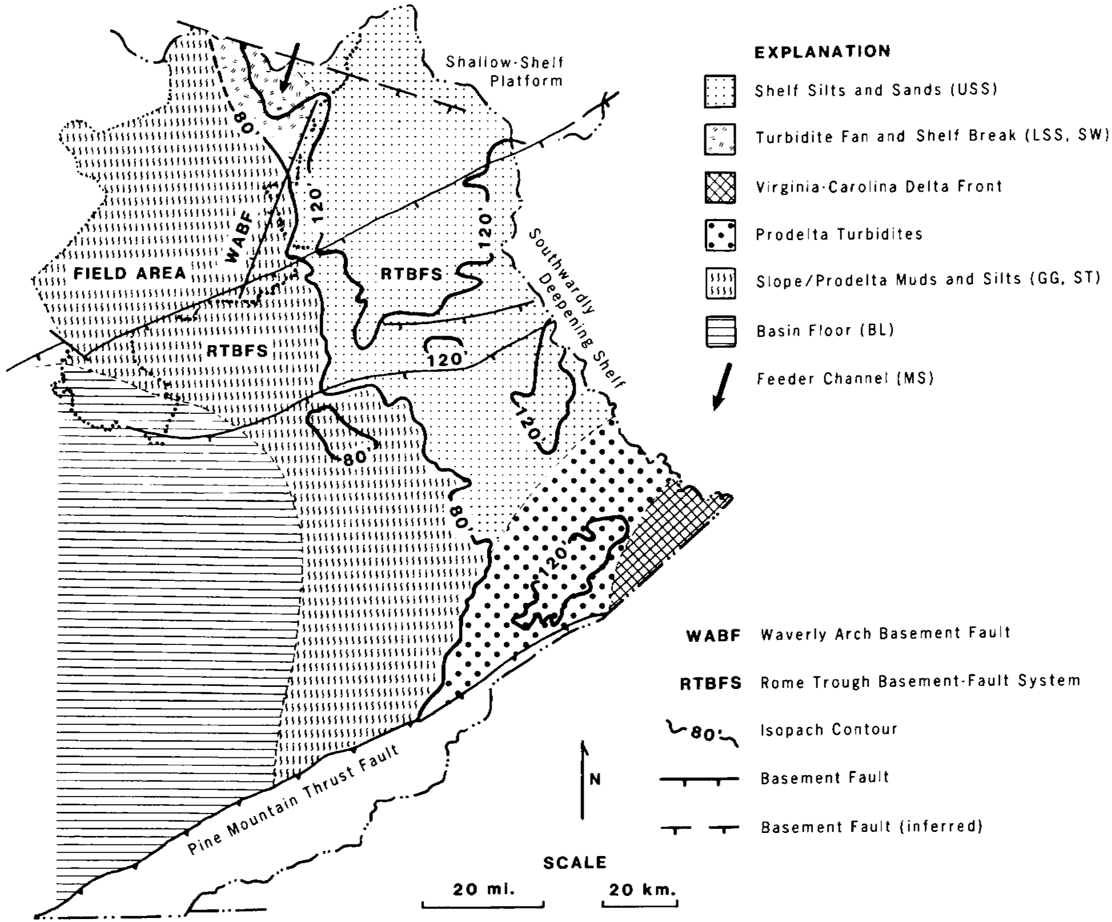

Fig. 11. Bedford-Berea paleogeography, eastern Kentucky. USS = upper-sheet-siltstone lithofacies, LSS = lower-sheet-siltstone lithofacies, SW = swaley-siltstone lithofacies, GG = Greenish-gray-shale lithofacies, ST = shale-and-siltstone lithofacies, BL = black-shale lithofacies, MS = massive-siltstone lithofacies.

sediments, such as the black-shale lithofacies, would be expected to dominate on the downthrown blocks. Furthermore, slope sediments would be expected to parallel locally controlling basement structures.

Although no subsurface data were collected in the present study, isopach data collected by Elam (ms) were extremely useful in determining probable relationships between Bedford-Berea sedimentation and basement faulting. Geometry of the Bedford-Berea clastic wedge in Kentucky seems best defined by the 24-m (80-ft) and 37-m (120-ft) isopach contours of Elam (ms), and what limited evidence is available (Pepper, deWitt, and Demarest, 1954; Ettensohn and Elam, 1983, 1985) indicates that the western limit of the Berea follows the 24 m (80-ft) contour rather closely. Cross sections included in Pepper, deWitt, and Demarest (1954), Walls (1975), and Kepferle, Beard, and Pollock (1982) show that the Berea generally thickens eastward. Core descriptions (Potter and others, 1983) provide further inferences into the nature of Berea deposition in the subsurface.

In the outcrop belt, the greenish-gray-shale lithofacies grades into the black-shale lithofacies within the area of the Rome Trough basement-fault system (fig. 11). Subsurface data presented by Elam (ms) and Ettensohn and Elam (1983, 1985) indicate that the southern termination of the thicker greenish-gray sediments has a northwest-southeast orientation, which parallels locally the southernmost fault of the basement-fault system, suggesting possible structural control. Farther east, however, the edge of the greenish-gray-shale lithofacies turns southward, and the Bedford-Berea sequence thickens rapidly eastward, apparently owing in part to proximity of the Virginia-Carolina Delta.

The 37 m (120 ft) contour (fig. 11) reaches its southern limit along one of the faults of the Rome Trough basement-fault system. Core descriptions (Potter and others, 1983) indicate that higher energy, shallower water shelf environments were present on the platform north of the basement-fault system and passed southward into deeper water, shelf environments characterized by weaker, more variable currents within the area of the basement-fault system (fig. 11). South of the fault system, deeper water shelf deposits ultimately pass into sediments more closely related to the Virginia-Carolina Delta (fig. 11). It is interesting to note that at an outcrop in easternmost Kentucky, Potter and others (1983) found that the Berea is composed of unrippled, horizontally laminated siltstones, some having flute casts at their bases, indicating a relatively deep-water origin. Following the leads of Potter and others (1983) and Walls (1975), we suggest that the Berea of easternmost Kentucky largely represents delta-front and prodelta-turbidite environments related to the Virginia-Carolina Delta (fig. 11). The apparent predominance of prodelta turbidites in the Berea of easternmost Kentucky suggests that the Virginia-Carolina Delta debouched into deeper water than did the other deltaic depositional systems of Pepper, deWitt, and Demarest (1954).

In central-northeast Kentucky, the 37-m (120-ft) contour has a north-south trend that parallels the Waverly Arch basement fault, and the Berea passes westward into deeper water sediments across the general trend of the fault (fig. 11). It is important to note that the thick lobe of Bedford-Berea sediments containing the lower-sheet-siltstone lithofacies, defined by the 37-m (120-ft) contour in Lewis County, Ky., is separated from the main body of the Berea where the fault is present and coalesces with the main body of the Berea north of where, according to Goble (ms), the basement fault terminates (fig. 11). Furthermore, deeper water, Bedford-Berea black-shale equivalents apparently are absent on uplifted areas east of the Waverly Arch basement fault and north of the Rome Trough basement-fault system (Elam, ms).

The Waverly Arch originally was proposed by Woodward (1961) as a structure that affected Early Paleozoic deposition. Calvert (1974), however, showed that the Waverly Arch of Woodward (1961) was based upon misinterpretation of subsurface data and was little more than a myth. Shortly thereafter, Ettensohn (ms) and Dever and others (1977) identified probable structural control of mid-Mississippian sedimentation along the general trend of Woodward's Waverly Arch and referred to the structure as the Waverly Arch, fostering continued usage of the name. Based on the present study, the Waverly Arch basement fault apparently expressed itself at the surface as a break in slope during Bedford-Berea deposition, and not until after Bedford-Berea deposition did the so-called arch develop.

Presence of an apparent submarine channel in Lewis County, Ky (massive-siltstone lithofacies; figs. 7, 9, and 11), suggests that local oversteepening of the clinoform was caused by basement-related growth faulting, because no other possible factors, such as presence of an older carbonate-platform edge, have been identified in this area. Despite evident structural control of Bedford-Berea deposition in the subsurface of eastern Kentucky, known structures are not available to explain the presence of the lower-sheet-siltstone and massive-siltstone lithofacies in Lewis County (fig. 11). Furthermore, known structures do not explain either the apparent north-south trend of the feeder channel (massive-siltstone lithofacies) indicated by Morris and Pierce (1967) or the southwardly dipping paleoslope indicated by the ripple orientations of Hyde (1911). Nor do any known structures explain the rapid northerly rise in section of the lower-sheet-siltstone lithofacies. Hence, we infer that another east-west-trending basement fault must be present near the Kentucky-Ohio border in order to explain the facies distribution (figs. 9 and 11).

The proliferation of lithofacies in the vicinity of the Ohio-Kentucky border (fig. 3) suggests possibilities regarding the nature and timing of movement on the inferred basement fault. For example, it is possible that movement on the fault occurred during Ohio Shale deposition, and it would be difficult to detect the effects of any such movement in a sequence of uniform black shales. However, the prevalence of flow rolls, load casts, and other soft-sediment deformation features in the Bedford-Berea may indicate penecontemporaneous seismicity related to this fault (see Kuenen, 1958; Allen, 1986). Furthermore, the exceptional thickness of the Bedford-Berea in the vicinity of the Ohio River (fig. 3) suggests possible syndepositional fault movement. Also, the fact that the feeder channel (massive-siltstone lithofacies) was deeply incised into older turbidites (lower-sheet-siltstone lithofacies) may well indicate that the slope reached maximum steepness at this time. Moreover, the northwardly shift of the locus of silt deposition and the thickening of the Bedford-Berea northward from the Ohio-Kentucky border (fig. 3) may indicate tilt on the upthrown fault block during this period. After any possible tilting, however, structural activity apparently declined, and the slope was obscured by rapid sedimentation.

CONCLUSIONS

Bedford-Berea sediments in northeastern Kentucky and south-central Ohio were evidently derived from a series of regressive, fluvio-deltaic and shore-zone complexes which were located along the margin of the epicontinental Appalachian Basin during latest Devonian and earliest Mississippian time. Silts were evidently transported by storms onto a relatively wide shelf area which bordered an euxinic basin where pelagic muds rich in organic matter accumulated. Intervening slope deposits were characterized by apparent turbidites, submarine channel fills, dysaerobic muds, distal tempestites, and swaley-stratified tempestites.

Results of this study indicate that initially steep slope gradients, related to possible growth faulting on basement structures, resulted in an early phase of turbidite deposition. Apparent progradation of slope deposits resulted in generally decreasing slope gradients over time, which in turn resulted in coalescence of turbidite and shelf sediments during earlier mid-Bedford-Berea deposition. However, renewed steepening of the slope during later mid-Bedford-Berea deposition, possibly related to tilting of the upthrown fault block, resulted in formation of a sinuous, submarine feeder channel which cannibalized older turbidites and probably conducted turbidity currents which deposited finer grained, thinly bedded silts on the lower slope. Finally, renewed progradation of shelf deposits late in Bedford-Berea deposition seems to have culminated in development of a storm-dominated shelf-break complex which obscured the effects of previous slope environments to the point that more classical epeiric sedimentation resumed.

Basement faulting in an epeiric situation may oversteepen slopes, resulting in deposition of channel-fed turbidite systems which generally are atypical of such settings. Comparison of facies distribution with the regional structural framework is the best way to reveal such structural influence. Furthermore, detailed facies analysis may be a useful tool in identifying ancient structural declivities and in determining the structural history of epeiric shelf-to-basin transitions.

References

Aigner, T., and Reineck, H.-E., 1982, Proximality trends in modern storm sands from the Helgoland Bight (North Sea) and their implications for basin analysis: Senckenbergiana Maritima, v. 14, p. 183–215.

Allen, J. R. L., 1986, Earthquake magnitude-frequency, epicentral distance, and soft-sediment deformation in sedimentary basins: Sed. Geology, v. 46, p. 67–75.

Ammerman, M. L., and Keller, G. R., 1979, Delineation of Rome Trough in eastern Kentucky by gravity and deep drilling data: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 341–353.

Bouma, A. H., 1962, Sedimentology of some flysch deposits: Amsterdam, Elsevier, 168 p.

Bourgeois, J., 1980, A transgressive shelf sequence exhibiting hummocky stratification: the Cape Sebastian Sandstone (Upper Cretaceous), southwestern Oregon: Jour. Sed. Pet., v. 50, p. 681–702.

Broadhead, R. F., Kepferle, R. C., and Potter, P. E., 1982, Stratigraphic and sedimentologic controls of gas in shale—Example from the Upper Devonian of northern Ohio: Am. Assoc. Petroleum Geologists Bull., v. 66, p. 10–27.

Butts, C., 1922, The Mississippian Series of eastern Kentucky: Kentucky Geol. Survey, ser. 6, v. 7, 188 p.

Byers, C. W., 1977, Biofacies patterns in euxinic basins: A general model: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 25, p. 1–25.

Calvert, W. L., 1974, Sub-Trenton structure of Ohio with views on isopach maps and stratigraphic sections as basis for structural myths in Ohio, Illinois, Pennsylvania, West Virginia, and Michigan: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 957–972.

Chan, M. A., 1983, Shelf and deep-sea sedimentation in Eocene forearc basin, western Oregon—Fan or non-fan?: Am. Assoc. Petroleum Geologists Bull., v. 67, p. 2100–2116.

Chaplin, J. R., 1980, Stratigraphy, trace fossil associations, and depositional environments in the Borden Formation (Mississippian), northeastern Kentucky, *in* Geol. Soc. Kentucky Ann. Field Conf.: Lexington, Kentucky Geol. Survey, 114 p.

Coogan, A. H., Heimlich, R. A., Malcuit, R. J., Bork, K. B., and Lewis, T. L., 1981, Early Mississippian deltaic sedimentation in central and northeastern Ohio, *in* Roberts, T. G., ed., Geol. Soc. America, Cincinnati, 1981, Guidebook; v. 1: Stratigraphy, Sedimentology, p. 113–152.

Dailly, G. C., 1983, Slope readjustment during sedimentation on continental margins: Am. Assoc. Petroleum Geologists Mem. 34, p. 593–608.

Dever, G. R., Jr., Hoge, H. P., Hester, N. C., and Ettensohn, F. R., 1977, Stratigraphic evidence for Late Paleozoic tectonism in northeastern Kentucky: Am. Assoc. Petroleum Geologists, Eastern Sec. Ann. Mtg., Kentucky Geol. Survey, Field Trip Guidebook, 80 p.

deWitt, W., Jr., 1970, Age of the Bedford Shale, Berea Sandstone, and Sunbury Shale in the Appalachian and Michigan basins, Pennsylvania, Ohio, and Michigan: U. S. Geol. Survey Bull. 1294-G, 11 p.

——— 1981, Revision of the areal extent of the New Albany, Chattanooga, and Ohio shales in Kentucky, *in* Roberts, T. G., ed., Geol. Soc. America, Cincinnati, 1981, Guidebook, v. II: Econ. Geology, Structure, p. 331–334.

Dott, R. H., Jr., and Bourgeois, J., 1979, Hummocky cross stratification—Importance of variable bedding sequences analagous to the Bouma sequence: Geol. Soc. America Abs. with Programs, v. 11., p. 414.

——— 1982, Hummocky stratification: significance of its variable bedding sequences: Geol. Soc. America Bull., v. 93, p. 663–680.

Duke, W. L., 1985, Hummocky cross-stratification, tropical hurricanes, and intense winter storms: Sedimentology, v. 32, p. 167–194.

Elam, T. D., ms, 1981, Stratigraphy and paleoenvironmental aspects of the Bedford-Berea sequence and the Sunbury Shale in eastern and south-central Kentucky: M. S. thesis, Univ. Kentucky, Lexington, 154 p.

Ettensohn, F. R., ms, 1975, Stratigraphic and paleoenvironmental aspects of Upper Mississippian rocks (upper Newman Group), east-central Kentucky: Ph. D. dissert., Univ. Illinois, Urbana, 320 p.

Ettensohn, F. R., 1984, The nature and effects of water depth during deposition of the Devonian-Mississippian black shale, *in* Proc. 1984 Eastern Oil Shale Symposium: Univ. Kentucky Inst. for Mining and Mineral Research and Kentucky Energy Cabinet, p. 333–346.

Ettensohn, F. R., and Barron, L. S., 1981, Depositional model for the Devonian-Mississippian black shales of North America: a paleogeographic-paleoclimatic approach, *in* Roberts, T. G., ed., Geol. Soc. America, Cincinnati, 1981, Guidebook, v. II: Econ. Geology, Structure, p. 344–357.

Ettensohn, F. R., and Elam, T. D., 1983, The Sunbury Shale and Bedford-Berea sequence near the black-shale outcrop belt in east-central and south-central Kentucky, *in* Proc. 1983 Eastern Oil Shale Symposium: Univ. of Kentucky Inst. Mining and Mineral Research and Kentucky Energy Cabinet, p. 143–149.

——— 1985, Defining the nature and location of a Late Devonian-Early Mississippian pycnocline in eastern Kentucky: Geol. Soc. America Bull., v. 96, p. 1313–1321.

Ettensohn, F. R., L. P. Fulton, and R. C. Kepferle, 1979, Use of scintillometer and gamma-ray logs for correlation and stratigraphy in homogenous black shales: Geol. Soc. America Bull., v. 90, Pt. II, p. 828–849.

Goble, R. S., ms 1972, The pre-Knox sequence and its relation to the Precambrian surface topography in eastern Kentucky: M. S. thesis, Eastern Kentucky Univ., Richmond, 59 p.

Goldring R., and Bridges, P., 1973, Sublittoral sheet sandstones: Jour. Sed. Pet., v. 43, p. 736–747.

Greenwood, B., and Miller, P. R., 1985, Sequence and lateral transitions in the facies of a barred nearshore environment: Jour. Sed. Pet., v. 55, p. 366–375.

Hamblin, A. P. and Walker, R. G., 1979, Storm-dominated shallow marine deposits: the Fernie-Kootenay (Jurassic) transition, southern Rocky Mountains: Canadian Jour. Earth Sci., v. 16, p. 1673–1690.

Haney, D. C., 1979, The Mississippian-Pennsylvanian systemic boundary in eastern Kentucky: Southeastern Geology, v. 21, p. 53–62.

Harris, L. D., 1975, Oil and Gas data from the Lower Ordovician and Cambrian rocks of the Appalachian Basin: U. S. Geol. Survey Misc. Inv. I-917 D, scale 1: 2,500,000.

Herrick, C. L., 1888, Geology of Licking County, O. Part IV: Denison Univ. Sci. Lab. Bull., v. 4, part I, p. 97–130.

Hoover, K. V., 1960, Devonian-Mississippian shale sequence in Ohio: Ohio Geol. Survey, Inf. Circ. 27, 154 p.

House, M. R., Gordon, M., Jr., and Hlavin, W. J., 1986, Late Devonian ammonoids from Ohio and adjacent states: Jour. Paleontology, v. 60, p. 126–144.

Howard, J. D., and Reineck, H.-E., 1981, Depositional facies of high-energy, beach-to-offshore sequence: Comparison with low-energy sequence: Am. Assoc. Petroleum Geologists Bull., v. 65, p. 807–830.

Hunter, R. E., and Clifton, H. E., 1982, Cyclic deposits and hummocky stratification of probable storm origin in Upper Cretaceous rocks of the Cape Sebastian area, southwestern Oregon: Jour. Sed. Pet., v. 52, p. 127–143.

Hyde, J. E., 1911, The ripples of the Bedford and Berea formations of central and southern Ohio with notes on the paleogeography of that epoch: Jour. Geology, v. 19, p. 257–269.

——— 1953, Mississippian formations of central and southern Ohio, *in* Marple, M. F., ed.: Ohio Geol. Survey Bull. 51, 335 p.

Ingram, R. L., 1954, Terminology for the thickness of stratification and parting units in sedimentary rocks: Geol. Soc. America Bull., v. 65, p. 937–938.

Kammer, T. W., ms, 1982, Fossil communities of the prodeltaic New Providence Shale Member of the Borden Formation (Mississippian), north-central Kentucky and southern Indiana: Ph. D. dissert., Indiana Univ., Bloomington, 301 p.

Kepferle, R. C., ms, 1972, Stratigraphy, petrology, and depositional environment of the Kenwood Siltstone Member, Borden Formation (Mississippian), Kentucky and Indiana: Ph. D. dissert., Univ. Cincinnati, Cincinnati, 245 p.

——— 1977, Stratigraphy, petrology, and depositional environment of the Kenwood Siltstone Member, Borden Formation (Mississippian), Kentucky and Indiana: U. S. Geol. Survey Prof. Paper 1007, 49 p.

——— 1978, Prodelta turbidite fan apron in Borden Formation (Mississippian), Kentucky and Indiana, *in* Stanley, D. J., and Kelling, G., eds., Sedimentation in Submarine Fans, Canyons, and Trenches: Stroudsburg, Pa., Dowden, Hutchinson, and Ross, Inc., p. 224–238.

Kepferle, R. C., Beard, J. G., and Pollock, J. D., 1982, Lithologic and stratigraphic description of cores of organic-rich shale of Late Devonian and Early Mississippian age in northeastern Kentucky: U. S. Geol. Survey Open-File Rept. OF 82-0219, 75 p.

Kepferle, R. C., Potter, P. E., and Pryor, W. A., 1981, Stratigraphy of the Chattanooga Shale (Upper Devonian and Lower Mississippian) in vicinity of Big Stone Gap, Wise County, Virginia: U. S. Geol. Survey Bull. 1499, 20 p.

Klein, G. deV., 1974, Estimating water depths from analysis of barrier island and deltaic sedimentary sequences: Geology, v. 2., p. 409–412.

Komar, P. D., Neudeck, R. H., and Kulm, L. D., 1972, Observations and significance of deep-water oscillatory ripple marks on the Oregon continental shelf, *in* Swift, D. J. P., Duane, D. B., and Pilkey, O. H., eds., Shelf Sediment Transport: Process and Pattern: Stroudsburg, Pa., Dowden, Hutchinson, and Ross, Inc., p. 601–619.

Kumar, N., and Slatt, R. M., 1984, Submarine-fan and slope facies of Tonkawa (Missourian-Virgilian) Sandstone in deep Anadarko Basin: Am. Assoc. Petroleum Geologists Bull., v. 68, p. 1839–1856.

Kuenen, Ph., H., 1958, Experiments in geology: Geol. Soc. Glasgow Trans., v. 23, p. 1–28.

Laury, R. L., 1971, Stream bank failure and rotational slumping: preservation and significance in the geologic record: Geol. Soc. America Bull., v. 82, p. 1251–1266.

Leckie, D. A., and Walker, R. G., 1982, Storm- and tide-dominated shorelines in Cretaceous Moosebar-Lower Gates interval—outcrop equivalents of deep basin gas trap in western Canada: Am. Assoc. Petroleum Geologists Bull., v. 66, p. 138–157.

Lundegard, P. D., Samuels, N. D., and Pryor, W. A., 1985, Upper Devonian turbidite sequence, central and southern Appalachian basin: Contrasts with submarine fan deposits: Geol. Soc. America Spec. Paper 201, p. 107–121.

Marsaglia, K. M., and Klein, G. deV., 1983, The paleogeography of Paleozoic and Mesozoic storm depositional systems: Jour. Geology, v. 91, p. 117–142.

Mason, C., and Yochelson, E. L., 1985, Some tubular fossils (*Sphenothallus:* "Vermes") from the Middle and Late Paleozoic of the United States: Jour. Paleontology, v. 59, p.85–95.

McCrory, V. L. C., and Walker, R. G., 1986, A storm and tidally-influenced prograding shoreline—Upper Cretaceous Milk River Formation of Southern Alberta, Canada: Sedimentology, v. 33, p. 47–60.

McDowell, R. C., 1978, Geologic map of the Levee Quadrangle, east-central Kentucky: U. S. Geol. Survey Geol. Quad. 1478, scale 1:24,000.

McDowell, R. C., and Weir, G. W., 1977, Geologic map of the Olympia Quadrangle, Bath and Menifee counties, Kentucky: U. S. Geol. Survey Geol. Quad. Map 1406, scale 1:24,000.

McFarlan, A. C., 1943, Geology of Kentucky: Frankfort, Ky., Waverly Press, 531 p.

Moore, B. R., and Clarke, M. K., 1970, The significance of a turbidite sequence in the Borden Formation (Mississippian) of eastern Kentucky and southern Ohio: Geol. Assoc. Canada Spec. Paper 7, p. 211–218.

Morris, R. H., and Pierce, K. L., 1967, Geologic map of the Vanceburg Quadrangle, Kentucky-Ohio: U. S. Geol. Survey Geol. Quad. 598, scale 1: 24,000.

Morse, W. C., and Foerste, A. F., 1909a, The Waverlian formations of east-central Kentucky: Jour. Geology, v. 17, p. 165.

——— 1909b, The Bedford fauna at Indian Fields and Irvine, Kentucky: Ohio Naturalist, v. 9, no. 7, p. 515–523.

——— 1912, Preliminary report on the Waverlian formations of east-central Kentucky and their economic values: Kentucky Geol. Survey, ser. 3, Bull. 16, 76 p.

Nelson, C. H., Normark, W. R., Bouma, A. H., and Carlson, P. R., 1978, Thin-bedded turbidites in modern submarine canyons and fans, *in* Stanley, D. J., and Kelling, G., eds., Sedimentation in Submarine Canyons, Fans, and Trenches: Stroudsburg, Pa., Dowden, Hutchinson, and Ross, Inc., p. 177–189.

Newberry, J. S., 1870, The Geological Survey of Ohio, its progress in 1869: report of an address delivered to the legislature of Ohio, Feb. 7, 1870: New York, 66 p.

Ohio Geol. Soc. and the Geol. Soc. of Kentucky, 1968, Geological aspects of the Maysville-Portsmouth region, southern Ohio and northeastern Kentucky: Joint Field Conf. Ohio Geol. Soc. and Geol. Soc. Kentucky: Kentucky Geol. Survey, 86 p.

Pashin, J. C., ms, 1985, Paleoenvironmental analysis of the Bedford-Berea sequence (Devonian-Mississippian), northeastern Kentucky and south-central Ohio: M. S. thesis, Univ. Kentucky, Lexington, 105 p.

Pepper, J. F., deWitt, W., Jr., and Demarest, D. F., 1954, Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin: U. S. Geol. Survey Prof. Paper 259, 111 p.

Potter, P. E., deReamer, J. H., Jackson, D. S., and Maynard, J. B., 1983, Lithologic and paleoenvironmental atlas of Berea Sandstone (Mississippian) in the Appalachian Basin: Appalachian Geol. Soc. Spec. Pub. 1, 157 p.

Rich, J. L., 1951, Three critical environments of deposition and criteria for the recognition of rocks deposited in each of them: Geol. Soc. America Bull., v. 62, p. 1–20.

Rothman, E. M., ms, 1978, The petrology of the Berea Sandstone (Early Mississippian) of south-central Ohio and a portion of northern Kentucky: M. S. thesis, Miami Univ., Oxford, Ohio, 105 p.

Seilacher, A., 1982, Distinctive features of sandy tempestites, *in* Einsele, G., and Seilacher, A., eds., Cyclic and Event Stratification: New York, Springer-Verlag, p. 333–349.

Stockdale, P. B., 1939, Lower Mississippian rocks of the east-central interior: Geol. Soc. America Spec. Paper 22, 248 p.

Swift, D. J. P., Figueiredo, A. G., Jr., Freeland, G. L., and Oertel, G. F., 1983, Hummocky cross-stratification and megaripples: a geological double standard?: Jour. Sed. Pet., v. 53, p. 1295–1317.

VanBeuren, V. V., ms 1980, Stratigraphy of the Sunbury Shale (Lower Mississippian) of the central Appalachian Basin: M. S. thesis, Univ. Cincinnati, Cincinnati, Ohio, 150 p.

Vanney, J.-R., and Stanley, D. J., 1983, Shelfbreak physiography: an overview: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 33, p. 1–24.

von der Borch, C. C., Grady, A. E., Aldam, R., Miller, D., Neumann, R., Rovira, A., and Eickhoff, K., 1985, A large-scale, meandering submarine canyon: outcrop example from the late Proterozoic Adelaide Geosyncline, South Australia: Sedimentology, v. 32, p. 507–518.

von der Borch, C. C., Smit, R., and Grady, A. E., 1982, Late Proterozoic submarine canyons of the Adelaide Geosyncline, south Australia: Am. Assoc. Petroleum Geologists Bull., v. 66, p. 332–247.

Walker, R. G., 1971, Nondeltaic depositional environments in the Catskill clastic wedge (Upper Devonian) of central Pennsylvania: Geol. Soc. America Bull., v. 82, p. 1305–1326.

———— 1978, Deep-water sandstone facies and ancient sub-marine fans: models for exploration and stratigraphic traps: Am. Assoc. Petroleum Geologists Bull., v. 62, p. 932–966.

———— ed., 1979, Facies models: Geosci. Canada Reprint Ser. 1, 211 p.

Walls, R. A., 1975, Late Devonian-Early Mississippian subaqueous deltaic facies in a portion of the southeastern Appalachian Basin, *in* M. L. Broussard, ed., Deltas: Houston, Houston Geol. Soc., p. 359–367.

Weir, G. W., 1976, Geologic map of the Means Quadrangle, east-central Kentucky: U. S. Geol. Survey Geol. Quad. 1324, scale 1:24,000.

Weir, G. W., and McDowell, R. C., 1976, Geologic map of the Preston Quadrangle, Bath and Montgomery counties, Kentucky: U. S. Geol. Survey Geol. Quad. Map 1334, scale 1:24,000.

Woodrow, D. L., and Isley, A. M., 1983, Facies, topography, and sedimentary processes in the Catskill Sea (Devonian), New York and Pennsylvania: Geol. Soc. America Bull., v. 94, p. 459–470.

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