THESIS

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STRATIGRAPHY AND PALEOENVIRONMENTAL ASPECTS OF THE BEDFORD-BEREA SEQUENCE AND THE SUNBURY SHALE IN EASTERN AND SOUTH-CENTRAL KENTUCKY

THESIS

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By

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INTRODUCTION

Purpose

The Bedford Shale and Berea Sandstone separate the overlying organic-rich, black Sunbury Shale (Mississippian) from the underlying black Ohio Shale (Devonian) and are previously unrecognized parts of the upper New Albany and Chattanooga Shale. Although recent studies have elucidated the stratigraphic and lithologic relations for much of the Devonian-Mississippian black-shale sequence, relationships in the upper part of the sequence, including the Bedford, Berea, and Sunbury, are not as well understood. The purpose of this study is to examine the Bedford Shale, Berea Sandstone, and Sunbury Shale in order to delineate stratigraphic and lithologic relationships between them and the adjacent black shales, to define their geographic limits, and to determine structural influence on the deposition of these units.

Both the Berea Sandstone and adjacent black-shale units have produced oil and gas for many years, and the black shales probably are the source beds of the indigenous oil. Recently, the Sunbury Shale has been investigated as an oil-shale and uranium resource (Robl et al., 1980) and thousands of acres in the Knobs outcrop belt of central and eastern Kentucky have been leased for possible commercial exploitation of the shale. The Commonwealth of Kentucky is currently formulating plans and regulations for possible shale development. Because the economic potential of these units is substantial, this characterization of the Bedford, Berea, and Sunbury will be useful.

Overview of the Devonian-Mississippian Black-Shale Sequence

Since all three formations are entirely within the Upper Devonian-

Lower Mississippian black-shale sequence, it is important to discuss this sequence briefly. In North America, Devonian-Mississippian black shales are widely distributed throughout parts of east-central, southeastern, midwestern, and southwestern United States. "Twelve basins in the United States and four in Canada contain black shales of Late Devonian or Early Mississippian age (Provo, 1977)." These shales were first recognized along the length of the Appalachian Basin from New York to Alabama. Their maximum thickness of 2000 feet (610 m) occurs in eastern Kentucky, eastern Ohio, and western West Virginia (Provo, 1977). Minimum thicknesses occur along the south and west periphery of the Appalachian Basin in southern Kentucky, Tennessee, and Alabama. The thinnest section may be in Cumberland County, Kentucky, near the crest of the Cincinnati Arch, where only four feet (1.2 m) of Chattanooga Shale has been reported (Cattermole, 1963).

Lithologic characteristics of the black shale have long intrigued geologists. These include the uniform brownish-black to black color, fine grain size, fissility, and petroliferous odor. Biostratigraphic zonation within the black shale has been based on conodonts and spores, but diversity and abundance of fauna and flora is generally limited (Provo, 1977).

It is generally thought that the sediments comprising the shales were deposited in anoxic marine waters, but there has been much disagreement regarding the depth of these waters. Geochemical, stratigraphic, paleontological, and sedimentological problems pertaining to the black shale remain despite significant advances in their understanding and characterization.

Devonian black shales were deposited when seas in the Appalachian

Basin and on the adjacent craton became deep enough during transgression that bottom waters could no longer be oxygenated (Ettensohn and Barron, 1981). Therefore, anaerobic bottom conditions occurred in which organic-rich muds were preserved. Because organic detritus is typically destroyed by oxidation in aerobic parts of the water column, anaerobic conditions are generally essential for the preservation of organic-rich muds. The Bedford Shale and Berea Sandstone (herein also called the Bedford-Berea sequence) represent a major regressive wedge of deltaic sediments which prograded from several different sources into seas where black-shale deposition was occurring (Pepper et al., 1954). The influx of gray, green, and red clastics represented by these deltaic units reflects the presence of aerobic conditions in the sea at this time. Following deposition of the Bedford and Berea, the black organic-rich Sunbury Shale was deposited, signifying a return to deeper, anaerobic, marine conditions. Overlying the thin Sunbury is another major wedge of deltaic clastics known variously as the Borden Formation, the Price Siltstone, the Grainger Formation, or the Pocono Sandstone. This clastic wedge reflects major deltaic progradation and the return of widespread aerobic conditions. This progradational event effectively ended the deposition of Devonian-Mississippian black muds in the Appalachian Basin.

PROCEDURES

Study Area

The study area lies within the west-central portion of the Appalachian Basin. "As commonly defined, the Appalachian Basin consists of the elongate area underlain by the large mass of downwarped Paleozoic rocks between the Blue Ridge anticlinorium on the east and the crest of the Cincinnati Arch on the west" (de Witt et al., 1979). Its axial trend is approximately N 40°E though local and regional segments vary considerably.

This study includes an investigation of both surface and subsurface Devonian and Mississippian rocks in all Kentucky counties east of the Cincinnati Arch. This includes all Kentucky counties east of a line extending from Lewis County in northeastern Kentucky to Cumberland County in south-central Kentucky (Fig. 1). Subsurface information was also obtained from peripheral areas, including Wayne and Mingo counties, West Virginia; Lawrence and Scioto counties, Ohio; Dickinson, Buchanan, and Wise counties, Virginia; and Scott, Campbell, Claiborne, and Pickett counties, Tennessee. Examination of radioactivity logs from these areas aided correlation and data control.

A combination of study methods was used in defining stratigraphic and lithologic relationships between units. Along the Knobs outcrop belt (Fig. 1), previous studies of surface units by Morse and Foerste (1909a) and Stockdale (1939) had already delineated some relationships. Data from those studies were compared with data from the subsurface from a series of shallow cores taken in the same region. Lithologic descriptions of pertinent intervals of the cores were made and are recorded in Appendix A. Gamma-ray logs, run in core and well boreholes,

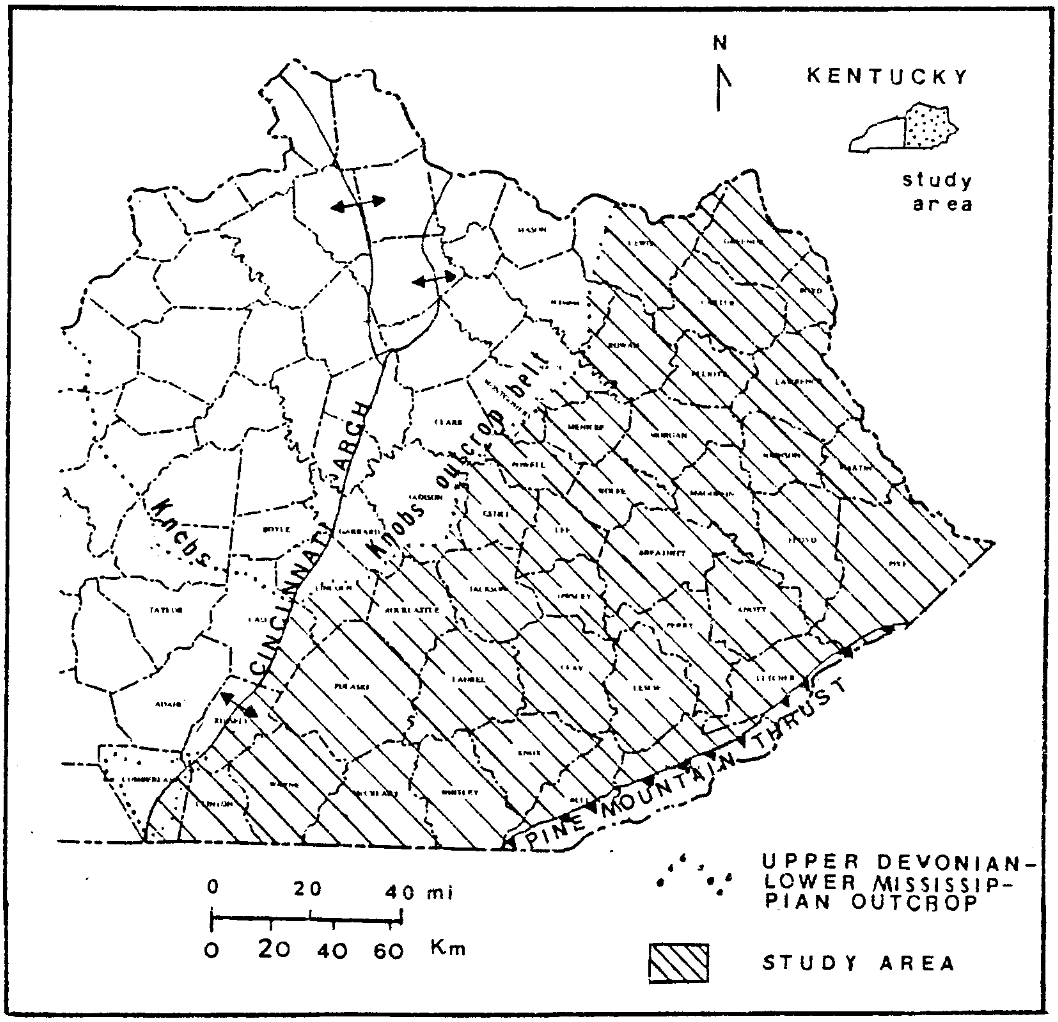


Figure 1. Eastern and south-central Kentucky study area.

and radioactivity profiles, measured from cores and exposures, were used to trace the units from the Knobs outcrop belt eastward into the subsurface in the central and eastern portions of the study area. In the subsurface, geophysical logs and lithologic descriptions from better driller's logs provided a means of tracing the units. Time constraints prevented extensive examination of well cuttings in this area, and lack of deep cores also limited direct lithologic study. Where the units are exposed on the Pine Mountain Thrust sheet, information from surface mapping supplemented the geophysical and driller's logs.

Log Library Examination

Construction of a series of isopachous and structure-contour maps was undertaken to help define relationships between units and their extent. Three primary methods were employed to collect the data used in constructing these maps. Most of the subsurface information was obtained from geophysical logs and driller's logs housed in the oil- and gas-well records room of the Kentucky Geological Survey on the campus of the University of Kentucky in Lexington. Data were also obtained from geophysical logs and driller's logs provided by the Institute for Mining and Minerals Research of the University of Kentucky. The Carter Coordinate grid system was used in plotting well locations. ~~Were~~ Where available, information from at least one gamma-ray log per Carter Coordinate section was recorded on data sheets. The data listed included the county, well name, Carter Coordinate location, elevation of datum, elevation of ground level, elevation of the top of the Sunbury Shale, elevation of the top of the Bedford-Berea sequence, and elevation of the top of the Ohio Shale. Thicknesses of the units and their elevations relative to sea level were later calculated and posted on data sheets. Density logs were occasionally used in place of gamma-ray logs where the gamma-ray curve was off-scale or where unit tops could not be otherwise determined. Driller's well-log data, which supplement information from gamma-ray or density logs, were recorded if pertinent. In Carter Coordinate sections with no other forms of control, high quality driller's logs were used as control points. Internal stratigraphy, such as major high- or low-radioactive zones, was recorded for most wells to determine (1) possible continuity of zones throughout the basin, and (2) possible correlation of the zones with distinct lithologies. Information from about 1200 geophysical logs was thus recorded on data sheets. In areas with potential structural and isopachous anomalies, additional geophysical log data were recorded in each Carter Coordinate section. In addition, 1700 driller's logs were used in map construction. All data sheets are now housed in the Department of Geology, University of Kentucky.

The third source of data was U.S. Geological Survey geologic quadrangle maps of the Knobs outcrop belt and south-central Kentucky. Mapped elevations and thicknesses of the Bedford-Berea, Sunbury, and portions of the New Albany and Chattanooga shales were recorded. In south-central Kentucky, the tops of the Bedford, Berea, and Sunbury were considered to be coincident with the top of the Chattanooga Shale because of their extreme thinness (less than five feet) (1.5 m) in this area compared to the contour interval of 100 feet (30.5 m). Approximately fifty such data points were used, largely in Lewis, Russell, Clinton, and Cumberland counties

From these elevations and thickness measurements, isopachous maps were made for the Bedford-Berea sequence and Sunbury Shale, and structure-contour maps were drawn on top of the Ohio Shale, on top of the Bedford-Berea, and on top of the Sunbury. These maps are regional, encompassing the entire study area of eastern and south-central Kentucky.

The number of points used in constructing the maps varied from 1060 for the Sunbury isopachous map to approximately 2800 for the Bedford-Berea isopachous map and the structure-contour maps on the base of the Sunbury and on top of the Ohio Shale. The number of points used varied for many reasons, including the depth of the hole and corresponding logs, amount of control needed, and consistency of driller's logs compared with local geophysical logs. Control points based on geophysical logs were relied upon more heavily in much of the area because driller's logs seldom recorded subtle lithologic changes necessary for determining formation boundaries. For instance, the presence of low-radioactive brownish-black shales in the lowermost Bordon Formation, determined from radioactivity logs and cores, commonly caused drillers to assign lower portions of the Borden to the "Coffee Shale", which in northeastern Kentucky includes only the highly-radioactive Sunbury Shale. Hence, lower parts of the Borden Formation were characteristically included with the Sunbury by many drillers, which greatly increased the true thickness of the Sunbury and inevitably led to inaccurate isopachous and structure-controur maps. Therefore, an effort was made to avoid the use of data from driller's logs in construction of the Sunbury isopachous map and the structure-contour map on top of the Sunbury.

Outcrop Examination

Uppermost portions of Chattanooga and New Albany Shale exposures along the western border of the study area were examined with a portable scintillometer to determine the possible presence of highly-radioactive shales equivalent to the Sunbury Shale and low-radioactivity shales equivalent to the Bedford-Berea sequence. The highly-radioactive Sunbury Shale equivalent is easily distinguished from lower portions of the New Albany or Chattanooga shales on scintillometer profiles as indicated by Ettensohn et al. (1979), in a New Albany section measured near Clay City, Powell County, Kentucky. All but two outcrop locations used in this study were obtained from a study by Swager (1978).

The technique used to measure radioactivity was modified from similar techniques used by Swager (1978) and Ettensohn et al. (1979). A tape measure was run down the exposure, and the radioactivity of the vertical sequence was measured with the hand-held scintillometer by placing it against the outcrop and recording measurements of radioactivity at every one- and some half-foot intervals and at visible lithologic breaks. Readings were quantitatively measured in counts per second (CPS). Compilation of the readings on a vertical graph yields a scintillometer profile, which is qualitatively similar to a gamma-ray log (Ettensohn et al., 1979, p. 840). A profile was constructed for each measured outcrop (Appendix D) and for all examined cores (Appendix A). Comparison and correlation of radioactivity profiles from outcrops with gamma-ray logs from nearby wells were later made. Some cross-sections show these scintillometer profiles and correlate then with gamma-ray logs taken from deeper protions of the Appalachian Basin (Appendix D). The locations of outcrops described with a scintillometer are shown in Figure 2, and locations of cross-sections are shown in Figure 3.

Relative radioactivity was measured from the base of the thin

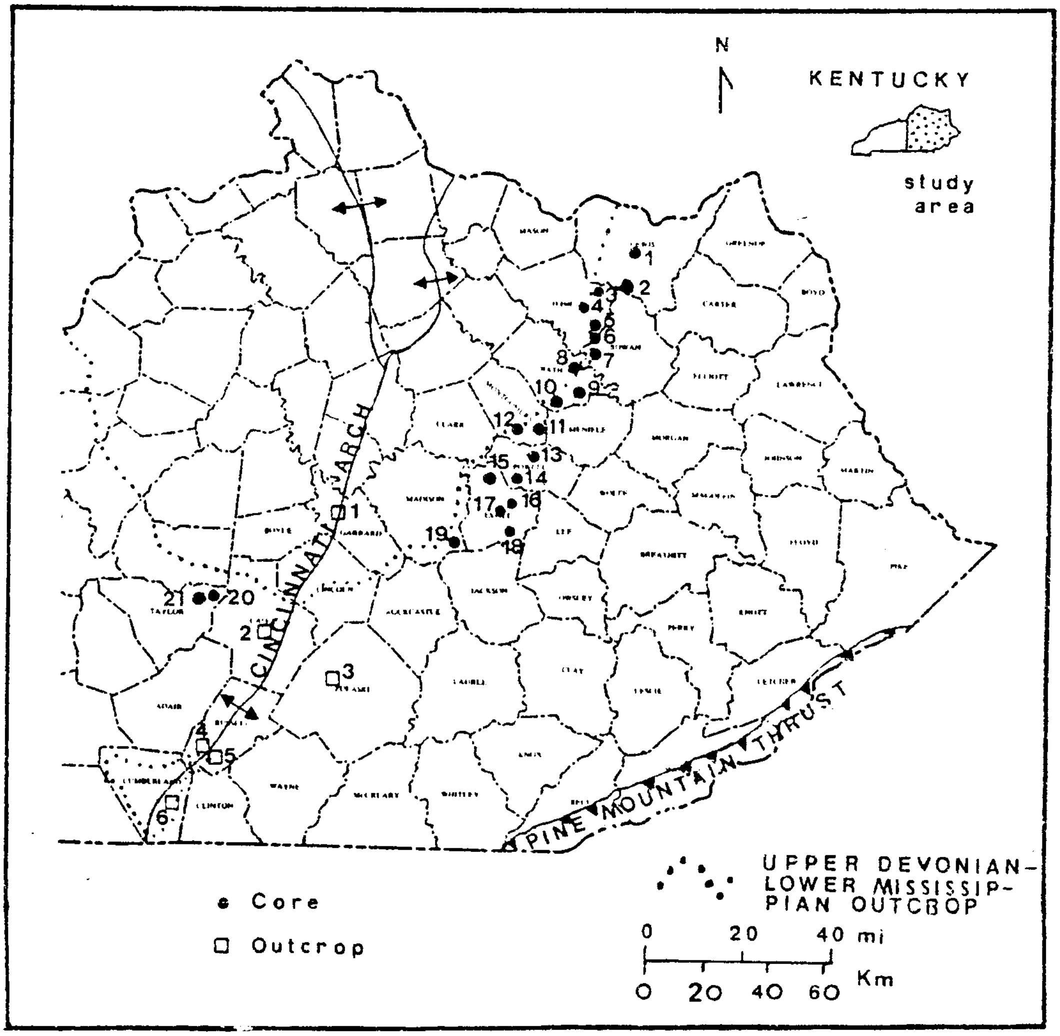


Figure 2. Location of examined cores and outcrops.

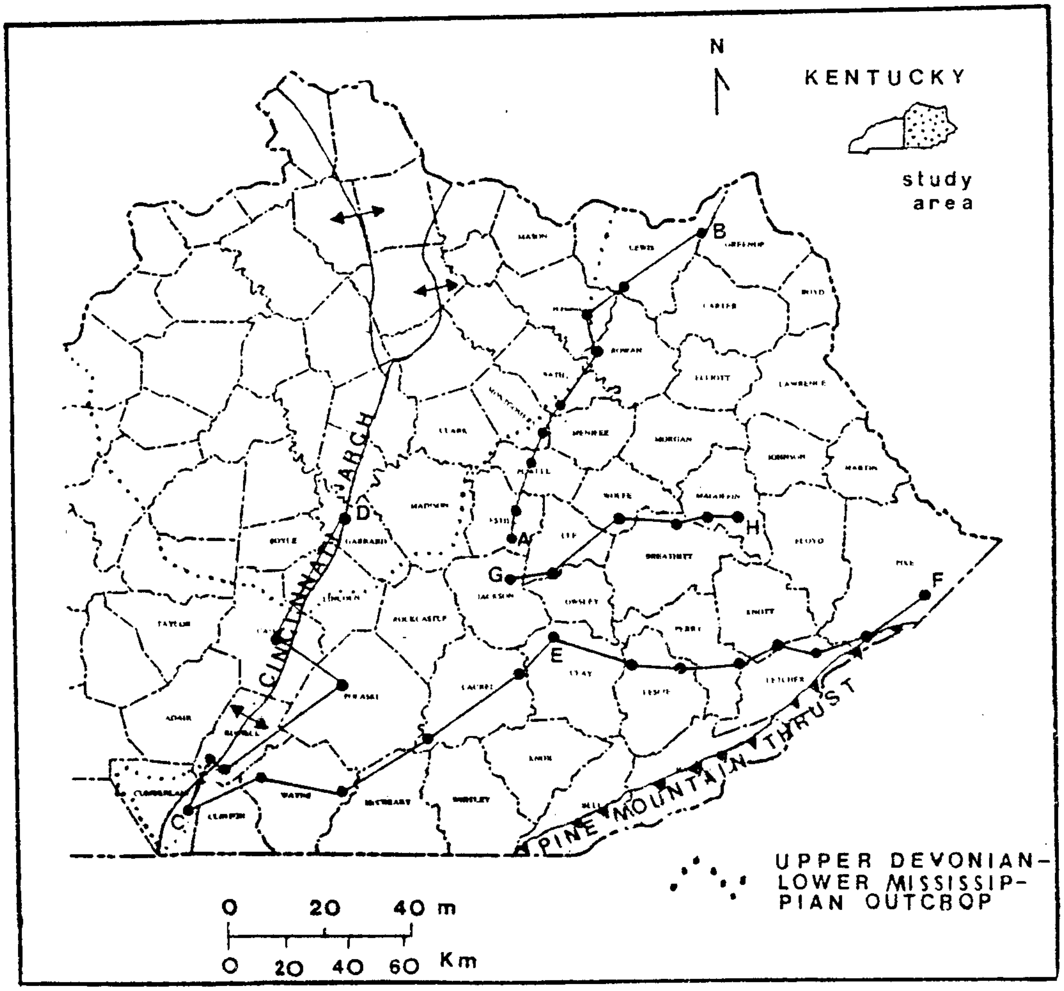


Figure 3. Location of cross-sections.

Three Lick Bed of Provo et al. (1978) to the base of the Maury or Borden formations (Appendix D, Fig. 22). The Three Lick Bed contains three greenish-gray, clayey shales separated by two black shales. This bed is traceable throughout eastern and south-central Kentucky on the surface because the green shales weather to form small reentrants within the black shales. In the subsurface, the green shales are indicated by three thin zones of low radioactivity which are commonly associated with deflections on the caliper log. Basal Maury and Borden shales are easily distinguishable from black shale because of their higher stratigraphic position, thicker nature, greenish-gray color, and low radioactivity.

Core Examination

Nineteen cores along the outcrop belt at the western edge of the study area were examined. The cores were taken along a line from Vanceburg, Lewis County, to Berea, Madison County. Most of the cores (14) were drilled during a project of the Institute for Mining and Minerals Research. Each of the cores contains complete Bedford-Berea and Sunbury sections. The other five cores were provided by the U.S. Soil Conservation Service, the U.S. Geological Survey, and Edward N. Wilson, consulting geologist. Two cores taken from Taylor County, outside the study area, were also examined. These were also provided by E. N. Wilson. Location of coreholes is shown in Figure 2.

Pertinent intervals of each core were described lithologically and were measured for radioactivity with a portable scintillometer (Appendix A), using the technique described by Ettensohn et al. (1979). Tops of the profiles constructed from these readings started usually a few feet above the base of the Borden Formation and continued downward into the

Cleveland Shale Member of the Ohio Shale or its equivalent in the New Albany and Chattanooga shales. All coreholes were assumed to have been spudded perpendicular to topographic contours except for the Madison County core (#19), which was angled 15° from vertical. Lithologic descriptions were corrected to vertical in this core.

Because gamma-ray logs were run in most holes from which cores were taken, comparison was made of the corehole log with the scintillometer profile of each core (Appendix A). The general pattern of high- and low-radioactivity readings characteristic of the Sunbury and the Bedford-Berea was recorded by the scintillometer, but the patterns for these cores are not as clear as they might be, probably due to the enhanced background radioactivity in the core-storage facility.

Radioactive Logging

Gamma-ray logs were chosen for subsurface study in eastern Kentucky because of their widespread use throughout the area and because parts of the shale interval studied are usually radioactive. In most instances they allow for quick, accurate interpretations of formation boundaries due to the sensitivity of the gamma-ray sonde in detecting the varying radioactivity associated with lithologic changes. Gamma-ray logs are especially useful in correlating formations, particularly those containing shales, because shales contain the radioactive isotope potassium 40 in the clay structure (Merkel, 1979) and are usually more radioactive. Unusually high radioactivity is often characteristic of brownish-black shales with abundant organic matter because of the close association of radioactive uranium and thorium with organic matter (Conant and Swanson, 1961). Clay minerals with adsorbed radioactive ions are another major source of radioactivity in these rocks.

Because any one geophysical log measures only one parameter or characteristic property of the rock body at any given instant, uncertainties regarding the placement of formation boundaries may occur when only one type of log is examined. Hence, formation-density and caliper logs are run concurrently with gamma-ray logs and may help solve these problems.

In eastern Kentucky, the organic-rich Sunbury and Ohio shales typically show high-radioactivity (rightward) deflections on the gamma-ray log, whereas the organic-poor Berea Sandstone and Bedford Shale are characterized by negative (leftward) deflections (Fig. 4). Even though the Bedford is relatively non-radioactive, it still exhibits a higher radioactivity than most other non-shale lithologies.

The formation-density log, an induced radioactivity log, is basically used for porosity determinations, but density measurements are useful in defining oil-shale yields (Schlumberger, 1972) and in defining some lithologic boundaries. Black shales such as the Sunbury and the Cleveland Member of the Ohio Shale typically have low-density signatures due to the presence of abundant, lightweight organic matter, and produce negative (leftward) deflections on the formation-density log, whereas the organic-poor Bedford-Berea shales and sandstones have higher densities and produce positive (rightward) deflections (Fig. 4). The density log of the Bedford-Berea and Sunbury in Kentucky often appears to be a near mirror image of the gamma-ray log from the same units (Fig. 4). Low-density zones generally correspond to highly-radioactive intervals, whereas higher-density zones correspond to low-radioactivity intervals. Schmoker (1978) demonstrated the linear relationship between density, gamma-ray intensity, and organic content in Devonian shales

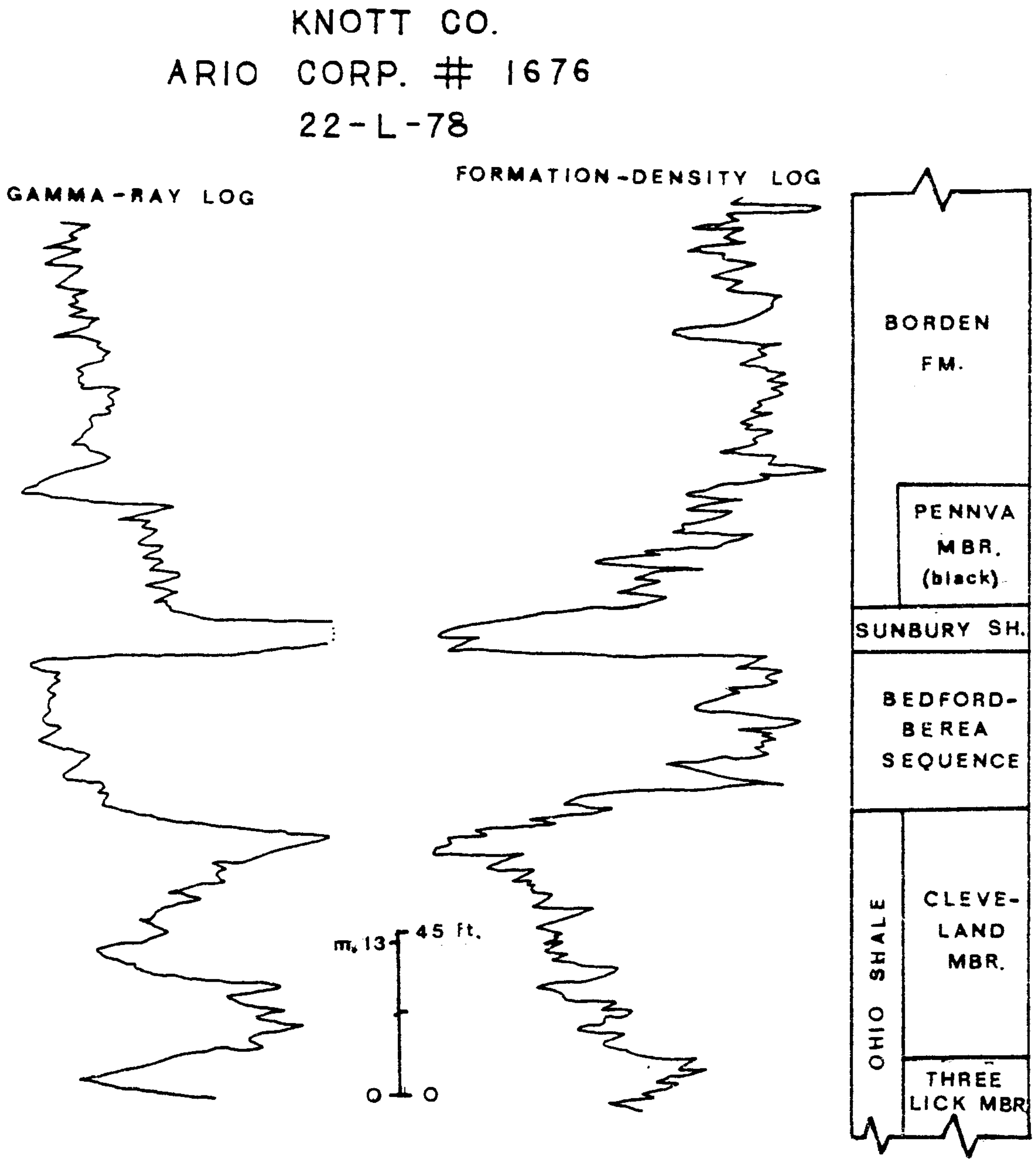


Figure 4. Comparison of gamma-ray and formation density logs, showing near-mirror images.

from Lincoln County, West Virginia.

The caliper log measures the borehole diameter, which reflects the amount of wallrock caving in the hole. Commonly, caving in flat-lying formations is due to the instability of clay-rich rocks which absorb water during drilling. Within the black-shale sequence, caving was most commonly noted in the greenish-gray, clayey shales of the Bedford Shale and the Three Lick Bed. The highly compacted, organic-rich black shales are tough and resistant and are not as subject to caving as are the greenish-gray shales.

PREVIOUS WORK

Literature on the Bedford Shale, Berea Sandstone, and Sunbury Shale is extensive, partly because of their significance in oil and gas production in the Appalachian Basin. Most study of these units has occurred in Ohio, where the type localities are located and where the units are best exposed on the outcrop belt. A review of lithostratigraphic equivalents as interpreted from previous work is presented in Figure 5. Regional nomenclature advanced by this author is presented in Figure 6.

Studies by Hyde (1911, 1953), Wilson (1950), Hoover (1960), and Rothman (1978) on the Bedford, Berea, and Sunbury were concentrated in central and southern Ohio but included portions of Lewis County, northeastern Kentucky.

Morse and Foerste (1909a,b) were the first to trace the surface extent of the Bedford Shale and Sunbury Shale in Kentucky, and they outlined the distribution of these units from the Ohio River to Estill County, Kentucky. They recognized the "wedging out" of the Bedford and subsequent onlap of the lower black shale (Ohio) by the Sunbury Shale. They identified a faunal assemblage of brachiopods, gastropods, cephalopods, and pelecypods from the thin Bedford Shale in east-central Kentucky.

Butts (1922) principally restated the pioneering work of Morse and Foerste, and provided a brief discussion of the units which included surface distribution, character, age and correlation. He also noted the lack of shale in the Bedford-Berea interval in northeastern Lewis County, and suggested that a five-foot (1.5 m), gray, clay shale between two black shales in Marion County might be equivalent to the Bedford Shale.

Stockdale (1939) did extensive surface work on Devonian-

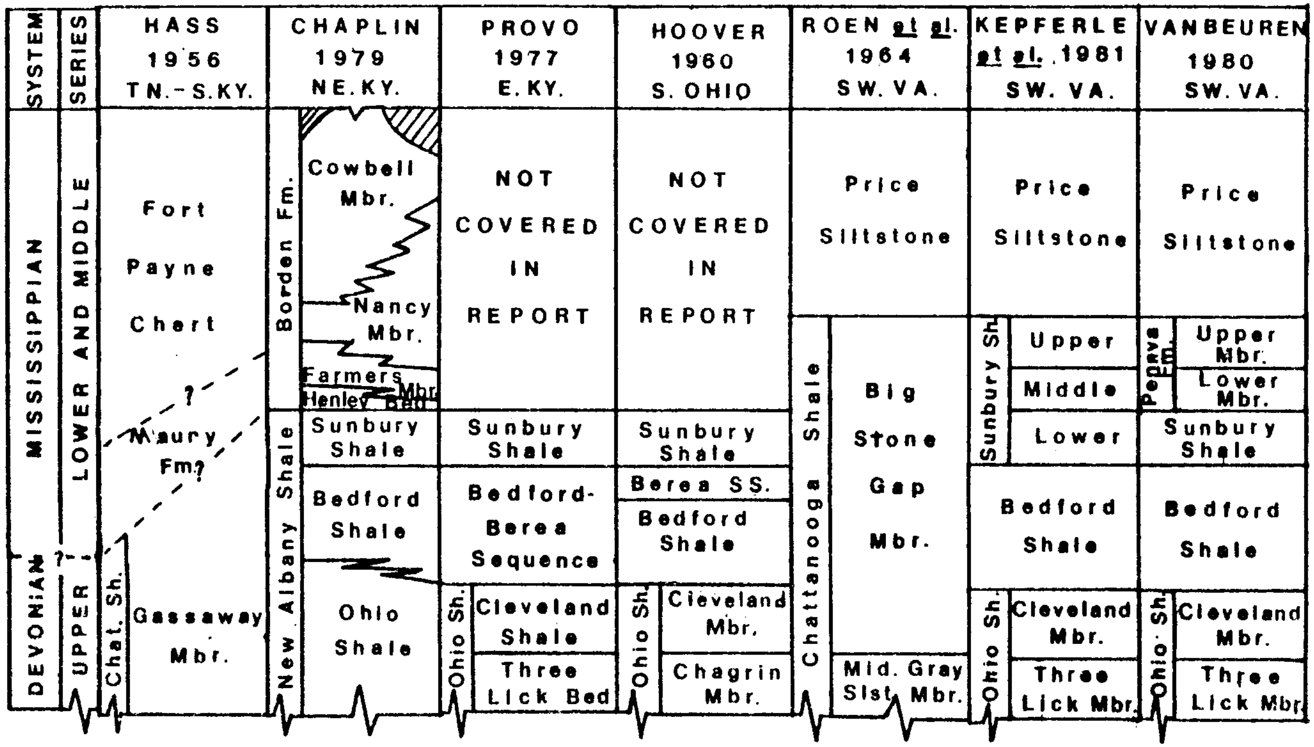


Figure 5. Approximate lithostratigraphic correlation near the Devonian-Mississippian boundary as interpreted from previous workers.

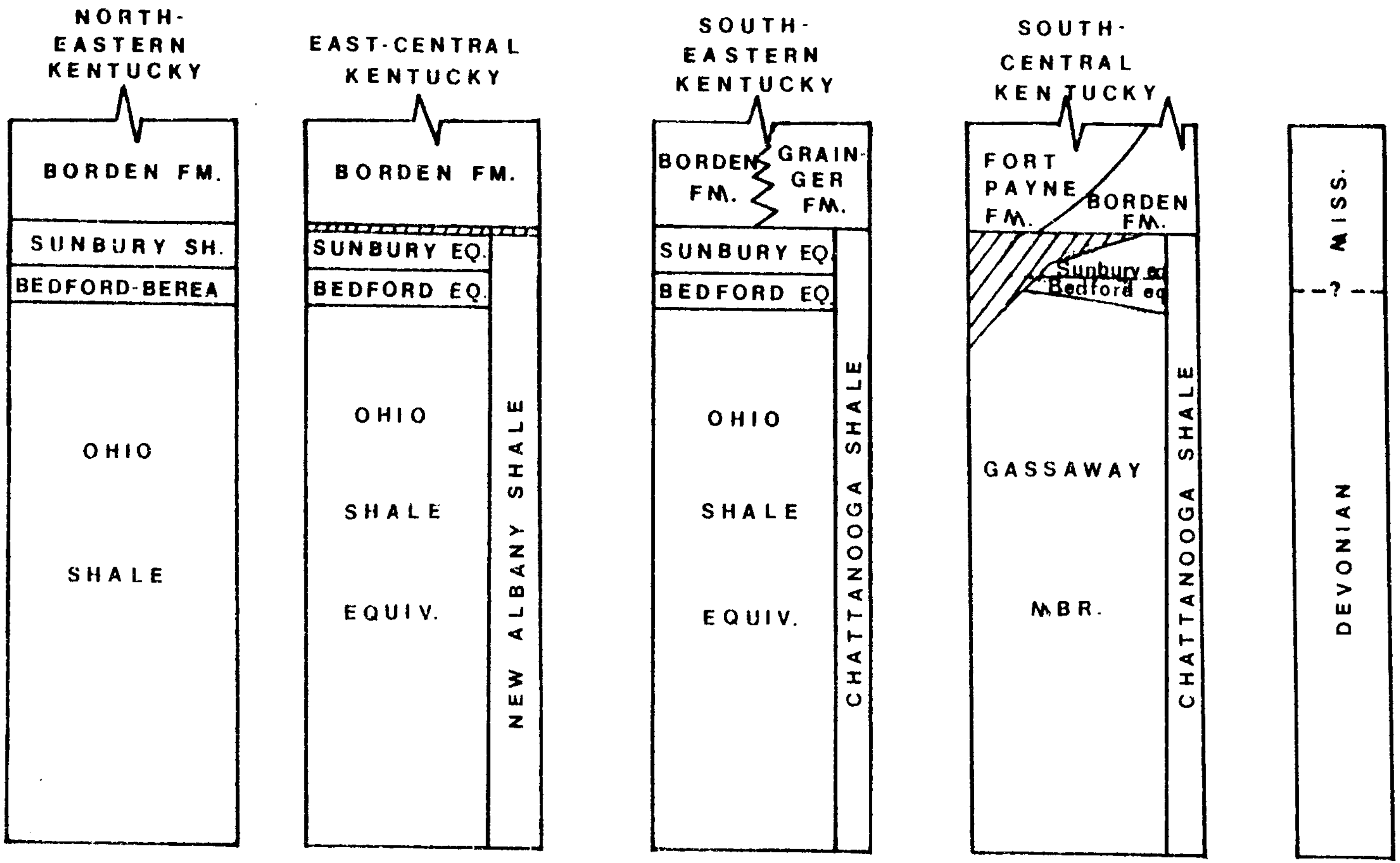


Figure 6. Stratigraphic relations and nomenclature within this study.

Mississippian shales in Tennessee, Alabama, and Kentucky and presented sections using 54 exposures along the Knobs outcrop belt. In Lewis County, he classified most of the pre-Cuajahoga Mississippian sandstones as parts of the Bedford Shale, but he also placed some of the upper sandstones in the Berea. He noted rapid thinning of the Bedford Shale in Montgomery County and Lewis County, and identified intertonguing of Sunbury-Bedford lithologies in Montgomery County. Moreover, he correlated the black Sunbury Shale with Mississippian beds of the New Albany Shale in southern Indiana.

Pepper et al. (1946) presented a preliminary isopachous map of the "Berea sand" in Ohio, West Virginia, and Kentucky during an eleven-year U.S. Geological Survey program to identify and evaluate oil and gas producing intervals in the Berea Sandstone and adjacent Appalachian Basin units. The map, constructed from thousands of driller's logs, shows areas of "Berea sand" production. A generalized cross-section through eastern Kentucky was constructed to show the stratigraphic variability of shale and sand units within the Bedford-Berea. Pepper et al. (1954) wrote the classic paper which compiled data produced by the program and which advanced significant ideas on stratigraphic interpretation, correlation, sedimentation, and paleogeography. Source areas for Bedford-Berea sediments were also identified, as were distinct cycles of sedimentation related to transgression and regression.

In a similar, but less widespread study, Walls (1975) evaluated subsurface data from the Bedford, Berea, and Sunbury, as well as for the Ohio Shale and its equivalents in West Virginia, Virginia, and extreme eastern Kentucky. He identified three lithofacies and suggested that each represented a contemporaneous, sub-aqueous environment in a deltaic complex. Each lithofacies was correlated with Upper Devonian-Lower Mississippian stratigraphic units, although he hesitated to assign traditional formation names.

Recent black-shale studies at the University of Kentucky and the University of Cincinnati have included the Bedford Shale, Berea Sandstone and Sunbury Shale. Provo (1977) and Dillman (1980) recognized these units in eastern Kentucky subsurface studies and noted the ability to correlate then with gamma-ray logs. Swager (1978) and Ettensohn et al. (1979) included the Bedford-Berea sequence and Sunbury Shale as two of seven radioactive stratigraphic units occurring in eastern and south-central Kentucky exposures, and easily delineated by their distinctive radioactivity signatures on scintillometer profiles. Swager (1978) characterized the Bedford-Berea sequence as a green shale and light siltstone unit of low radioactivity sandwiched between the more highly radioactive black shales of the underlying Ohio Shale and overlying Sunbury Shale. Miller (1978) recognized five microfacies from petrographic examination of eastern Kentucky black-shale core and outcrop samples. He noted that the homogenous organic-rich facies predominates in the Sunbury Shale, but that the Bedford Shale showed a "bimodality between laminated organic-rich and organic-deficient microfacies" (Miller, 1978).

Negus-de Wys (1979) primarily studied the variability of Devonian black shales, but noted the increasingly shaly character of the Bedford-Berea southward across the Eastern Kentucky Gas Field. Maynard (1980) studied Devonian-Mississippian shales in the Appalachian Basin and concluded that a correspondence between sulfur isotopes and relative sedimentation rates was present. VanBeuren (1980) presented a depositional model for the Sunbury Shale and adjacent units comprising the "Sunbury cycle," based on outcrop and subsurface study primarily in eastern Kentucky and southwestern Virginia. He identified two genetic black-shale types, transgressive and regressive, and explained the relationship between basinal black shales and adjacent non-black, delta-slope shales and siltstones. Robl *et al*. (1980) examined the Bedford, Berea, Sunbury, and Ohio along the Knobs outcrop belt. They presented good localized stratigraphic reviews and isopachous maps for the units. They also characterized the quality and quantity of the Sunbury Shale as an oil-shale resource.

LITHOSTRATIGRAPHY

The Bedford Shale, Berea Sandstone, and Sunbury Shale crop out in two regions of the Appalachian Basin. Best exposures are along an outcrop belt extending from northern Ohio to central Kentucky. The southern portion of this belt, the Knobs outcrop belt, is within the study area (Fig. 1). "The Upper Devonian-Lower Carboniferous rocks of eastern Kentucky and southern Ohio form an arcuate pattern of outcrop around the Cincinnati Arch with a gentle easterly dip of approximately 5 m per kilometer (25 ft/mi) on the east flank of the arch. . . . The outcrop belt is 32-40 km (20-25 mi) wide . . ." (Chaplin, 1979). A second belt occurs in eastern Kentucky and western Virginia at the base of the Pine Mountain Thrust sheet.

In northern Ohio, where type localities of the Bedford Shale and Berea Sandstone exist, the contact of these units is easily identified. This is because the Bedford is predominantly red and gray shale, and the Berea is wholly sandstone and siltstone; moreover, the units are separated by an unconformity. South of Columbus, Ohio, however, there is no unconformity between the units, and both the Bedford and Berea are predominantly siltstone and gray shale. In most of southern Ohio, the Bedford contains more shale than the overlying Berea, but near the Ohio River, the Bedford and Berea thicken and contact of the units is difficult to discern (Pepper et al., 1954; Rothman, 1978).

Knobs Outcrop Belt

Bedford-Berea Sequence

Along the Ohio River in Scioto County, Ohio, siltstones of the Bedford intertongue with Berea siltstones, and they are mapped as a single unit (Pepper _et al_., 1954). Hyde (1911) encountered the same situation and merely included the Berea as a facies of the Bedford due to the difficulty in separating the units. In contrast Butts (1922) noted that nearly the entire interval at Garrison, Kentucky across the Ohio River, was siltstone. Mapping by Denny (1964) and Chaplin and Mason (1978) confirmed the presence of this same lithology in the Brushart and Garrison-Pond Run quadrangles in northeastern Kentucky. Thickness of the Bedford-Berea, or "Berea Sandstone" of the mappers is 90-160 feet (27.4-48.8 m) in this area (Chaplin and Mason, 1978).

To the west, near Vanceburg, Kentucky, Morse and Foerste (1912) noted an interval of shale and thin shaly siltstones which appeared to separate two tongues of siltstone and fine-grained sandstone. Butts (1922) also recognized this tripartite interval and classified the lower sandstone and shale as "Bedford Shale", and the upper sandstone as "Berea Sandstone." Morris and Pierce (1967) diagrammed the relationship between sections at Garrison and Vanceburg, noting an eastward thinning of the shaly siltstone interval. They mapped both sandstone tongues as Berea Sandstone and the shale and shaly siltstones as Bedford Shale. The upper and lower sandstone tongues thin to zero in the Stricklett quadrangle, southwestern Lewis County, Kentucky. However, blue-gray shale with very thin siltstone beds comprises the entire Bedford-Berea sequence near Petersville, Kentucky, and Morse and Foerste (1912) named this sequence the Petersville Shale after a 46-foot (14.0 m) shale section exposed near the town.

The Bedford Shale in Fleming, Rowan, and northern Bath counties is lithologically similar to the Petersville Shale of Morse and Foerste, although the amount of silty beds and laminae decrease as the unit is traced to the southwest; in this area it averages 10-15 feet (3.0-4.6 m) in thickness. Lithologic descriptions by the author (Appendix A) are consistent with those of Stockdale (1939) and local mappers (McDowell, 1976; Philley, 1978). The Bedford is sparsely fossiliferous, though rare articulate and inarticulate brachiopods are found. Small strands of brown organic debris locally are seen on bedding planes. The upper part of the Bedford Shale contains many nodules of pyrite and marcasite, rarely associated with sphalerite, and these are sometimes aligned along bedding planes. In the lower part, discontinuous siderite bands and nodules are locally common. In Rowan and Bath counties, thin beds of cone-in-cone limestone are found locally in the upper few feet (m). These were present in Core #8 and Core #9 (Appendix A). "Calcitic" concretions also have been noted in the Bedford by McDowell (1976) in the Colfax quadrangle, Bath and Fleming counties, Kentucky.

Upper and lower Bedford contacts appear everywhere conformable. Locally, minor intertonguing of gray-green Bedford Shale laminae with black Ohio Shale laminae is seen through a few inches (cm). In southeastern Bath and Montgomery counties, the Bedford quickly thins to two-four feet (0.6-1.2 m). Stockdale (1939) noted an unusual series of sections in Montgomery and Powell counties where Sunbury and Bedford lithologies appeared mixed, but their combined thicknesses were constant (approximately 18 feet) (5.5 m). He speculated that the dark gray-green shale was a local facies of the Sunbury Shale. He also noted a wavy contact of the Bedford Shale with the underlying Ohio Shale, with the Bedford Shale occupying troughs or pockets up to 1.5 feet (0.5 m) thick (Stockdale, 1939). The Bedford Shale was noted by mappers to be discontinuous in Montgomery and Powell counties, occurring in lenses less than three feet (0.9 m) thick. In these areas, the Bedford Shale and Sunbury Shale are mapped as part of the New Albany Shale, Devonian and Mississippian in age. Mappers have not identified the Bedford southwest of Clay City, Powell County, but Morse and Foerste (1909a) and Stockdale (1939) described sections bearing the unit near Irvine, Estill County. Cores examined by the author in Powell, Estill and Madison counties all contained green Bedford Shale, though less than one foot (0.3 m) thick and often much siltier and fossiliferous than that in Bath County. In five of the cores, the interval was largely calcareous siltstone with minor shale. The thin green Bedford equivalent usually occurred four to six feet (12-1.8 m) below the top of the black (Sunbury) shale. A green, bioturbated fossiliferous siltstone containing tests of gastropods and both articulate and inarticulate brachiopods was noted by this author in the upper few feet (m) of black shale in cores from Madison, Estill, and Powell counties (Appendix A). Interestingly, Morse and Foerste (1909b) identified brachiopod and mollusc tests, which they named the "Bedford fauna" from greenish-gray Bedford shale in Estill County. The thin siltstone noted by this author and the shale identified by Morse and Foerste (1909b) are probably equivalent to parts of the Bedford-Berea sequence farther north. If these are so, then the overlying black shale is a Sunbury equivalent whereas the underlying black shale is largely an Ohio Shale equivalent.

This author has also noted the presence of previously unreported gray shale laminae in the uppermost few feet (m) of New Albany Shale near Bryantsville, Garrard County. Campbell (1946) reported a six-inch (0.2 m) gray shale 2.5 feet (0.8 m) below the New Albany Shale - New Providence Formation (Borden Formation) contact in Lincoln County.

Butts (1922) found a five-foot (1.5 m) gray clay shale in the upper part of the New Albany Shale in Marion County, Kentucky, and suggested that it might be related to the Bedford Shale farther northeast. Some or all of these maybe genetically related to the Bedford Shale. These thin gray shales in the upper parts of the sequence are especially interesting in view of the fact that Stockdale (1939) noted that the Bedford is only a few inches (cm) thick over a considerable area. Overall, however, the upper part of the New Albany Shale, including the Bedford equivalent, is totally black in these areas.

Sunbury Shale

The Sunbury Shale was named by Hicks (1878) for exposures of the black shale on Rattlesnake Creek near Sunbury in Delaware County, Ohio. Along the Knobs outcrop belt, the Sunbury Shale is a thin, persistent, lithologically homogenous unit, a black shale similar to the Cleveland Member of the Ohio Shale. In northeastern Ohio and Pennsylvania, however, the Sunbury grades into the Orangeville Shale, becoming siltier and dark gray (Pepper *et al*., 1954). It is slightly thicker in much of northern and central Ohio than in southern Ohio and Kentucky, reaching maximum thicknesses of 60 feet (18.3 m) (Pepper *et al*., 1954).

The Sunbury Shale in Kentucky is brownish-black to black, finely-laminated, and carbonaceous. It yields a petroliferous odor when freshly broken, contains pyrite in many forms, and its fissility is excellent. Macroscopic fossils are not abundant in the unit as a whole, but occasionally fragments of *Lingula melie* and *Orbiculoidea herzeri*, and "fish parts" are found (Chaplin and Mason, 1979). These fossils are, however, abundant in a lag zone or "bone bed" which commonly is present in the basal few inches. Microscopic examination of the Sunbury, especially the lag zone, yields an abundant conodont fauna. Recorded species include: Apatognathus varians, Bispathodus aculeatus aculeatus, B. aculeatus plumulus, B. spp., Elictognathus spp., Gnathodus delicatus, G. cf., G. commutatus, C. spp., Hindeodella spp., Ligonodina spp., Lonchodina spp., Neoprioniodus spp., Ozarkodina spp., Polygnathus communis communis, P. delicatula, P. inornatus, P. spp., Pseudopolygnathus triangula triangula, P. dentineatus, P. spp., and Spathognathodus spp. (Chaplin and Mason, 1979). Rothman (1978) and Pepper et al. (1954) reported that sandy, pyritic laminae occur at the contact with the Berea Sandstone in southern Ohio. Similar laminae were observed in one Kentucky core (Appendix A, Core #1), though they have not been previously noted in Kentucky literature.

The thickness of the Sunbury Shale is fairly uniform throughout Lewis, Fleming, and Rowan counties, and thicknesses of 10-20 feet (3.0-6.1 m) are common, though Robl et al. (1980) reported local thicknesses of 30-50 feet (9.1-10.7 m) in northern Lewis County. Variations in thickness are probably more influenced by sediment filling of topographic lows and draping over topographic highs than distance from source areas.

Bedford-Sunbury stratigraphic relations are more difficult to define in Montgomery and Bath counties, as previously noted by Stockdale (1939). He indicated that the Sunbury is locally lighter in color in Montgomery County. Subtle color differences from the typical black (N1) Sunbury color were noticed on cores south of Rowan County examined by the author. Brownish-black (5Y 2/1) and dark gray (N3) colors were common, and light gray (N7) calcareous silt laminae were also present. These lighter-colored intervals typically corresponded to zones which broke easily upon washing, suggesting they had a higher clay content. Phosphatic nodules and macrofossil fragments are more common in areas where the Sunbury is thinner.

Southwest of Rowan County, the Sunbury Shale gradually thins until apparent local pinchout and color change of green Bedford shale and siltstone leaves black Bedford shale and possibly Sunbury Shale onlapping lithologically indistinguishable Ohio Shale in parts of Powell, Estill, Montgomery, and Madison counties. Here the entire black-shale sequence is designated New Albany Shale (Swager, 1978; Fig. 6).

Pine Mountain Outcrop Belt

The Bedford Shale, Berea Sandstone, and Sunbury Shale occur in a northeast-southwest trending outcrop belt at the edge of the Pine Mountain Thrust sheet in southeastern Kentucky. The units are folded or faulted and are not usually well exposed except for ridge and cliff-forming Berea sandstone. Because of the difficulty in defining a Bedford-Berea contact, these units were mapped together throughout much of the area, though some workers make a distinction on the basis of lithology (Alvord and Miller, 1972; Alvord, 1971).

Bedford and Berea units are exposed as far northeast as the Elkhorn City quadrangle, Pike County, where the interval is wholly a fine-grained sandstone, 45-55 feet (13.7-16.8 m) thick. Local small-scale intertonguing of the Berea and Ohio Shale has been reported (Alvord and Miller, 1972). Thickness and shale content of the interval increases in a southwestward direction. In the Jenkins East and Jenkins West quadrangles, Pike and Letcher counties, Bedford and Berea sediments are 140 feet (42.7 m) thick. Siltstone and sandstone occur as tongues and lenses within the shale (Rice, 1973). The shale is light to medium-gray, clayey to silty, and the fine-grained sandstone contains much quartzose silt in beds three- to eight-inches (7.6-20.3 cm) thick (Rice, 1973). Recognizable gray shales and siltstones thin in a southwestward direction and become darker in color so that the Bedford-Berea and Sunbury are mapped as members of the Chattanooga Shale (Froelich, 1973; Maughan, 1976), or as units within the Grainger Formation (Rice and Wilcott, 1973). Southwest of the Louellen quadrangle, Letcher, Perry, and Harlan counties, the Bedford, Berea, and Sunbury are not recognized by mappers, though gamma-ray logs indicate their presence in the extended Chattanooga Shale.

The Sunbury Shale is consistently 40-55 feet (12.2-16.8 m) thick, and it has the same mapped distribution as the Bedford-Berea. The shale is medium dark gray to grayish-black, carbonaceous, finely- and evenly-laminated, and weathers in a fissile manner. The unit is more argillaceous and siltier than in the Knobs outcrop belt. It is recognized as a discreet unit in Pike and northern Letcher counties, but farther to the southwest, it is included as a subunit within the Chattanooga Shale or Grainger Formation (Englund, 1968; Csejtey, 1970). Radioactivity studies outlined later show that the mapped Sunbury Shale in this area includes a portion of the Borden or Grainger formations (Pennva Formation of VanBeuren, 1980).

Age of the Units

The Devonian-Mississippian boundary within the black-shale sequence in the Appalachian Basin has long been a topic of discussion. Most later workers have designated the Berea and Sunbury as Early Mississippian (Kinderhookian) and the Ohio Shale as Late Devonian, but systemic placement of the Bedford Shale, Maury Formation, and upper Chattanooga Shale in eastern Kentucky has been a problem. Significant studies are briefly reviewed.

Butts (1922) did not assign an age to the Bedford Shale, suggesting that this unit may be included in the Devonian in northeastern Kentucky, making the Berea Sandstone the basal Mississippian unit. Cooper et al. (1942) presented correlations of Upper Devonian units in the central Appalachian Basin and suggested that the Bedford Shale was Devonian or Mississippian in age, but regarded the Berea and Sunbury as Mississippian. Pepper et al. (1954) regarded the Bedford Shale, where underlain by black shale, to be Mississippian on the basis of faunal similarities with the Kinderhookian Glen Park Limestone of the mid-continent. On the basis of conodont and palynologic data, de Witt (1970) designated the Sunbury Shale, Berea Sandstone, and most of the Bedford Shale as Early Mississippian, but noted that the basal few feet (m) may be Devonian.

In central and southern Kentucky, where Devonian (Ohio) and Mississippian (Sunbury) black shales are not separated by green Bedford Shale, the entire black-shale sequence has been called the New Albany Shale. Conodont studies undertaken during the mapping of the Berea quadrangle, Madison County, indicated the presence of Siphonodella sp., a definite Mississippian conodont (Chaplin, 1979) in the upper few inches (cm) of the New Albany Shale (Weir, 1967). A subsequent study by Ettensohn (1979b) also indicated the presence of Siphonodella. These finds indicate that at least the upper few inches (cm) of the New Albany Shale are Mississippian in age (J. W. Huddle, written comm., 1966; Weir, 1967; Ettensohn, 1979b). Accordingly, mappers of quadrangles in Rockcastle, Garrard, and Lincoln counties have assigned a Devonian and a Devonian-Mississippian age to the New Albany Shale. Upper Devonian and Lower

Mississippian black shales extend across the Cincinnati Arch to the Illinois and Appalachian basins in the Cumberland saddle (Potter et al., 1981).

Swager (1978) in his discussion of black-shale nomenclature, noted that the New Albany-Chattanooga boundary could be approximated with an east-west line through Adair, Lincoln, Casey, and Pulaski counties. Traditionally along the outcrop belt in this area, exposures of Devonian and Mississippian black shale have been designated the New Albany Shale, whereas exposures in south-central Kentucky where the black shale was thought to be wholly Devonian in age have been designated the Chattanooga Shale.

Conodont studies by Hass (1956) suggested a Late Devonian age for black (Chattanooga) Shale in southern Kentucky, as he suggested pinch-out of Mississippian black shales to the south. Radioactivity studies by this author, outlined later, show that shales equivalent to the Sunbury and Bedford-Berea sequence are locally present in the Chattanooga Shale in southern Kentucky. This means that upper parts of the Chattanooga may also be Mississippian in age, but this remains to be confirmed. Hass also classified the Maury Formation, a thin widespread green shale with abundant phosphatic nodules overlying the Chattanooga Shale, as Mississippian (Kinderhookian and possibly Osagean) in southern Kentucky. The Borden Formation and the Fort Payne Formation, which also overlie the black shale in central and southern Kentucky with apparent conformity, are wholly Mississippian units. Hass (1956) concluded that a change in conodont assemblages denoted a hiatus in deposition between the Borden or Fort Payne and the underlying black (Chattanooga) shale, although no apparent evidence of an unconformity existed.

In southeastern Kentucky, the age of the Chattanooga Shale has been controversial. Hass (1956) concluded that the Chattanooga in Tennessee and surrounding states was Late Devonian and possibly Middle Devonian, based on conodont examination. He placed gray and black shale of the Olinger and Big Stone Gap members within the Maury Formation. (Most later workers have placed the equivalents of these members within the Chattanooga Shale). Englund (1968) and Csejtey (1970), following the lead of Hass, classified the Chattanooga along Pine Mountain as Devonian only. Roen, Miller, and Huddle (1964), however, recognized the Big Stone Gap Member of the Chattanooga Shale to be both Devonian and Mississippian in age at its type locality. Froelich (1973), citing personal communications with J. W. Huddle and J. H. Schopf regarding included conodonts and spores respectively and their age significance, suggested that the upper Chattanooga Shale in the Louellen quadrangle, Harlan, Letcher, and Perry counties, grades eastward into Sunbury, Bedford, and Berea strata of Early Mississippian age. De Witt and McGrew (1979) also recognized that the uppermost parts of the Chattanooga Shale in eastern Kentucky are Mississippian in age, though at best only a few feet (m).

ENVIRONMENTAL IMPLICATIONS

Depositional Settings

The origin of the Devonian-Mississippian black shale has been a subject of controversy for many years and must be examined again in this study because black shales are present in parts of the Bedford-Berea sequence, in the Sunbury, and in basal parts of the Borden Formation. Most workers have proposed either shallow- or deep-water depositional models. In contrast Hard (1931) and Provo (1977) indicated that depth may not be an essential factor, because evidence indicates that black shales may be deposited in a variety of depths and in basins with different configurations. Following the lead of Hard and Provo, Ettensohn and Barron (1981) presented a model that indicated black-shale deposition in a sea that deepened and changed configuration through time. VanBeuren (1980) proposed a model for Mississippian black shale that emphasized genetic differences between black shale deposited during transgressive and regressive regimes.

One characteristic of black shales that is important in understanding their depositional environment is the vast amount of organic matter contained within the shales. Black shales contain up to 33% organic material by volume, and by weight organic matter may comprise nearly one-sixth of the rock. The presence of abundant terrestrial and marine organic matter in the shales is generally regarded by most investigators to indicate the presence of anoxic, reducing conditions at the place of deposition. They have indicated that organic matter is typically not preserved in this abundance in oxidizing conditions. Rhoads and Morse (1971), Byers (1977), Heckel (1977), and Ettensohn and Barron (1971) indicated that such anoxic conditions are best developed in a stratified water column such as the one shown in Figure 7. Based on studies of stagnant water bodies (Caspers, 1957; Hülsemann and Emery, 1961), three layers are found to develop in the stratified water column. The upper layer is characterized by warm, oxygenated waters of light density and lower salinity, possibly even brackish. The bottom layer is cooler, denser, more saline, and has little or no oxygen most of the time. An intermediate zone, termed the pycnocline (Byers, 1977) is a region of rapid downward decreases in oxygen content and temperature, and rapid increases in density and salinity. Rhoads and Morse (1971) and Byers (1977) assigned depths to each of the three zones based on the depth of the zones in the modern Black Sea. He noted that the oxygenated layer extends from the surface to a depth of 164 feet (50 m). The pycnocline occupies a zone from 164-492 feet (50-150 m) and the lowest poorly-oxygenated zone occurs in waters deeper than 492 feet (150 m) (Byers, 1977; Fig. 7).

Rhoads and Morse (1971) and Byers (1977) classified each of these three zones based on the oxygen concentration and the type of biofacies that developed. The three facies resulting from a combination of water-column stratification and faunal distribution are:

1. Aerobic zone - shallow water above the pycnocline; greatest faunal diversity; calcareous epifauna and abundant infauna are present; sediment is strongly bioturbated.
2. Dysaerobic zone - within the pycnocline; few if any calcareous epifauna; those present are typically thin-shelled; sediments bioturbation by resistant infauna and highly-specialized epifauna.
3. Anaerobic zone - below the pycnocline; lack of nearly all

benthos, except bacteria, metazoans, and protozoans specially adapted for low-oxygen conditions. Sediment-rich turbidity currents may bring in oxygen and short-lived benthic communities such that infaunal burrowing may be present for a short time within this facies (Ettensohn and Barron, 1981).

From examination of Upper Devonian strata in New York, Byers (1977) discovered that the lower two facies can be distinguished on the basis of color and composition as well as on the amount of bioutrbation. Sediments with a gray-green color typically reflect deposition in a dysaerobic environment (within the pycnocline) and contain little organic matter. Black sediments generally reflect deposition below the pycnocline, and contain much greater amounts of organic matter.

A recent study be Ettensohn and Barron (1981) demonstrated that ideas regarding deposition of black and green shales presented by Byers (1977) are also applicable to shales in the west-central Appalachian Basin. They noted that the development of a stratified water column was related to increasing depth and rainshadow conditions over the sea west of the Acadian Mountains. They demonstrated that deposition of green and black shales in this area is cyclic and can be related to changes in sea level as well as tectonism and climate in the Acadian Mountains to the east. The black shales appear to represent anaerobic conditions developed in deepening transgressive seas, whereas green shales and coarser clastics appear to represent dysaerobic and aerobic condition in shallowing regressive seas. VanBeuren (1980) examined the Sunbury and stratigraphically higher black shales and also noted a similar cyclic deposition.

In light of these facts, it is important to discuss characteristics and depositional settings of the uppermost parts of the black-shale sequence examined in this investigation; this includes the Cleveland (uppermost Ohio) Shale, Bedford-Berea sequence, Sunbury Shale, and lowermost portions of the Borden Formation.

Cleveland Shale

The Cleveland Shale is a black, fissile, bituminous shale, with abundant pyrite and occasional phosphatic nodules. Megafossils are limited to fish fragments and phosphatic tests of brachiopods, though microscopic examination yields abundant conodonts. Throughout most of eastern Kentucky, the contact of the Cleveland with overlying Bedford-Berea is sharp and conformable. In parts of southeastern Kentucky, however, intertonguing of the Cleveland and the Bedford-Berea occur.

The basinal Cleveland Shale was deposited below the pycnocline in the anaerobic zone of Byers' (1977) environmental model (Fig. 7). This unit can be viewed as one end member of a transgressive-regressive depositional cycle. The Cleveland represents deep-water deposition during a time of maximum transgression of Late Devonian seas within the west-central Appalachian Basin. The regressive part of the cycle is represented by the overlying Bedford-Berea sequence which reflects deltaic progradation into parts of the basin.

Bedford-Berea Sequence

The Bedford Berea in eastern Kentucky is traditionally considered to be composed wholly of light-colored sandstones, siltstones, and shales. Moreover, the Bedford-Berea was thought to pinch out in east-central Kentucky. However, by comparing driller's logs, cores, and outcrops examined with a scintillometer with gamma-ray logs, it was

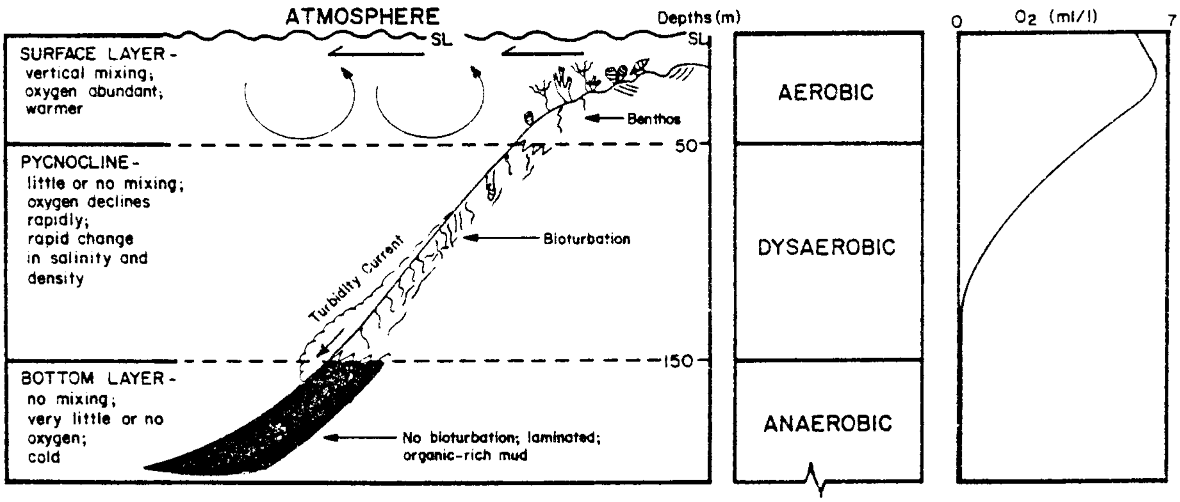


Figure 7. Schematic diagram showing characteristics of a stratified water column and the sediments accumulating within each water layer. Depths and oxygen content are general estimates based on the Black Sea (adapted from Rhoads and Morse, 1971; and Byers, 1977; from Ettensohn and Barron, 1981).

discovered that the Bedford continues into much of south-central Kentucky where it is brownish-black in color. These black Bedford equivalents have essentially gone unnoticed until now and were commonly included as upper parts of the Chattanooga or New Albany shales by drillers and mappers in these area. The "black" Bedford shale can be easily distinguished on gamma-ray logs as a zone of consistently low radioactivity between the highly-radioactive deflections of the Sunbury and Cleveland (Ohio) shales (Fig. 8). Black shales within the Bedford are consistently present along the Knobs outcrop belt south of the Means quadrangle, Montgomery County, Kentucky. Areal distribution of "black Bedford" sediments is shown in Figure 9.

Sediments within the Bedford-Berea, therefore, probably represent deposition in all three zones of Byers' (1977) model. Black Bedford sediments reflect deposition below the pycnocline, but have moderately low radioactivity because of the high amount of fine-grained clastic matter within the black shale relative to the adjacent organic-rich Sunbury and Cleveland shales. Black Bedford sediments occur far south and west of postulated clastic sources in Ohio, West Virginia, and Virginia and were deposited slowly. These black shales in southeastern and south-central Kentucky represent deposition in anaerobic conditions and are probably distal basinal equivalents of lighter-colored (gray, green, and red) Bedford and Berea sediments deposited above the pycnocline (anaerobic zone) in northeastern and eastern Kentucky. Green and gray pyritic Bedford shales along central parts of the outcrop belt, usually thoroughly bioturbated, but lacking shelled fauna, may represent deposition within the pycnocline (dysaerobic zone). Red Bedford shales and Berea sandstones are probably shallow-water deposits

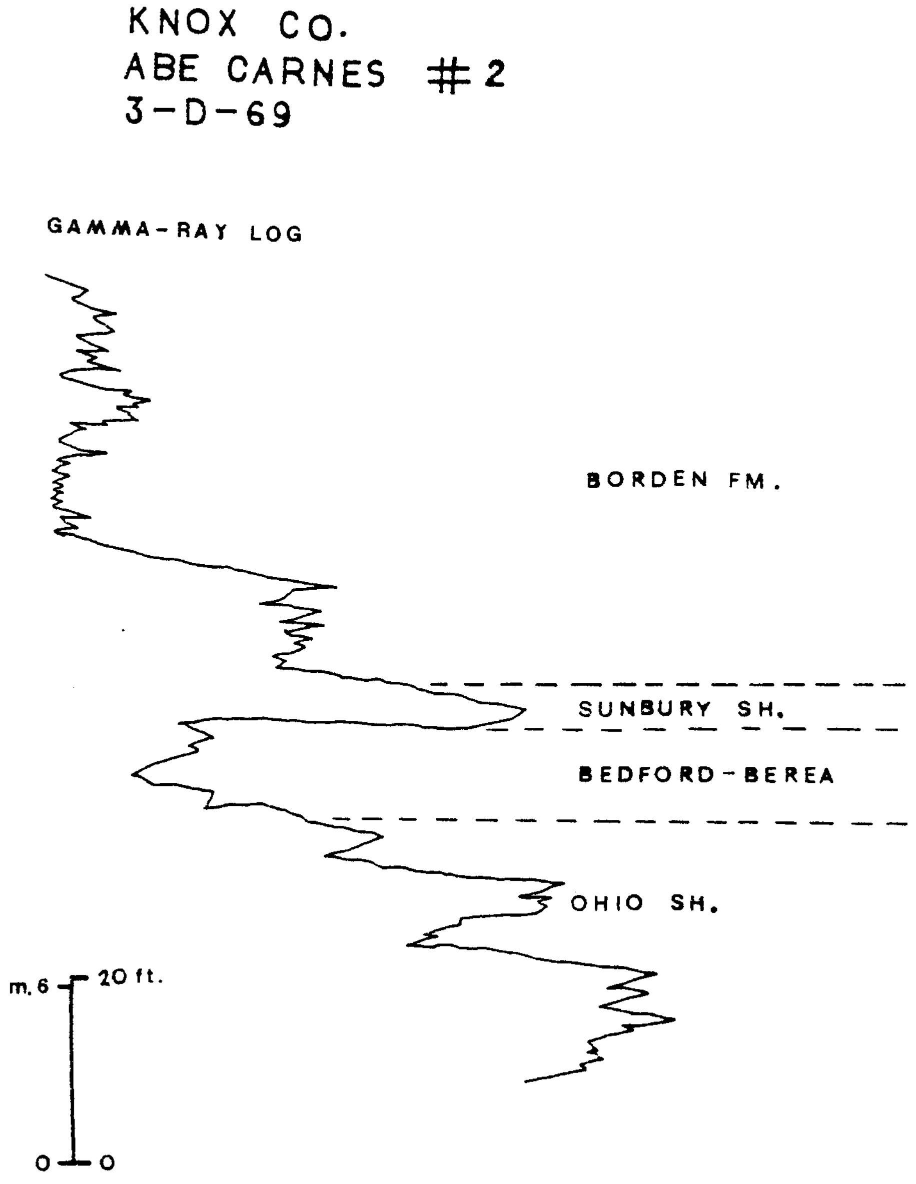


Figure 8. Gamma-ray signature in southeastern Kentucky showing negative deviation of "black" Bedford Shale between Sunbury and Cleveland (Ohio) shales.

above the pycnocline (aerobic zone) in the proximal portions of a deltaic system.

By considering the Bedford-Berea to be a deltaic sequence prograding into a deeper black-shale (Cleveland Shale) basin, estimations of the water depth into which Bedford-Berea sediments prograded may be possible. Klein (1974) presented a model for estimating the water depth of basins into which delta and barrier-island sequences prograded. The model basically states that the minimum depth of water into which these sequences migrate is approximately equivalent to the maximum thickness of water-laid detrital sediment within the sequence. This model does not, however, take into consideration the effects of compaction and concurrent basin subsidence. Application of this model to the Bedford-Berea deltas is difficult, because of uncertainties regarding source areas and thicknesses. Nowhere in eastern Kentucky are Bedford and Berea sediments greater than 200 (61.0 m) feet thick. In West Virginia and Virginia, thicknesses of the units are no greater than 100 feet (30.5 m). In Ohio, maximum thickness for the Bedford-Berea is approximately 250 feet (76.2 m), but this figure does not account for the thickness of Bedford eroded prior to and during the higher-energy Berea deposition. At separate localities in northern Ohio, the Bedford is 150 feet (45.7 m) thick and the Berea is 235 feet (71.6 m) thick (Pepper et al., 1954). Together these depths suggest that the underlying Cleveland black shale could not have been deposited at depths any less than 385 feet (117.3 m) and that the black Bedford should have been deposited at somewhat shallower depths. These depths, however, do not approach the 492 feet (150 m) suggested by Byers (1977) as a minimal depth for black shale deposition in the basal layer (anaerobic) of a stratified water column, as exhibited in the Black Sea. Obviously, Klein's model does not give a realistic depth in this instance, though the reasons for this are uncertain. Perhaps the effects of compaction on black shales are more significant in clay-rich sections like these because the muds forming shales may undergo compaction by as much as 80%. Another explanation may be that subsidence was greater during the deposition of the Sunbury than during the earlier deposition of the Cleveland. The undetected presence of tectonic activity, a sill, or high organic productivity within the basin, each of which may have created a stratified water column with unusually high boundaries, may have caused black-shale formation in the Bedford and Cleveland at higher-than-usual levels. It also may be that depths in the modern Black Sea provide an unsuitable model for much larger cratonic seas like those in which the Devonian-Mississippian shales were deposited. Perhaps the most convincing argument may be the uncertainty regarding the thickness of the Bedford eroded prior to and during Berea deposition. Combined thickness of Bedford and Berea sediments may have been greater than 492.1 feet (150 m) if eroded Bedford sediments (thickness of lacuna) were included. Overall, the Bedford-Berea sequence represents the regressive episode in the Cleveland-Bedford-Berea cycle, but this regression apparently did not lower sea level sufficiently to allow oxidizing conditions to develop uniformly throughout the entire study area. Dysaerobic and aerobic conditions were established in areas of more rapid sedimentation to the north and east, where coarse Bedford-Berea sediments occur. In distal areas far south and west of these source areas, however, fine-grained clastic equivalents of the coarser Bedford-Berea sequence accumulated in deeper anaerobic parts of the water column. Hence the Bedford-Berea equivalents in southeastern and south-central Kentucky are black and greatly reduced in thickness. Following the regressive Bedford-Berea event, deposition of the transgressive Sunbury Shale took place, beginning the next cycle.

Sunbury Shale

The Sunbury appears to be uniform in color and composition throughout the study area (Fig. 1). It is black, bituminous, and fissile and contains phosphatic nodules and abundant pyrite. Megafossils are locally common and include tests of phosphatic brachiopods and fish fragments. The Sunbury is easily distinguished on gamma-ray logs because of its extremely high radioactivity, which is discussed in a later section. This unit is thickest in easternmost portions of the study area, where subsidence and resulting depths were apparently greatest and were clastic source areas were nearby (e.g. West Virginia, southwestern Virginia). Source areas for Sunbury clastics appear to be similar to those postulated for the Bedford-Berea. The Sunbury thins as its laps onto the Cincinnati Arch, and to the west, near the arch, the unit is difficult to recognize on gamma-ray logs, but scintillometer profiles definitely prove its existence (Appendix D, Fig. 21). The uniformly black coloration of the Sunbury and absence of benthic fauna indicates that is was deposited below the pycnocline (anaerobic zone) throughout the study area.

Ettensohn and Barron (1981) employed Klein's (1974) model in estimating the depth of the "Black Shale Sea" during Sunbury time. They assumed that the Sunbury was deposited as a basinal mud and that the overlying Borden Formation is composed of deltaic clastics which prograded into the basin. The maximum thickness of the Borden in east-central Kentucky is approximately 700 feet (213.4 m), which approximates a minimum depth of 700 feet (213.4) for the Sunbury Shale. The minimum basin depth easily satisfies the requirement of 492 feet (150 m) (Byers, 1977) for separation of dysaerobic and anaerobic waters and the consequent formation of black shales below the pycnocline. A similar depth was also obtained by Potter et al. (1980). Again, it should be noted that these are minimum depths, because the effects of compaction and subsidence cannot be accounted for (Klein, 1974).

Similarly, VanBeuren (1980) suggested that the basinal Sunbury Shale was deposited following Bedford-Berea deposition during a rapid transgression, which was partly due to the rising of sea level that accompanied subsidence in the Appalachian Basin.

Borden Formation

The Borden Formation, which conformably overlies the Sunbury Shale, represents the regressive phase of the Sunbury-Borden cycle and was deposited during a major deltaic progradation into the west-central portion of the Appalachian Basin. This regression at least partly resulted from deposition of clastic sediments from northern and eastern source areas.

Borden sediments reflect deposition in aerobic, dysaerobic, and anaerobic zones of Byers' (1977) environmental model (Fig. 7). The aerobic facies is represented by fossiliferous green, gray, and red shales and limestones of the Cowbell and Nada members of the Borden. Dysaerobic facies are represented by the Nancy Member, which is predominantly dark gray pyritic and sideritic shale, and the Henley Bed (greenish-gray shale), both of which lack abundant benthic fauna. Black shale, characteristic of the anaerobic facies, is present in lowermost portions of the Borden in the deeper parts of the basin that lie within the study area (Fig. 10). These black shales are easily distinguished as a moderately radioactive shoulder on gamma-ray logs between the low-radioactive Borden gray shales and the highly-radioactive Sunbury Shale (Figs. 3, 8). Black Borden shales are probably not as highly radioactive due to a higher ratio of clastic matter to organic matter.

VanBeuren (1980) was the first to report these black "Borden" shales and separated them into a new formation which he called the Pennva Formation. He suggested however, that formal nomenclature changes should consider the Pennva interval to be a member of the Borden (Price) Formation. He suggested that these moderately radioactive black shales, deposited below the pycnocline, are basinal equivalents of gray shales and siltstones deposited above the pycnocline in southwestern Virginia. He further suggested that these shales and siltstones of the Price Formation represent prodelta and delta-front sedimentation. VanBeuren (1980) reported that these black shales thin and pinch out to the west along a north-south line from Greenup County to Knox County. Examination of logs and cores, as well as construction of cross-sections by this author (Appendix D, Figs. 21-25) also indicate that a dramatic thinning of Borden (Pennva) black shales occurs in a northwestward direction. Although some real thinning does occur in this direction, some of the thinning of the black shale is apparently related to facies changes and lateral gradation of the black shales into gray Borden shales in a westward direction (Fig. 11). This suggests that the intersection of the base of the pycnocline by the basin (limit of black shale deposition; Fig. 7) also had a western limit, and that the position of

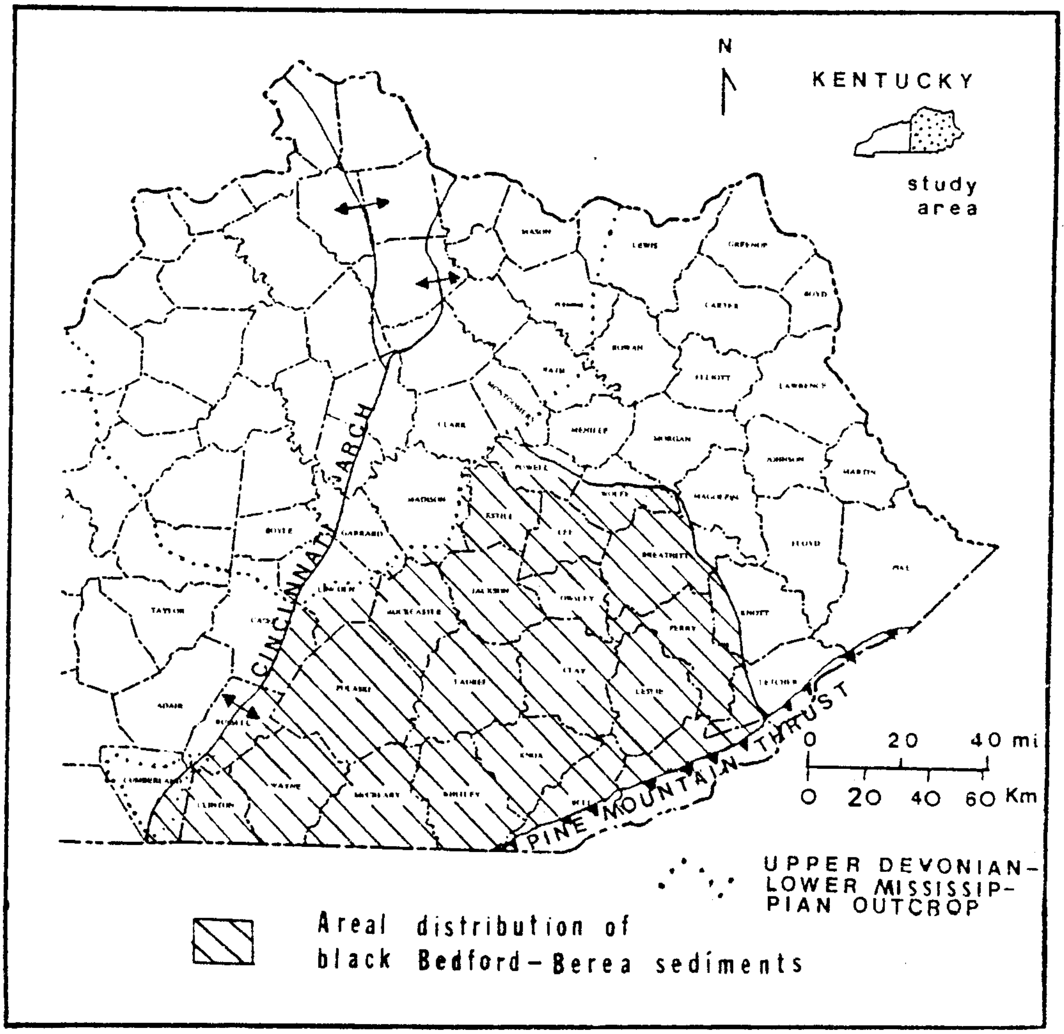


Figure 9. Areal distribution of black Bedford-Berea sediments.

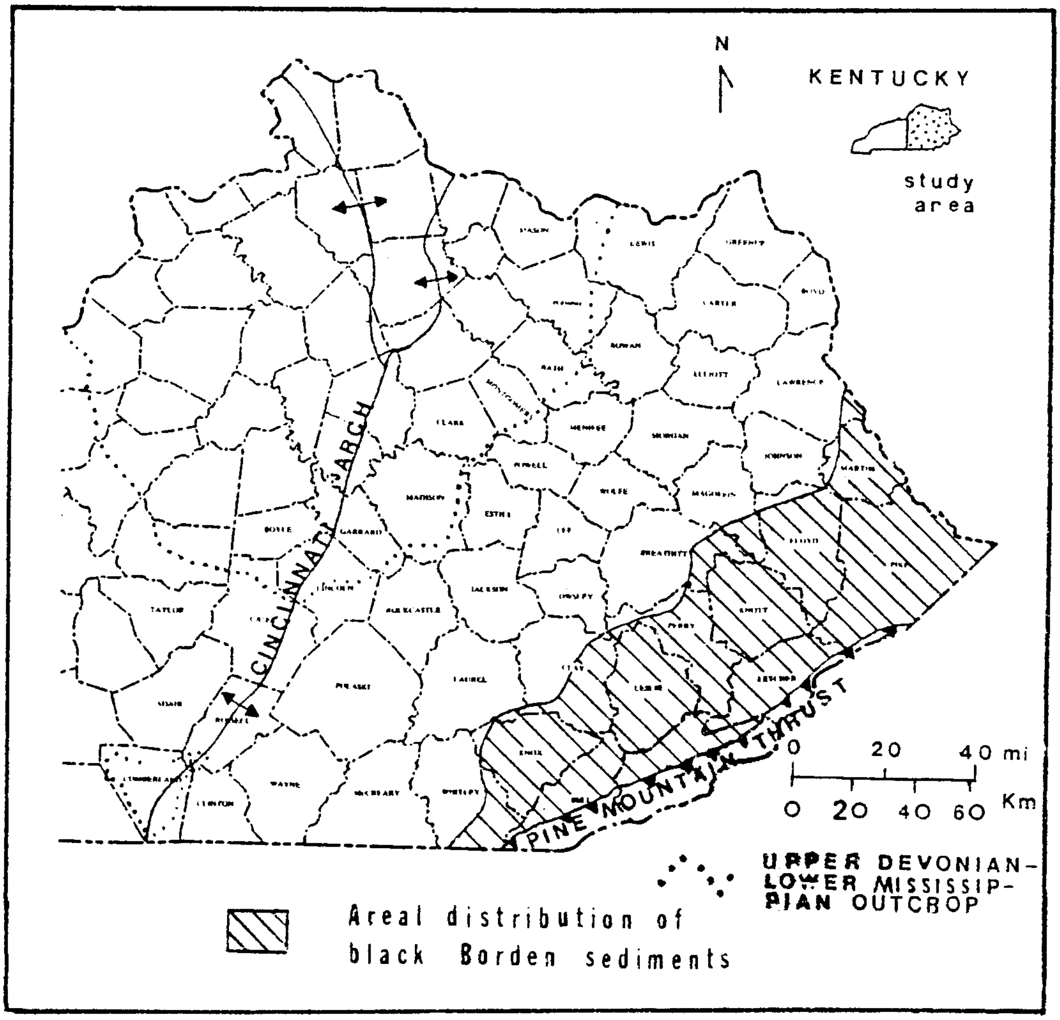


Figure 10. Areal distribution of black Borden sediments.

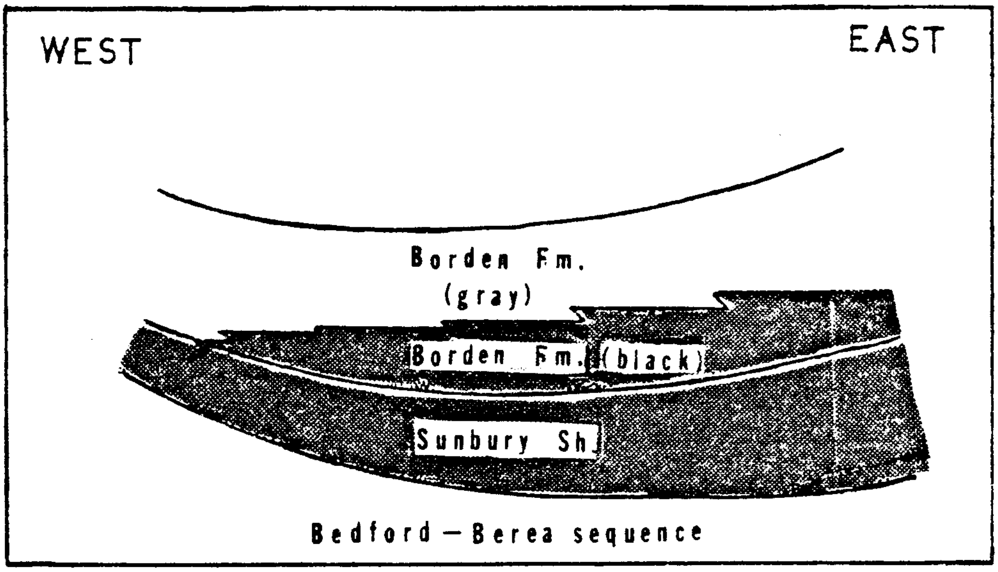


Figure 11. Stratigraphic relationship of Sunbury and lower Borden sediments across southeastern Kentucky.

the pycnocline controlled the preservation of organic matter. Hence, black shales in the Pennva or basal Borden formations were deposited below the pycnocline and are apparently equivalent to gray Borden and Price shales and siltstones deposited above the pycnocline to the east and west respectively.

Some environmental interpretations can be made from observations of the lithologic characteristics of the Bedford, Berea, and Sunbury observed in outcrops and core samples. Among these characteristics are lag zones, bioturbation, presence of phosphate, and iron mineralization. These characteristics are discussed below.

Lag Zones

"Lag zones" also referred to as "bone beds" or "zones of invertebrate fossils" were observed in both cores and outcrops of the Sunbury Shale. Such zones are typically no thicker than fractions of an inch (cm) and are commonly only as thin as a bedding plane. The zones characteristically contain an abundance of conodonts and tests of phosphatic brachiopods. The zones also usually contain fish bone fragments and sand and silt grains in greater concentrations than in other parts of the black-shale sequence. Some of the lag zones appear to be very minor, composed entirely of phosphatic brachiopod tests. These minor zones are especially common in the thin Sunbury Shale near the Cincinnati Arch.

A well-developed lag zone in the basal few inches (cm) of the Sunbury Shale was noted in nearly all the cores examined. Such a zone in the basal few inches of the Sunbury Shale also has been noted by many other workers (Pepper et al., 1954; Chaplin and Mason, 1979; Ettensohn, 1979a; Conkin et al., 1980). Conkin et al. (1980) have designated a silty lag zone at the base of the Sunbury Shale to be Bone Bed #19 and have reported tracing this zone around the Cincinnati Arch. Along the Knobs outcrop belt, they suggested that this zone was a remnant of the Berea Sandstone, although sediments comprising the zone may have accumulated during slow sedimentation while major Berea deposition continued farther to the north. This zone appears to correspond to thin fossiliferous siltstone and silty shale that occurs in upper parts of the Bedford Shale in east-central Kentucky.

Most workers suggest that these lag zones represent times of extremely slow clastic deposition because of the nature of the fossil assemblage and the lack of clay. The fossil assemblage reflects simple suspension sedimentation of the remains of planktic, epiplanktic and nektic fauna which lived in upper parts of the water column; rarely are benthic forms found. Even phosphatic brachiopods like Lingula were apparently epiplanktic (Barron and Ettensohn, 1981). The only detrital particles, the silt and sand grains, were probably transported in suspension or by floating plant matter before settling. Conkin and Conkin (1975) have traced many such zones in the Illinois and Appalachian basins. They suggested such zones represent shallow-water paracontinities or diastems which were followed by rapid transgression. Ettensohn and Barron (1981) agree with their interpretations regarding the possibilities of diastems but also suggested the likelihood of a deep-water origin.

Trace Fossils

The amount of faunal activity can help interpret depositional environments, as previously demonstrated by Byers (1977). Commonly, the major form of faunal activity in the dysaerobic and anaerobic shales of this sequence is bioturbation. Evidence of bioturbation was rarely observed wholly within the black-shale facies, though this is possibly due to the difficulty of trace recognition. Where green shale overlies black shale, a few vertical and sub-vertical burrows were commonly detected because of the contrast between the green shale filling the burrows and the surrounding black shale matrix. Bioturbation at such places was occasionally observed in the upper six inches of black shale at both the Bedford-Ohio Shale contact and the Borden Formation (Henley Bed) - Sunbury Shale contact. However, these are burrows that usually start in the overlying green shale and end in the black shale.

As expected from Byers' (1977) biofacies model, (Fig. 7) evidence of bioturbation appeared most abundantly in the green shales and silt-stones of the Bedford. Laminations in this unit typically are poorly developed or absent, suggesting destruction by bioturbation occurred, though particular traces are difficult to classify. Soft-bodied worms, not otherwise recorded in the fossil record, may be responsible for much of the bioturbation, though Morse and Foerste (1909b) noted pelecypods, gastropods, and brachiopods from the Bedford. Basal parts of the Borden (Henley Bed) shales are also thoroughly bioturbated.

The fine, widespread parallel laminations typical of these black shales probably reflect the lack of infauna and epifauna living in the anoxic environment of black mud accumulation. Where burrows filled with green shale appear in the uppermost few inches (cm) of black shale, burrowing animals were living in the dysaerobic environment that ac-companied deposition of the overlying green shales. They may have bur-rowed into the organic-rich black muds seeking food or shelter, tempor-arily tolerating the anaerobic environment. Howard (1975) reported that animals living in these conditions still commonly depend on surface waters for food, respiration, and nutrients in bioturbated sediments like the Bedford and Henley Bed. Howard (1975) noted that reworking of sediments such as these is commonly so complete that the sediments record multiple burrowing overprints where sedimentation rates are slow.

Phosphate

The occurrence of phosphate reinforces ideas regarding slow deposition of green and black shales in deeper water. In upper portions of the black-shale sequence, especially the Cleveland Shale Member of the Ohio Shale, the Sunbury Shale, and upper parts of the New Albany and Chattanooga shales in central and southern Kentucky, phosphate in the form of ellipsoidal or spheroidal phosphatic concretions occurs. These nodules, which are usually flattened parallel to bedding, were observed in exposures and cores at the western edge of the study area. Nodules also occur abundantly in outcrops of the Early Mississippian Maury Formation in southern Kentucky and Tennessee and at the base of the Borden Formation in central and southern Kentucky. These occurrences have been noted by many previous authors, including Campbell (1946), Hass (1956), Conant and Swanson (1961) and Ettensohn and Barron (1981). Disseminated microscopic phosphate also occurs throughout most of the black shale sequence (Conant and Swanson, 1961; Miller, 1978).

Heckel (1977) indicated that phosphate formation is evidence of slow clastic deposition far from source areas and the presence of upwelling. Ettensohn and Barron (1981) consider formation of Appalachian Basin nodules to be syndepositional and evidence of deepening in the "Black Shale Sea" during the latest Devonian and Early Mississippian time. They postulated that the upwelling of deep, oceanic, phosphate-rich waters into warmer platform waters caused precipitation of the phosphate. Ettensohn and Barron (1981) noted that abundant phosphate, a critical nutrient of phytoplankton, could have helped maintain a high level of organic productivity.

Iron Mineralization

Abundance of the iron minerals pyrite, marcasite, and siderite, is further evidence for a reducing environment in parts of the water column. Pyrite is very common as scattered grains, laminae, nodular bodies, and other irregular masses throughout both black- and green-shale facies (Cleveland, Bedford, and Sunbury shales). Pyrite is also present in the Berea Sandstone. Some burrows and joints are commonly lined with iron sulfides. Marcasite is also commonly associated with pyrite in these units.

From macroscopic examination of cores and outcrops in the Knobs area of northeastern Kentucky, a distinct stratification of iron mineralization is apparent. Pyrite is more common in the upper portion, whereas siderite dominates in lower parts of the formation. A thin zone where both exist may or may not be present. Though both siderite and pyrite are precipitated in local and regional reducing environments, siderite is associated with slower sedimentation, and is stable only below the sediment-water interface (Curtis and Spears, 1968). As might be expected, the presence of siderite in basal parts of the Bedford can be correlated with a decreasing concentration of silt and sand downward in the Bedford. Hence, the sedimentation rate during the later stages of Bedford deposition was apparently far greater than that during the earlier stages of deposition.

Maynard (1980), in studying Devonian-Mississippian shales, stated that the pyrite-marcasite nodules often bear "large pyrite crystals on their upper surface, a texture that suggests slow precipitation from the water column at the sediment water interface, and this same feature has been noted by the author. The abundance of pyrite further confirms evidence of reducing conditions in anaerobic and dysaerobic environments during the deposition of black and some green shales.

INTERNAL STRATIGRAPHY (RADIOACTIVE)

The internal stratigraphy of the studied units was examined to determine if subunits could be recognized consistently throughout the study area by any distinctive patterns of high and low-radioactivity as recorded on gamma-ray logs. Although distinct subunit gamma-ray signatures can be traced only locally in the Bedford-Berea, the gamma-ray signatures of subunits in the Sunbury can be traced throughout large parts of the study area; these are discussed below.

Sunbury Shale

The Sunbury Shale has long been used as a subsurface stratigraphic marker in eastern Kentucky. Before wireline logs were commonly used, driller's logs for most wells easily distinguished the "Coffee shale" or "black slate" (drillers' names for the Sunbury) from lighter-colored lithologic units above and below (Pepper et al., 1954). Even with the advent of geophysical logs, the Sunbury still remains a prominent stratigraphic marker, because it is widespread, of relatively constant thickness, and shows an extremely strong positive (rightward) deflection in the borehole gamma-ray log (Fig. 4; Appendices A, D). The following sections discuss the differing radioactivity patterns observed in the study area.

Northeastern Kentucky

Throughout most of northeastern Kentucky, gamma-ray logs of the Sunbury Shale exhibit two very high positive deviations separated by a low negative deflection (Appendix D, Fig. 21). This pattern also is seen in portions of western West Virginia and at least as far north as Pike County, southern Ohio. No lithologic distinction could be made between these high- and low-radioactive zones in outcrop or core examinations. Scintillometer profiles also clearly show this "high-low-high" pattern (see Swager, 1978), but scintillometer profiles of cores from the study only vaguely suggest this three-part subdivision (Appendix A). Gamma-ray logs exhibit readings of 400 to 450 API units for the upper and lower positive radioactive deviations and 300-350 units for the middle negative deviation. The lower level high-radioactivity deflection is usually slightly stronger than the upper level deflection. The thickness of the Sunbury averages 15-20 feet (4.6-6.1 m) throughout the area. The highly-radioactive upper and lower subunits average four to seven feet thick (1.2-2.1 m), whereas the middle low-radioactivity unit is thinner (three to five feet; 0.9-1.5 m).

In gamma-ray logs from eastern Lawrence County, three or four positive radioactive deviations are separated by minor intervals of lower radioactivity. These low radioactivity zones may represent local turbidites from an eastern source. Some of the low-radioactive peaks correspond to deflections on the caliper log and probably reflect downhole caving of clay-rich clastic units. Maximum thicknesses for the Sunbury in northeastern Kentucky occur in this area (i.e., 31 feet (9.4 m) within Carter Coordinate rectangle 10-S-83).

All the stratigraphic intervals in the Sunbury, which have to be subdivided on the basis of radioactivity, thin to the south and west from northeastern Kentucky. The "high-low-high" deviation pattern in gamma-ray logs of the Sunbury is last observed on the outcrop belt in eastern Montgomery and Bath counties (Appendix D, Fig. 21), and this same signature locally is present in Wolfe, Morgan, Menifee, and northern Lee and Breathitt counties. Loss of the "high-low-high" pattern coincides with gross thinning of the unit. Although the thicknesses of all three subunits decrease, the Sunbury as a whole appears to thin through pinch-out of the middle unit (the low-radioactivity negative deviation), leaving the lower and upper units superimposed on each other so that only a thicker, highly-radioactive "spike" is present on gamma-ray logs (Appendix D, Fig. 21).

East-central and South-central Kentucky

The single radioactive spike has been noted on outcrop scintillometer profiles by Swager (1978), Ettensohn et al. (1979), and VanBeuren (1980). Despite the thinness of the unit, this spike provides a good geophysical correlation marker, useful in differentiating the Sunbury from black shales lying immediately above and below. This single thin "kick" on gamma-ray logs can be traced westward to Cumberland County and at least as far south as Campbell and Scott counties, northern Tennessee. In areas near the western edge of the basin (Cincinnati Arch), where the Sunbury is thinnest, this marker is difficult to recognize on borehole gamma-ray logs, either because the Sunbury may not be present or because the marker may appear as only a shoulder or slight deviation in the uppermost Chattanooga Shale (Appendix D, Fig. 23). However, on scintillometer profiles of outcrops in Garrard, Russell, Casey, and Cumberland counties, a narrow, "low-amplitude" version of this spike does occur, indicating the presence of a thin Sunbury equivalent (Appendix D, Fig. 22).

On both gamma-ray logs and scintillometer profiles from the southwestern portions of the study area, the Sunbury equivalent is less radioactive. This may be partly related to decreased unit thickness and concomitant exposure time. Scintillometer readings on exposures are also greatly influenced by the degree of weathering (Glover, 1959), and thus the profile curves are compared only qualitatively. Cross-section C-D (Appendix D, Fig. 22) illustrates correlations of scintillometer profiles along the east flank of the Cincinnati Arch. Cross-sections C-E, E-F (Appendix D, Figs. 23, 24) show that the thin radioactivity "spike" seen in gamma-ray logs on the crest of the Cincinnat Arch is equivalent to the signature of the Sunbury Shale deep in the Appalachian Basin, even though lithologically the Sunbury is mapped as part of the New Albany and Chattanooga shales.

Southeastern Kentucky

The Sunbury Shale in northern and western parts of the study area is easily distinguished as a highly radioactive shale exhibiting one or two prominent positive deflections on gamma-ray logs (Appendix D, Fig. 21). However, this is not the case with the Sunbury near Pine Mountain (Fig. 12). Because parts of overlying units (Borden-Price) are lithologically similar to and include as parts of the Sunbury on Pine Mountain, and because the radioactive signature of the unit near Pine Mountain differs markedly from that of other areas, the mapped Sunbury near Pine Mountain apparently includes more and thicker organic-deficient clastic-rich zones. The Sunbury "spike" on gamma-ray logs noted farther to the west, increases in thickness and loses its spike-like form to the east in Pike and Letcher counties near Pine Mountain, as low-radioactive sequence increase in number and thickness (Fig. 12). One of these zones is most prominent, and gives a "high-low-high" pattern of radioactivity. Significant numbers of low-radioactivity zones can be seen as far west as Leslie County. These zones of lower radioactivity probably represent organic-deficient turbidites which enter the basin from nearby clastic

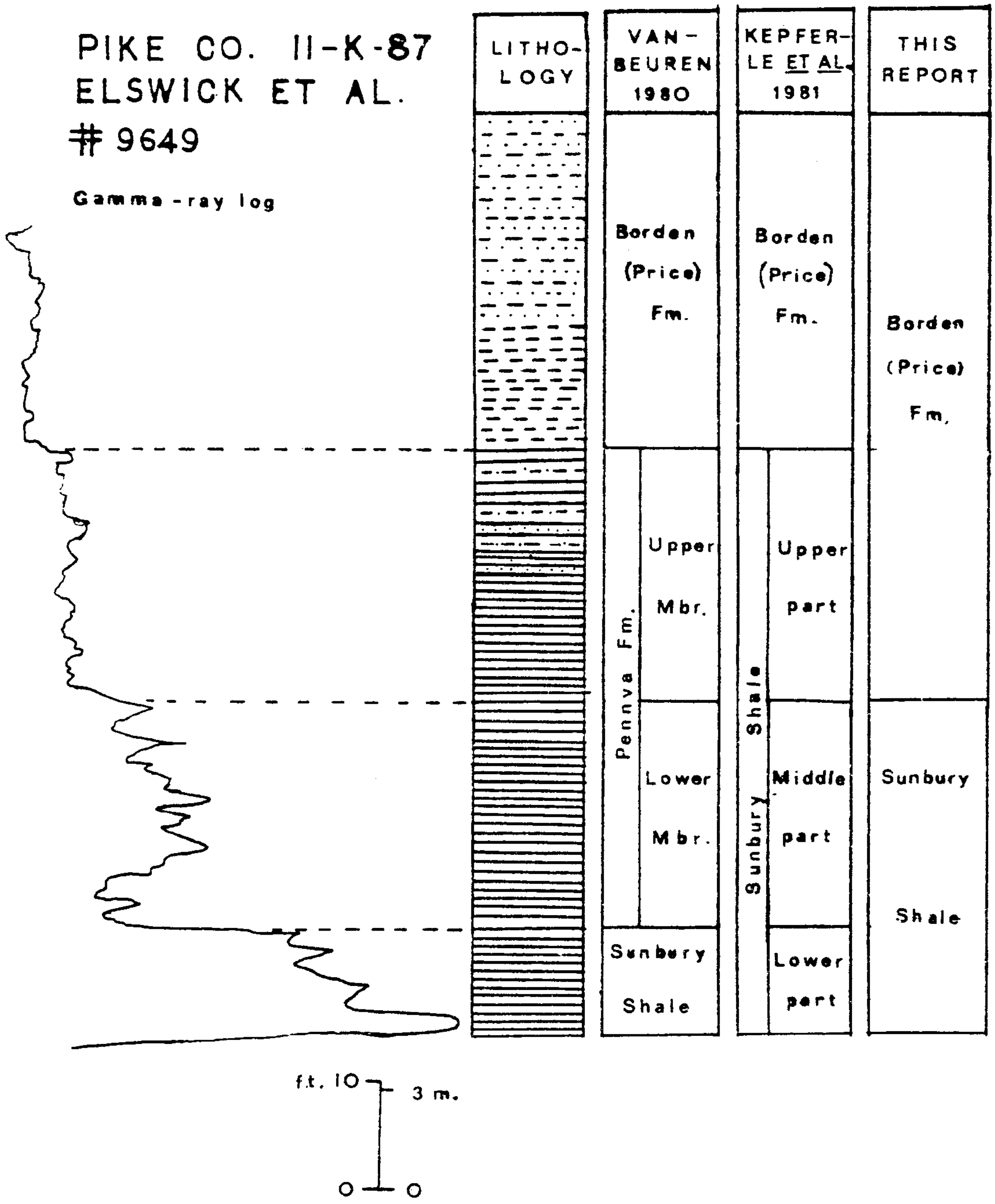


Figure 12. Gamma-ray log showing comparison of recent nomenclature. "high-low-high" pattern of radioactivity in the Sunbury, which is seen in Pike and Letcher counties, is exhibited.

clastic sources to as previously discussed, black shales of the Borden (Pennva) Formation, which overlies the Sunbury Shale, are easily distinguished by their radioactivity, which is lower than that of the Sun-Bury.

Bedford-Berea Sequence

Interpretation of the internal stratigraphy of the Bedford-Berea sequence is not as clear as that of the Sunbury, because only minor differences in radioactivity can be seen throughout the section in eastern and south-central Kentucky. Considerable gradation between sandy and shaly lithologies in the Bedford-Berea sequence limits regional correlations based on gamma-ray logs alone.

In the western portion of the study area, the boundary between the Ohio Shale and the Bedford-Berea sequence can be clearly distinguished using gamma-ray logs, because Devonian black shales have significantly higher radioactivity, and only minor intertonguing between units occurs. However, this boundary is progressively more difficult to identify as one moves eastwardly into the Appalachian Basin because the Devonian black shales become less radioactive due to increased clastic influx. Negus-de Wys (1979) noted this problem in the Eastern Kentucky Gas Field and stated that there is not general agreement even among experts on delineating the boundary between the Bedford-Berea sequence and the Ohio Shale. She noted that this fact is especially characteristic of areas where the Bedford-Berea is very shaly and where the Cleveland (Ohio) Shale is silty and light-colored. She concluded that a combination of lithologic, radioactivity, and biostratigraphic studies may be needed to solve the problem.

Because gamma-ray logs were the sole means available to subdivide the Bedford-Berea sequence stratigraphically, very few internal contacts were traceable for long distances. Despite the fact that shales are generally more radioactive than coarser clastic units, lithologic interpretation from gamma-ray logs alone was difficult. Gradations from fine sandstone to siltstones, shaly siltstones and shale made the tracing of sub-units difficult, even for short distances. Figure 13 shows a schematic representation of the complex Bedford-Berea relationship across eastern Kentucky.

In northeastern Kentucky, where the Bedford-Berea sequence is mostly siltstone (Berea sand of the drillers), no regional radioactivity patterns could be delineated. Driller's logs are only rarely useful in determining lithology within this interval because the entire sequence is commonly listed as "Berea sand", with no shale breaks noted.

In southeastern Kentucky, thin sand bodies within the thicker shale intervals could be identified locally as low-radioactive zones on gamma-ray logs. These sand bodies may represent the lowermost parts of fining-upward sequences with sharp basal contacts. These sandstones grade upward into shale. Miller (1978) identified sandstone in the lower part of the Bedford-Berea sequence in Letcher County which corresponded to a zone of low radioactivity.

Bedford-Berea shales, siltstones, and sandstones typically have natural radioactivities of 100-150 API units (Fig. 4). In general, however, Bedford-Berea sand bodies have the same or slightly lower radioactivity than overlying Borden shales. Bedford shales, on the other hand, all have radioactivities equal to or slightly greater than Borden gray shales, but considerably lower than those of the Sunbury Shale (Figs. 4, 8).

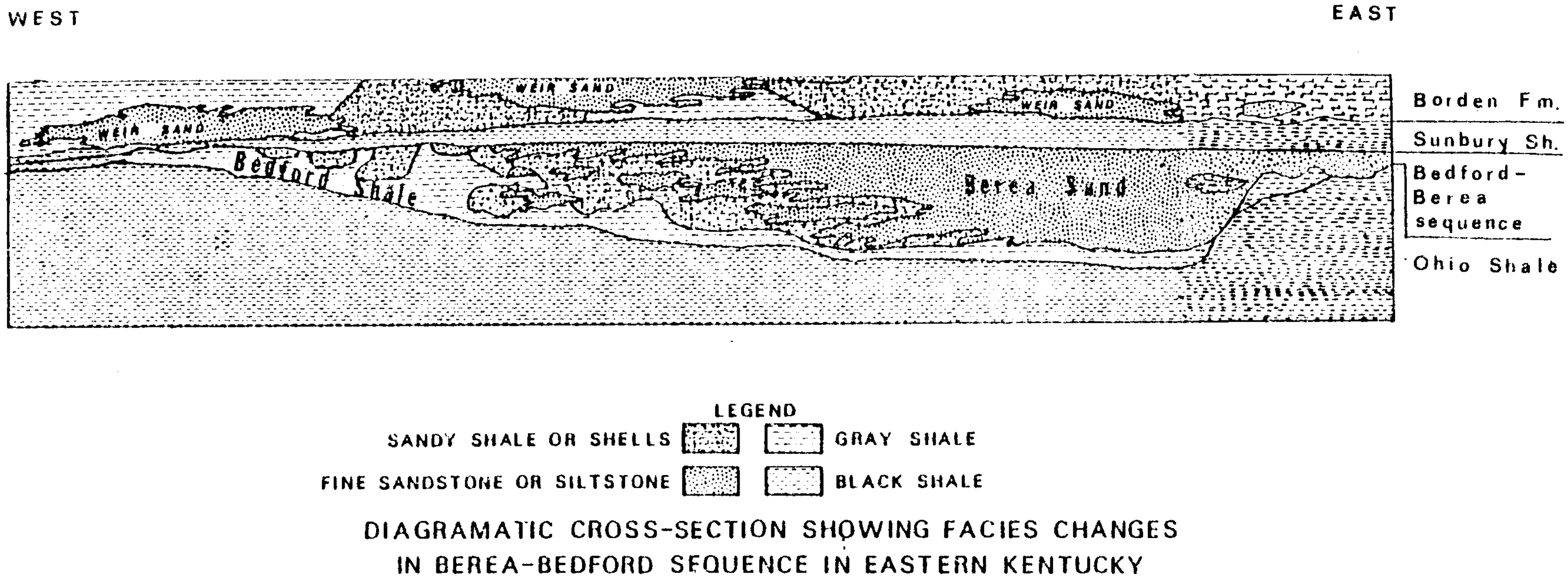


Figure 13. Diagrammatic cross-section showing facies changes in Bedford-Berea sequence in eastern Kentucky (after Pepper, Demarest, Merrels, and de Witt, 1946, and Negus-de Wys, 1979).

In southeastern and south-central Kentucky, the Bedford Shale is often described as brownish-black on driller's logs and in cores. This organic-rich shale is more highly radioactive than gray Bedford shales, but much less radioactive than the Sunbury or Ohio shales (Fig. 8). The formation-density log shows that this shale is also much denser than other black shales. Therefore, despite lithologic similarities, black Bedford, Sunbury, and Ohio shales can be differentiated on close examination of wireline logs.

MAP INTERPRETATION

Structure

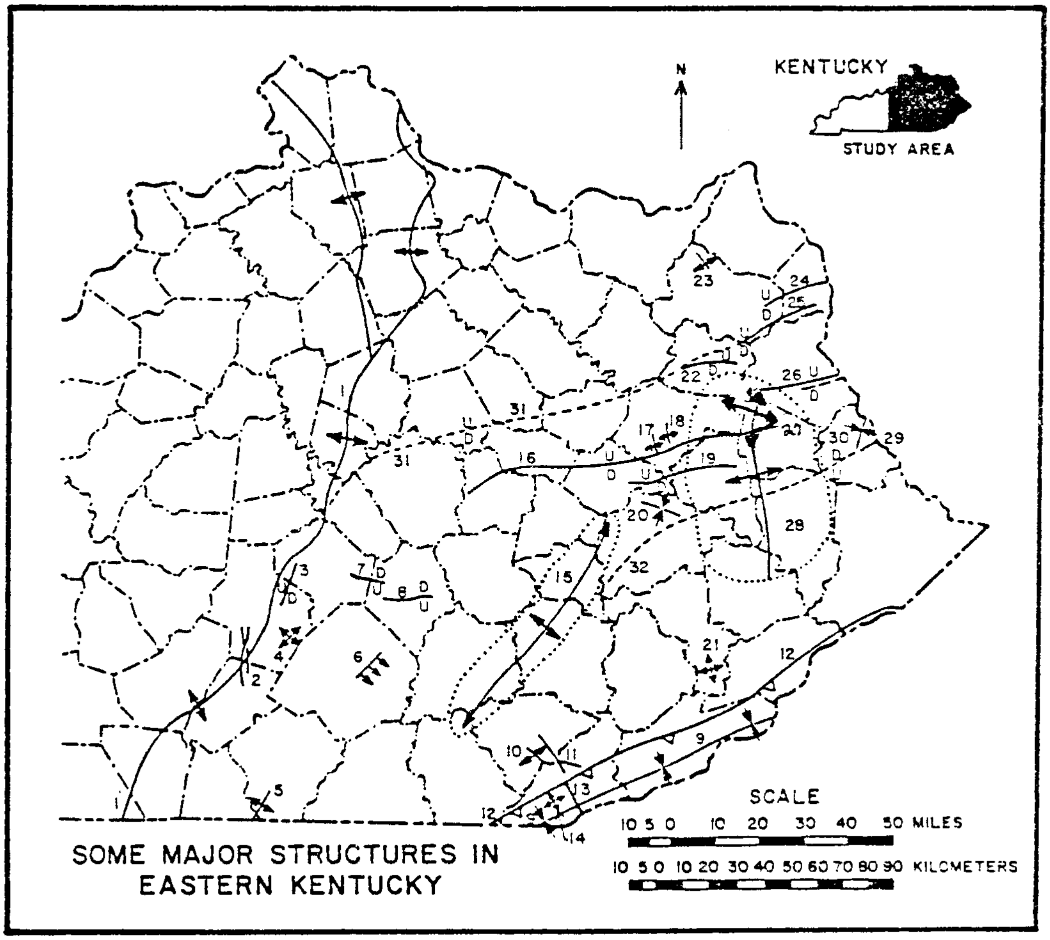
Regional structure-contour maps (Appendix C) were constructed on top of the Ohio Shale, on top of the Bedford-Berea sequence, and on top of the Sunbury Shale. The maps were examined for evidence of possible structural influence as well as for evidence of possible structural changes relative to the adjacent units. These maps were also compared with other structure-contour maps drawn on the tops of adjacent or nearby units; these maps included those by Dillman (1980), Wood and Walker (1954), Provo (1979), Potter (1978), Thomas (1951), and Haught (1959). Comparison of these maps made it possible to determine the likelihood of structural movement during or between depositional events. Only the major structures, however, were examined in this study

Tectonic Overview

In the central part of the Appalachian Basin, latest Devonian and earliest Mississippian time was characterized by tectonic quiescence following the Acadian orogeny, although apparently some minor movement on local structures did occur (Negus-de Wys, 1979; Dillman, 1980). Earlier in the Late Devonian, however, great amounts of sediment, eroded from mountains to the northeast and east, were shed into the basin via the Catskill delta complex and related delta systems. These deltaic clastics did not always prograde completely into western parts of the basins due to climatic and structural causes (Ettensohn and Barron, 1981). Hence, black muds derived largely from organic detritus in upper parts of the water column were deposited in western parts of the basin (e.g., eastern Kentucky) in the absence of abundant clastic sedimentation. The orogenic event which formed the Acadian Mountains also may have "caused reactivation of certain basement structures and periods of broad epeirogenic uplift and subsidence which influenced the black-shale deposition" (Ettensohn and Barron, 1981), and minor structural activity apparently continued on into the Early Mississippian. Some areas of local structural activity were identified by Negus-de Wys (1979) and include the Paint Creek Uplift, the Pike County Uplift, and the Perry County High (Figs. 14, 15). This author noted similar evidence for minor movement on some of these structures during the latest Devonian and earliest Mississippian time. A review of the major structural features of the study area and their effect, if any, on deposition of the Bedford Shale, Berea Sandstone, and Sunbury Shale follows.

Cincinnati Arch

The Cincinnati Arch (Fig. 14) marks the western boundary of the Appalachian Basin and of the study area (Fig. 1). The Ordovician axis, shown on the map, is from Jillson (1931). Dillman (1980), however, reported that the axis of the Devonain arch in Lincoln, Casey, and Russell counties was six to twelve miles east of the Ordovician axis. Maps prepared for the present study appear to confirm a more easterly Late Devonian and Early Mississippian axis for the arch in southern Kentucky. The structure-contour maps prepared in this study, however, utilize essentially the same control points used by Dillman (1980). On these maps, due to the thinness of the Mississippian units (less than five feet [1.5 m]) and the contour interval of 100 feet (30.5 m), the top of the Chattanooga Shale was also considered to be the top of the Bedford-Berea and Sunbury where the latter units could not otherwise



1 CINCINNATI ARCH
2 GOOSE CREEK GRABEN AND FAULTS
3 TRACE FORK FAULT
4 MINTONVILLE DOME
5 SUNNYBROOK ANTICLINE
6 SHOPVILLE MONOCLINE
7 GUM SULFUR FAULT
8 MT. VERNON FAULT
9 MIDDLESBORO SYNCLINE
10 FLAT LICK ANTICLINE
11 WHITE MTN. AND DORTON BRANCH FAULT ZONES
12 PINE MOUNTAIN THRUST FAULT
13 ROCKY FACE FAULT
14 FOUR MILE DOME
15 ROCKCASTLE RIVER UPLIFT
16 PAINT CREEK FAULT ZONE
17 STACY FORK ANTICLINE
18 WEST LIBERTY DOME
19 JOHNSON CREEK FAULT
20 TAULBEE SYNCLINE
21 OWENS BRANCH DOME
22 LITTLE SANDY FAULT
23 ROCK SPRINGS ANTICLINE
24 MAVITY MONOCLINE
25 ROSS CHAPEL MONOCLINE
26 BLAINE FAULT SYSTEM
27 LAUREL CREEK DOME
28 PAINT CREEK UPLIFT
29 WARFIELD FAULT
30 TURKEY CREEK BASIN
31 APPROXIMATE NORTHERN BOUNDARY OF ROME TROUGH ----
32 APPROXIMATE SOUTHERN BOUNDARY OF ROME TROUGH ----

Figure 14. Some major structures in eastern Kentucky (after Dillman, 1980).

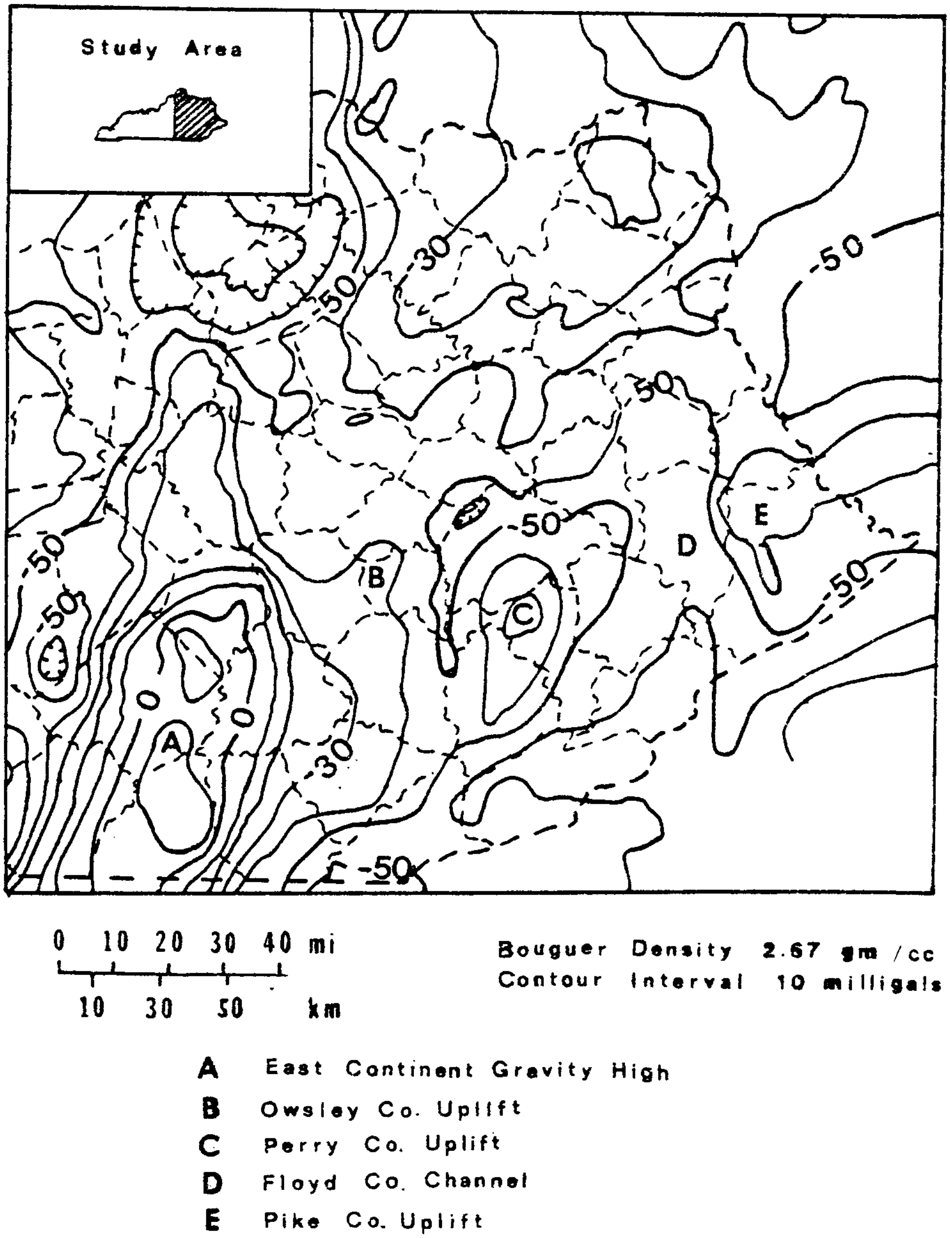


Figure 15. Simple Bouguer gravity map of eastern Kentucky (after Ammerman and Keller, 1979; and Dillman, 1980).

be distinguished.

Contours on all structural maps are sub-parallel to the arch, except in extreme south-central Kentucky, where they cross the arch showing the broad structural low called the Cumberland Saddle between the Jessamine and Nashville domes (Appendix C, Figs. 18, 19, 20). Due to the thinness or possible absence of studied units on the arch, which may be partly due to their distance from postulated source areas, it is difficult to determine from the structure-contour maps the possible effects of tectonism during or after deposition of the Bedford-Berea and Sunbury. The arch is, however, a well-developed feature on each of the three structure-contour maps, and other studies (Provo, 1977; Swager, 1978; Ettensohn et al., 1979a; Dillman, 1980; and Ettensohn and Barron, 1981) indicate that the arch was probably a positive feature during much of Devonian-Mississippian black-shale deposition.

Rockcastle River Uplift

The Rockcastle River Uplift (Fig. 14) appears to be a doubly-plunging anticline, trending northeast-southwest and is well-defined on all structure-contour maps (Appendix C). The uplift is centered over Clay and Laurel counties, and its northern end extends into Owsley County. A small trough bounds the uplift to the northwest and is well developed on all maps (Appendix C, Figs. 18, 19, 20). The position of the Rockcastle River Uplift coincides with the position of a minor Bouguer gravity anomaly, the Owsley County Uplift (Fig. 15) of Ammerman and Keller (1979). The Rockcastle River Uplift was also identified on the structure maps prepared by Dillman (1980) on the bases of several Upper Devonian black-shale units. Dillman also suggested that some Late Devonian movement had occurred on the structure based on the comparison of isopachous maps and structure-contour maps for the same and adjacent units. This author found no evidence of movement when comparing the structure-contour and isopachous maps of this study with the maps constructed by Dillman (1980). However, this lack of recognition maybe due to the thinness of the units.

Rome Trough

The Rome Trough (Fig. 14) is bounded by the Kentucky River Fault System on the north and by a series of gravity highs to the south and southeast (Fig. 15). An extremely thick sequence of Early Paleozoic rocks is present within the trough, and its growth is probably related to synsedimentary growth faulting, best developed in the Middle Cambrian. The faulting may have been controlled by zones of Precambrian weakness (Heyl, 1972). Webb (1969) reported that these faults were active at least into the Pennsylvanian, but decreased in magnitude with time. Though some evidence of movement along the Kentucky River Fault System is expressed on the structure-contour maps of this study (Appendix C, Figs. 18, 19, 20), the movement was largely post-Early Mississippian as indicated by displacement of Pennsylvanian surface units in Elliott County. Dillman (1980) noted that Upper Devonian and Lower Mississippian units were displaced below the Ross Chapel and Mavity monoclines (Fig. 14), which indicates that these monoclines are faults at depth.

Paint Creek Uplift

The Paint Creek Uplift (Fig. 14) is a broad anticlinal uplift trending north-northeast. Centered over northern Magoffin, eastern Morgan, western Johnson, and southwestern Lawrence counties, it appears to have northern and southern apices (Fig. 20). In fact, Negus-de Wys (1979) identified the Paint Creek Uplift as a Mississippian structure that domes the Ohio Shale in a north-south trend across the Rome trough. The higher southern apex, located in west-central Johnson County, is displaced by the Irvine-Paint Creek Fault System (Fig. 14; Appendix C, Figs. 18, 19, 20). The lower northern apex, located in northwestern Johnson County, coincides with the well-defined, petroleum-producing Laurel Creek Dome (Fig. 14). The higher southern apex also appears on a structure-contour map prepared by Thomas (1951) on top of the Berea. Dillman (1980) reports only a northwest-trending axis for the uplift (Fig. 14), whereas this study indicates a north-northeast trending axis (Appendix C, Figs. 18, 19, 20). These differences, therefore, suggest that uplift on the southern apex probably occurred during the latest Devonian or Mississippian. On the other hand, it is also possible that Dillman's lack of data did not allow for suitable definition of structure. Dohm (1963) suggested that this uplift may have been controlled by vertical forces different from those that formed east-trending faults and more typically-oriented Appalachian structures, which usually have northeast-southwest trends. He noted that the trend and geographic position of the axis of the Paint Creek Uplift approximately coincides with Woodward's (1961) axis for the Waverly Arch and suggested that recurrent movement along its southern extension may have been the controlling factors. Erosion and thinning of the Borden Formation on the flanks of the uplift may be evidence for uplift on this structure during Osagean and Meramerican time (Dohm, 1963). Ettensohn (1975, 1979a, 1980) moreover found evidence of uplift on the Waverly Arch occurring as late as the Late Mississippian and Early Pennsylvanian.

Dillman (1980), however, reported that the Paint Creek Uplift was quiescent during the Late Devonian and Early Mississippian and apparently has no expression in the basement rocks. He suggested that the area was apparently less subject to subsidence and tectonic forces associated with Acadian or Appalachian orogenic events.

An unnamed structural feature which may be a southern portion of the Paint Creek Uplift extends southward to Knott County (Appendix C, Figs. 18, 19, 20). The feature is a broad anticline, but, like the Paint Creek Uplift, does not coincide with Bouguer gravity highs. A small structural "low" straddles the crest of the anticline in Knott County, but is not developed at the same geographic position on each map.

Pine Mountain Thrust-Middlesboro Syncline

Subsurface data on the above two features (Fig. 14) is limited, though recent drilling activity provides some control in southeastern Kentucky. Units of Upper Devonian-Lower Mississippian black shales have been subject to thrusting, and their interpretation on gamma-ray and driller's logs is difficult due to the repetition of units along the faults. Therefore, no contours were drawn on the Pine Mountain Thrust block.

Minor Structures

Many smaller structures were partially delineated during the generation of the maps. However, the use of only one data point per Carter Coordinate section and a large contour interval made it difficult to adequately define their extents. A series of east-west trending structural highs and lows with axes parallel to the Kentucky River Fault System are present in Lawrence, Johnson, Boyd, and Elliott counties (Appendix C, Figs. 18, 19, 20; Fig. 14). A structural "low" is also present in Morgan County on a downdropped block of the Irvine-Paint Creek Fault System. This "low" is wholly within the Rome Trough and corresponds to a "low" on the Bouguer gravity map of eastern Kentucky (Fig. 15). Many small anticlines and synclines also are present near the Pine Mountain Thrust in Pike and Letcher counties and may be genetically related to the forces that caused the Pine Mountain Thrust. The Flat Lick Anticline (Fig. 14) can easily be seen on structure contour maps in Knox and Bell counties, but the stratigraphic control is limited because few gamma-ray logs are available. Previous structure maps constructed by Wood and Walker (1954) and Dillman (1980) were relied upon for definition of minor structures. The Sunnybrook Anticline (Fig. 14) in Wayne and Clinton counties is evident on all maps although the elevational datum for all units appears constant because the three studied units are much thinner than the contour interval (Appendix C, Figs. 18, 19, 20).

Overall, there are few differences between the structure maps generated during this study and those of Wood and Walker (1954) and Dillman (1980) for underlying Upper Devonian units. This suggests that little tectonism occurred in the study area during the latest Devonian and the Earliest Mississippian.

Anomalies on Isopachous Maps

Regional isopachous maps were prepared for the Bedford Shale-Berea Sandstone and for the Sunbury Shale (Appendix C, Figs. 16, 17). Because the radioactive signature on gamma-ray logs was used to define thickness of the Sunbury for the map, the Sunbury on these maps does not necessarily correspond to the Sunbury Shale of drillers and mappers in southeastern Kentucky, because their Sunbury usually includes overlying black Borden shales as previously discussed. The Bedford-Berea isopachs are based primarily on gamma-ray log control in the western portion of the study area, where color and lithology are not distinctive. In the east, however, where the unit is thicker, distinct color and lithology are recognized. Here, both gamma-ray and driller's logs were used. The thickest Bedford-Berea in eastern Kentucky occurs along a north-south trend, bounded by areas of thin clastics to the east and west (Appendix C, Fig. 16). The boundaries of the central thick body are fairly sharp, and the body itself appears to be related to an increased thickness of sandstone and siltstone compared to shale within the sequence. More specifically, this central thick body occurs where the "Berea sands" in the Bedford-Berea sequence are thickest. In the laterally adjacent thin areas to the east and west, the number and thickness of these sandstone are greatly reduced. East of the thick body, a thin Bedford-Berea equivalent is primarily composed of thin sandstone and siltstone beds, whereas in the west the interval is mostly "Bedford" shale. To the north, in southern Ohio, the Bedford-Berea is also thin. Hyde (1953) suggested that the widespread, thick "Berea sand" in eastern Kentucky had a northern source area somewhere above a southern Ohio shoreline, whereas Pepper _et al_. (1954), suggested that the primary source of clastics was to the east.

Within the thick Bedford-Berea body, slightly thicker sections lie at the extreme northern and southern ends of the body (Appendix C, Fig. 16). The northern lobe, in Lewis, Carter, Greenup, and Boyd counties, contains Bedford-Berea sediments up to 170-180 feet (51.8-54.9 m) in thickness. It coincides with the geographic position of a lobe of thicker Devonian black shale identified by Harris _et al._ (1978).

This area of thickening could be related to an increase of sediment supply or to greater subsidence in the area. The thick southern lobe occurs in Pike, Floyd, and Letcher counties, where the Bedford-Berea is up to 140 feet (46.6 m) thick. The thickness can be explained largely by its proximity to a postulated source area, the Virginia-Carolina delta of Pepper et al. (1954). Walls' (1975) study also showed a concentric pattern of isopachous indicating thinning away from this source. The southern thickened lobe, however, apparently contains a much greater amount of shale than does the northern area (Negus-de Wys, 1979). As with the northern lobe, the southern lobe also occupies an area where Upper Devonian sediments are thicker. Dillman (1980) attributed the thickened Devonian sediments in this area to subsidence within the Floyd County Channel of Ammerman and Keller (1979) (Fig. 16). A combination of sediment supply and concurrent downwarping may actually be responsible for the thickening.

A north-south "hingeline" marking a line along which Bedford-Berea sediments quickly thin can be recognized in a portion of Pike County, but is best seen in adjacent parts of West Virginia (Pepper et al., 1954; Haught, 1959; Larese, 1974). In extreme eastern Pike County, the Bedford-Berea sequence thins from 130 feet (39.4 m) to ten feet (3.0 m) in an eastward direction over a distance of only ten miles (16.1 km) (Thomas and Lauffer, 1964; Appendix C, Fig. 16). A northern extension of this thinning pattern is also seen in western West Virginia. Pepper et al. (1954), who did not extend this thinning pattern as far east, showed a thin Bedford-Berea sequence farther north in parts of Kentucky near the West Virginia border. According to Harris et al. (1978), the thinning of the Bedford-Berea in West Virginia occurs above thin underlying Devonian black shales in the same area. This thinning may outline the position of a hingeline. East of this irregular line, most of the sequence consists of fluvial and shallow marine sands (Larese, 1974), suggesting that much of western West Virginia might have been a pre-Mississippian topographic "high" or an area of lesser subsidence.

In the area west of the thick "Berea sand", the interval consists largely of shale ("Bedford Shale") (Fig. 13) and rare argillaceous siltstone beds with a maximum thickness of approximately 50 feet (15.2 m). Although the eastern boundary of this predominantly shale unit is marked by an area of rapid thickening, this boundary has a very irregular north-south trend (Appendix C, Fig. 16). Occasionally the Bedford is well exposed in the Knobs outcrop belt, which marks the western limit of the study area. The Bedford gradually thins, however, toward the south and west.

The Bedford-Berea shale facies thins toward the Cincinnati Arch in central Kentucky. Portions of the arch probably exposed during deposition of the Bedford-Berea may have supplied a minor amount of the clastics that appear in the Bedford (Pepper _et al._, 1954). Thin siltstones, less than one foot (0.3 m) thick occur in the Bedford Shale in Powell, Estill and Madison counties and may reflect a source on the adjacent Cincinnati Arch. A Jackson County driller's log listed "Bedford siltstone" as six feet (1.8 m) thick which corresponded to a low-radioactivity zone on the gamma-ray log from the same borehole; this siltstone, far from the usual postulated eastern and northern source areas, also may have been derived from the Cincinnati Arch. Similarly, a slight thickening of the Bedford-Berea section probably exists in Whitley, Laurel, Knox, Clay and Jackson counties (Appendix C, Fig. 16) and may also reflect a source on the Cincinnati Arch. The arch was most probably a positive feature during the Upper Devonian and could have acted as a minor clastic source (Provo, 1977; Swager, 1978; Ettensohn et al., 1979; Hoover, 1960).

In a few other cases, minor anomalies on the isopachous maps may be related to movement on small structures, distance from source area, or relief on the underlying surface. One such anomaly is shown by the area of closed contours on the Bedford-Berea isopachous map in Breathitt and Magoffin counties (Appendix C, Fig. 16).

Sunbury Shale

The Sunbury is very thin but persistent throughout the study area. The constant thickness over local structural features indicates the general absence of synsedimentary movement. The Sunbury thins regionally to the south and west, though a thick lobe is present in Pike and Letcher counties (Appendix C, Fig. 17). The thick lobe in Pike and Letcher counties and another thickened section in Lawrence County occur above two lobes of thicker Devonian black shale which were identified by Harris et al. (1978). Greater thicknesses of Sunbury Shale apparently are due to the greater number and thickness of coarser clastic-rich zones within the highly-radioactive organic-rich shale as previously discussed. These clastic zones, recognizable by their low radioactivity and negative deviations (Fig. 12) thicken to the east and probably represent distal turbidite facies from eastern source area. Interestingly, turbidites in lowermost parts of the overlying Borden Formation in Lawrence County are thought by Clarke (1969) to have had similar eastern sources.

In south-central Kentucky, the Sunbury is extremely thin, usually five feet (1.5 m) or less, and hence it becomes difficult to identify on gamma-ray logs (Appendix D, Fig. 23). West of Pulaski County, it is commonly indistinguishable on these logs, though scintillometer profiles clearly indicate its presence (Appendix D, Fig. 22). Locally, the Sunbury may be absent, probably due to post-depositional erosion.

HYDROCARBON PRODUCTION AND POTENTIAL

The Bedford-Berea interval has long been an important oil- and gas-producing interval in the Appalachian Basin (de Witt et al., 1979). Berea oil was first produced in northern Ohio a few years after the drilling of the Drake well in Pennsylvania in 1859, and production in West Virginia began in Wood County in 1864 (de Witt et al., 1979; Larese, 1974). Production in those states remained significant for many years, and some fields are still yielding hydrocarbons from the Bedford and Berea units. Drillers use the term "Berea sand" to denote sandy intervals between the easily recognized Ohio and Sunbury shales. In much of eastern Kentucky, sandstone and siltstone dominate in the sequence.

Petroleum occurrences in the "Berea sand" appear to be related to paleo-shorelines, especially nearshore beaches, bars, and channels, and represent "stratigraphic traps which resulted from differences in the competency of the depositing currents, the degree to which the sands were reworked by marine currents, and selective post-depositional cementation of parts of the sand body" (de Witt et al., 1979). Structural influence and modification of stratigraphic traps are probably less important to reservoir location than presence of porous sandy and silty zones (Dohm, 1963; de Witt et al., 1979). Gas production from Upper Devonian black shale is also best developed in these zones. This black shale is generally recognized as the source bed for producing zones.

In the study area, two of the larger producing Berea fields are located in stratigraphic traps related to structural "highs". The Redbush Gas Field in Johnson County is located on the southeast flank of Laurel Creek Dome, and the Brushy Creek (Cordell) Gas Field straddles the Hoods Creek Anticline (Dohm, 1963). Minor Berea oil and gas has been produced in scattered areas of Greenup, Carter, and Boyd counties (Wood and Walker, 1954). Berea gas is desirable due to its high BTU content, a reflection of its association with oil in the northern part of the Eastern Kentucky Gas Field (J. Avila, Ashland Oil, Inc., pers. comm., 1981). South and east of Johnson County, most of the "Berea sand" production is gas.

In general, oil and gas occur together in Devonian and Mississippian rocks from the western part of the Appalachian Basin in Boyd, Greenup, Carter, and Lawrence counties. To the south in deeper parts of the basin, gas only occurs, where greater heat and pressure, which accompany the greater thicknesses of section, have led to increased maturity and conversion of oil to gas. Patterns of regional maturation have been examined by Potter et al. (1981).

The most recent emphasis on hydrocarbons in the Berea has been in Pike County and adjacent portions of Virginia, where gas is currently being produced (E. Jenkins, Kentucky-West Virginia Gas Co., pers. comm., 1981). Thomas and Lauffer (1964) have noted that local and regional structure appear to have little effect on production. Clean sandstones within the argillaceous and silty section appear to be the best reservoirs after stimulation. They also speculated that the Ohio and Sunbury shales are the source beds for the Berea hydrocarbons.

Again, it is important to note that Bedford-Berea and lower Borden clastics are commonly logged as "brown shale" in southeastern Kentucky. Often, this entire brown-shale column is fractured to stimulate production, so that gas from the lower Borden, Sunbury, Bedford-Berea, and Ohio clastic units is combined. After examining temperature logs from wells in Perry County, Ray (1968) stated that the interbedded green and black shales in the upper part of the Bedford-Berea sequence and the lower part of the Huron Member of the Ohio Shale produced gas. Such interbedded shales may be good exploration targets, for the greenish-gray shales may act as petroleum reservoirs, whereas black-shale fracture systems may function as hydrocarbon-carrying conduits.

Although recognized as a probable source rock, the Sunbury Shale is not a major oil and gas producer. Hunter (1935) reported that gas had been obtained from the Sunbury in southern Ohio and eastern Kentucky. This gas was found while drilling for gas in adjacent units and was obtained only after borehole stimulation.

CONCLUSIONS

1. Bedford-Berea and Sunbury units in eastern and south-central Kentucky can be traced farther west and south than previously reported. Gamma-ray logs and scintillometer-generated radioactivity profiles have helped to trace these units from eastern Kentucky at least as far west as Cumberland County, Kentucky, and as far south as northernmost Tennessee. Because of lithologic similarities, these units are mapped as parts of the underlying Chattanooga and New Albany shales.
2. The Bedford-Berea near the Cincinnati Arch is more silty in Estill and Madison counties than in Montgomery and Powell counties to the east. This could indicate that the arch was a minor source of clastic debris during latest Devonian and earliest Mississippian time.
3. Based on interpretation of driller's logs, gamma-ray logs, and outcrop studies, the Bedford-Berea sequence in much of east-central, southeastern, and south-central Kentucky is a brownish-black shale. This shale is generally indistinguishable lithologically from the black shales of the underlying Ohio Shale equivalent and from the overlying Sunbury Shale equivalent. In outcrop, these brownish-black shales are mapped as parts of the New Albany or Chattanooga shales.
4. In southeastern Kentucky, black shales equivalent to basal parts of the Borden Formation are mapped as parts of the Sunbury and Chattanooga shales. However, gamma-ray logs and scintillometer profiles show these shales are equivalent to basal parts of the Borden and are stratigraphically higher than the type Sunbury or

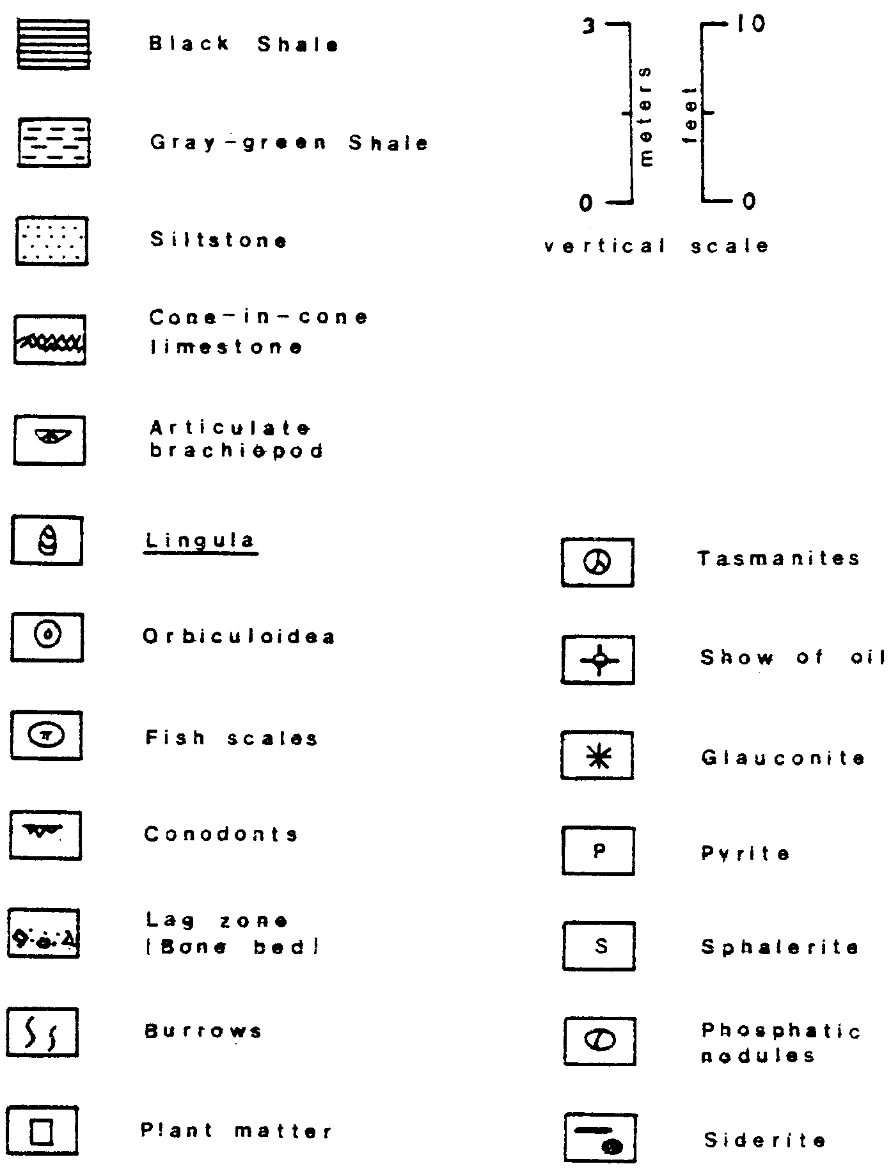
Chattanooga shales.

5. A persistent internal stratigraphy, determined from gamma-ray logs, can be recognized throughout much of the study area. A "high-low-high" pattern of radioactivity in the Sunbury can be traced throughout northeastern Kentucky. A separate "high-low-high" pattern for the Sunbury Shale can be seen in Pike, Letcher, Knott, and Perry counties, southeastern Kentucky. Bedford-Berea, Sunbury, and lower Borden (Price) units are equivalent to part of the Big Stone Gap Member of the Chattanooga Shale in Virginia.
6. Along the Knobs outcrop belt, the basal contact of the Sunbury is easily defined lithologically, except in east-central and south-central Kentucky where the underlying part of the Bedford-Berea sequence becomes black. In these parts of the outcrop belt, the contact cannot be picked lithologically, but can be determined from scintillometer profiles and gamma-ray logs.
7. Structures previously identified from structure-contour maps on the basis of Upper Devonian units in eastern and south-central Kentucky, including the Cincinnati Arch, Rockcastle River Uplift, Paint Creek Uplift, and Rome Trough, are also present on structure-contour maps constructed on the tops of Upper Devonian and Lower Mississippian units during this study.
8. Movement on the Paint Creek Uplift probably occurred in latest Devonian and earliest Mississippian based on comparison of structure-contour maps constructed during this study for Devonian-Mississippian units with structure-contour maps made by Dillman for underlying Upper Devonian units.
9. Structural activity affecting distribution and thicknesses of

Bedford-Berea and Sunbury sediments is minor. Two possibilities may explain this fact: (1) little movement took place, and/or (2) the Bedford-Berea and Sunbury section is too thin to detect significant thickness or structural changes with the contour interval used in this study.

APPENDIX A

LEGEND



Core #1 (IMMR Core Kep #2)
17-Y-74, 2770' FSL x 3520' FEL
Charters Quadrangle, Lewis Co., KY
Elevation 940'   Background Rad. 37 cps.

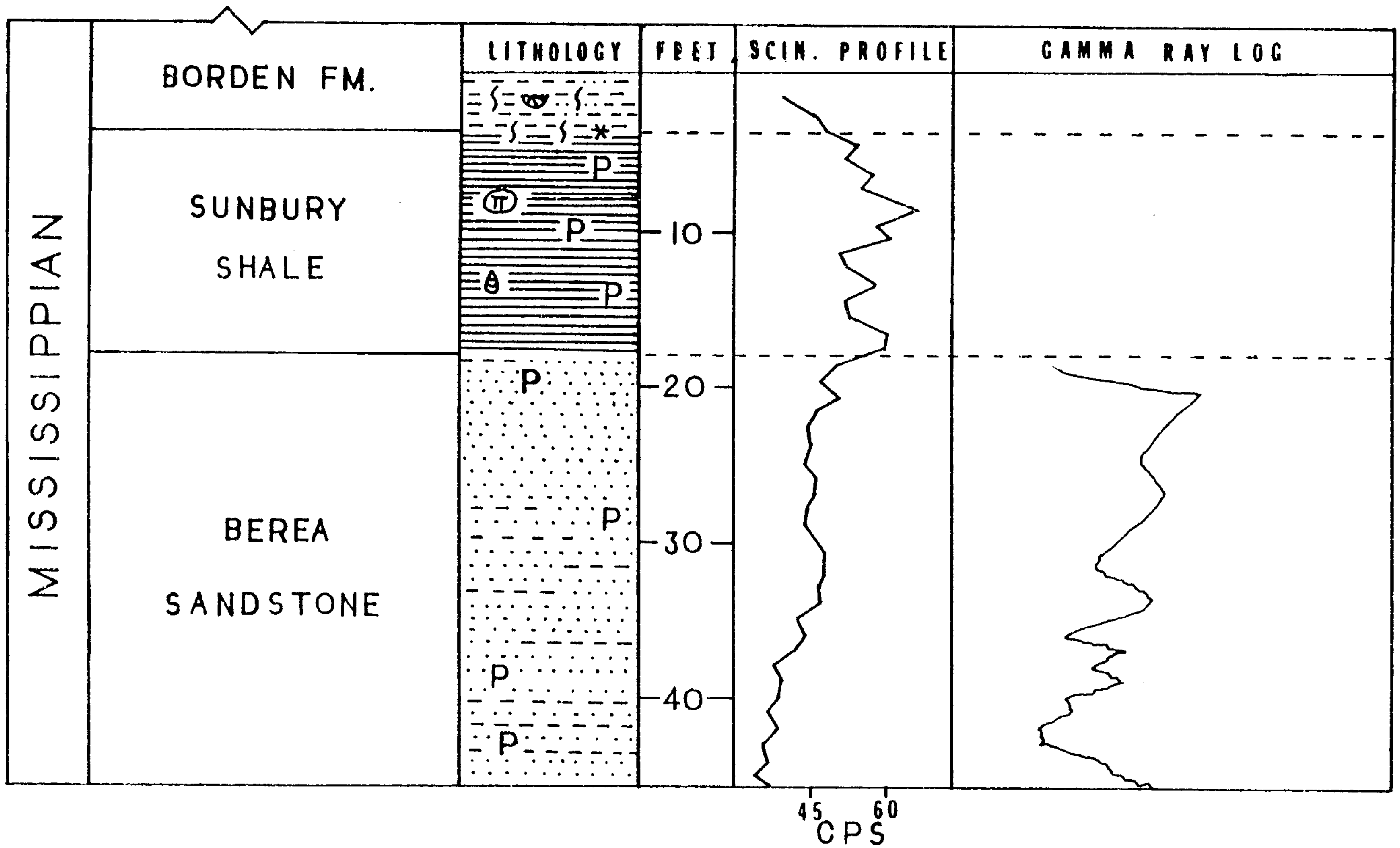
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
17.0-19.9	2.9	Shale, greenish gray (5G 5/1) to dark olive gray (5G 3/1), silty, rare glauconitic laminae; bioturbated, rare brachiopods.
		Sunbury Shale
19.9-34.2	14.3	Shale, black (N1), finely laminated, bituminous, fissile, occasional *Lingula*, fish scales; granular pyrite common; nodular pyrite rare.
		Berea Sandstone
34.2-34.3	0.1	Siltstone, dark greenish gray (5G 4/1), argillaceous, wavy laminated, abundant pyrite; sulfate efflorescence.
34.3-43.4	9.1	Siltstone, light olive gray (5Y 6/1), with medium gray laminae (N5) near top, inclined parallel bedding; occasional pyrite granules.
43.4-53.0	9.6	Siltstone, as above, and shale, olive gray (5Y 4/1) to medium dark gray (N4) and dark greenish gray (5GY 4/1). Shale laminae and very thin beds occur every six inches; wavy to mildly contorted stratification; occasional pyrite.
53.0-60.0	7.0	Siltstone, as above, 50%; shale, as above, 50%, thin, wavy-bedded; cross-laminated on small scale; non-calcareous, pyrite common in shale, occasional in siltstone.
60.0-61.3	1.3	Siltstone, as above, with no shale.
		Bedford Shale
61.3-72.0	10.7	Siltstone, greenish gray (5GY 6/1), 50%; shale, dark greenish gray (5GY 4/1), 50%; siltstone beds 1" thick or less; occasionally calcareous; small, nodular pyrite occasionally in shale.

Core #1, Continued

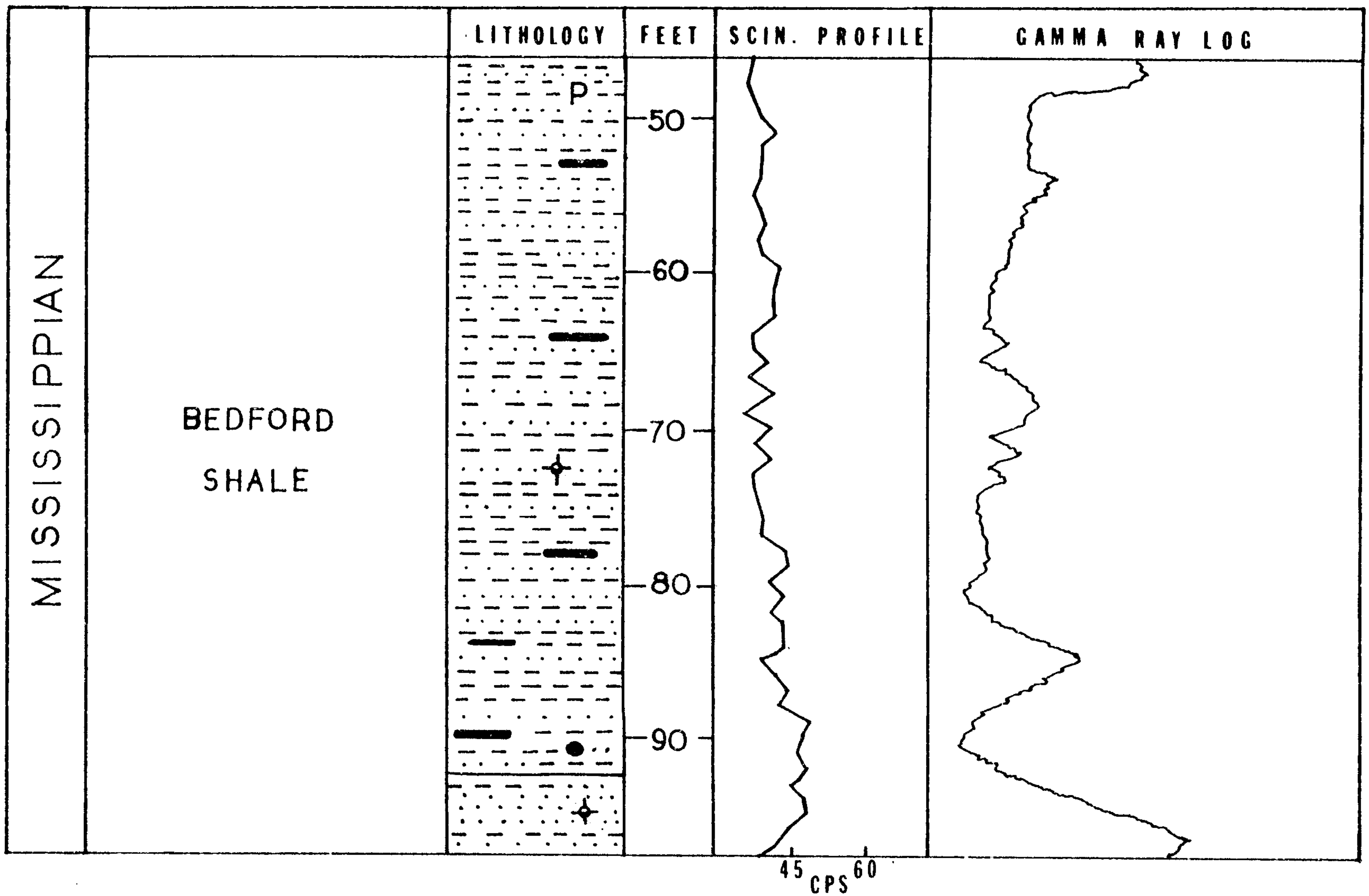
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
72.0-82.0	10.0	Siltstone and shale, as above; rare siderite bands or nodules.
82.0-92.0	10.0	Shale, dark greenish gray (5GY 4/1), approx. 60%, wavy-bedded, bioturbated, occasional siderite bands or nodules. Siltstone, greenish gray (5GY 6/1), calcareous, oil-stained.
92.0-107.8	15.8	Shale, as above; siderite bands or nodules increase in lowest five feet; siltstone, as above; laminae decrease in number and thickness.
107.8-108.5	0.7	Shale, as above; occasional very thin black shale laminae; siltstone, as above, laminae increase in number and thickness.
108.5-109.1	0.6	Siltstone, medium dark gray (N4) to dark gray (N3); wavy-bedded, bioturbated; thin black shale laminae at 108.7.
109.1-112.3	3.2	Siltstone, light olive gray (5Y 6/1), planar-bedded, slight oil stain and odor.
112.3-112.5	0.2	Shale, dark greenish gray (5GY 4/1), silty.
112.5-112.9	0.4	Siltstone, light olive gray (5Y 6/1), planar-bedded, slight oil stain and odor.
112.9-114.3	1.4	Shale, dark greenish gray (5GY 4/1-5G 4/1) to greenish-black (5G 2/1), 80%; siltstone, greenish gray (5GY 6/1) to medium gray; wavy-bedded and laminated.
114.3-114.5	0.2	Siltstone, medium gray (N5), finely laminated.
114.5-117.2	2.7	Shale, dark greenish gray (5G 4/1-5GY 4/1) to greenish black (5G 2/1), 80%; siltstone, greenish gray (5GY 4/1-5G 4/1), 20%; wavy-bedded and laminated, occasional siderite bands or nodules.
117.2-117.6	0.4	Siltstone, light olive gray (5Y 6/1), finely-laminated.

Core #1, Continued

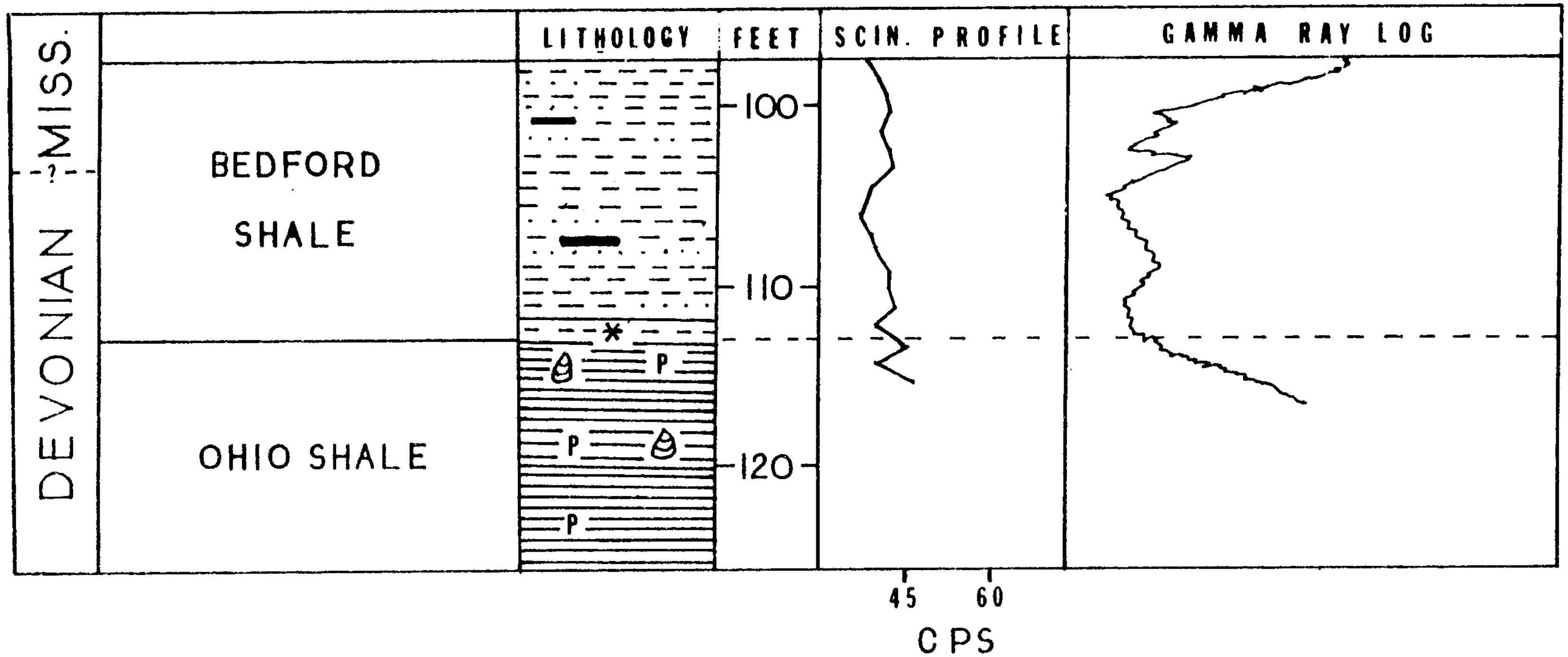
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
117.6-122.5	4.9	Shale, dark greenish gray (5GY 4/1-5G 4/1) to greenish black (5G 2/1), 80%; siltstone, greenish gray (5GY 6/1-5G 6/1) 20%; wavy-bedded and laminated; graded bedding observed; occasional siderite bands or nodules.
122.5-123.4	0.9	Siltstone, light olive gray (5Y 6/1), planar-bedded, non-calcareous, slight oil stain and odor.
123.4-127.7	4.3	Shale, dark greenish gray (5G 4/1), 80%; siltstone, greenish gray (5GY 6/1) 20%; wavy-bedded, non-calcareous.
127.7-128.0	0.3	Shale, grayish black (N2) to black (N1), finely laminated bituminous, fissile; interlaminated with shale, dark greenish gray (5GY 4/1), argillaceous.
128.0-129.0	1.0	Shale, dark greenish gray (5GY 4/1-5G 4/1), argillaceous, finely laminated; shale grayish-black (N2) to greenish-black (5G 2/1) to black (N1), silty, finely laminated, glauconitic.
		Ohio Shale
129.0-142.0	13.0	Shale, black (N1), finely laminated, bituminous, fissile, occasional Lingula, pyrite common.



CORE #1, 17—Y—74 LEWIS COUNTY, KY.


MISSISSIPPIAN
BEDFORD
SHALE
LITHOLOGY
P
FEET
50
60
70
80
90
SCIN. PROFILE
45
CPS
60
GAMMA RAY LOG

CORE # 1, CONTD.


MISS.
?
DEVONIAN
BEDFORD
SHALE
OHIO SHALE
LITHOLOGY
FEET
100
110
120
SCIN. PROFILE
45
60
CPS
GAMMA RAY LOG

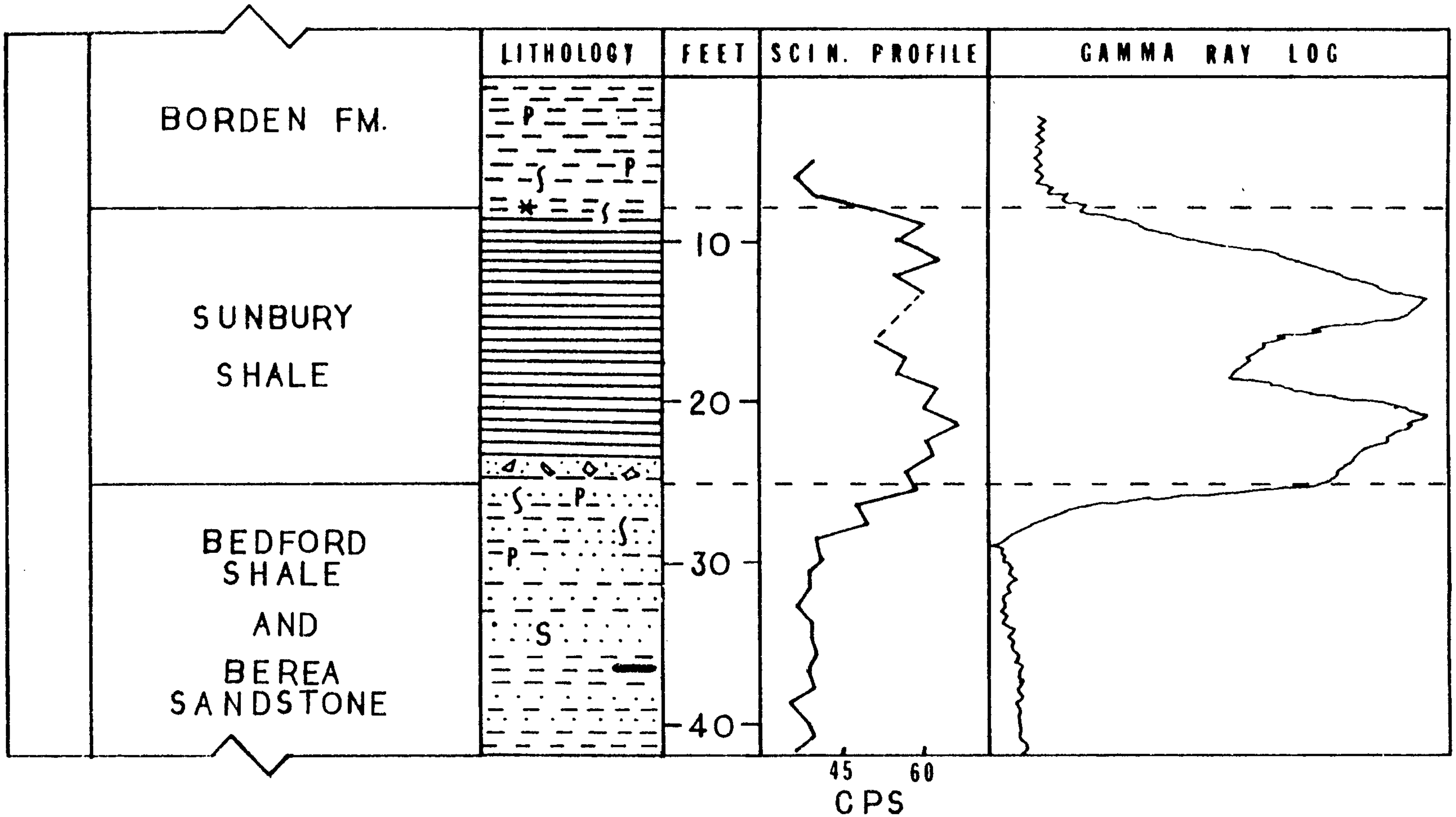
CORE #1, CONTD.

Core #2 (IMMR Core Kep #3)
2-W-73, 3250' FSL x 1150' FEL
Stricklett Quadrangle, Lewis County, KY
Elevation 932 Background Rad. 35 cps.

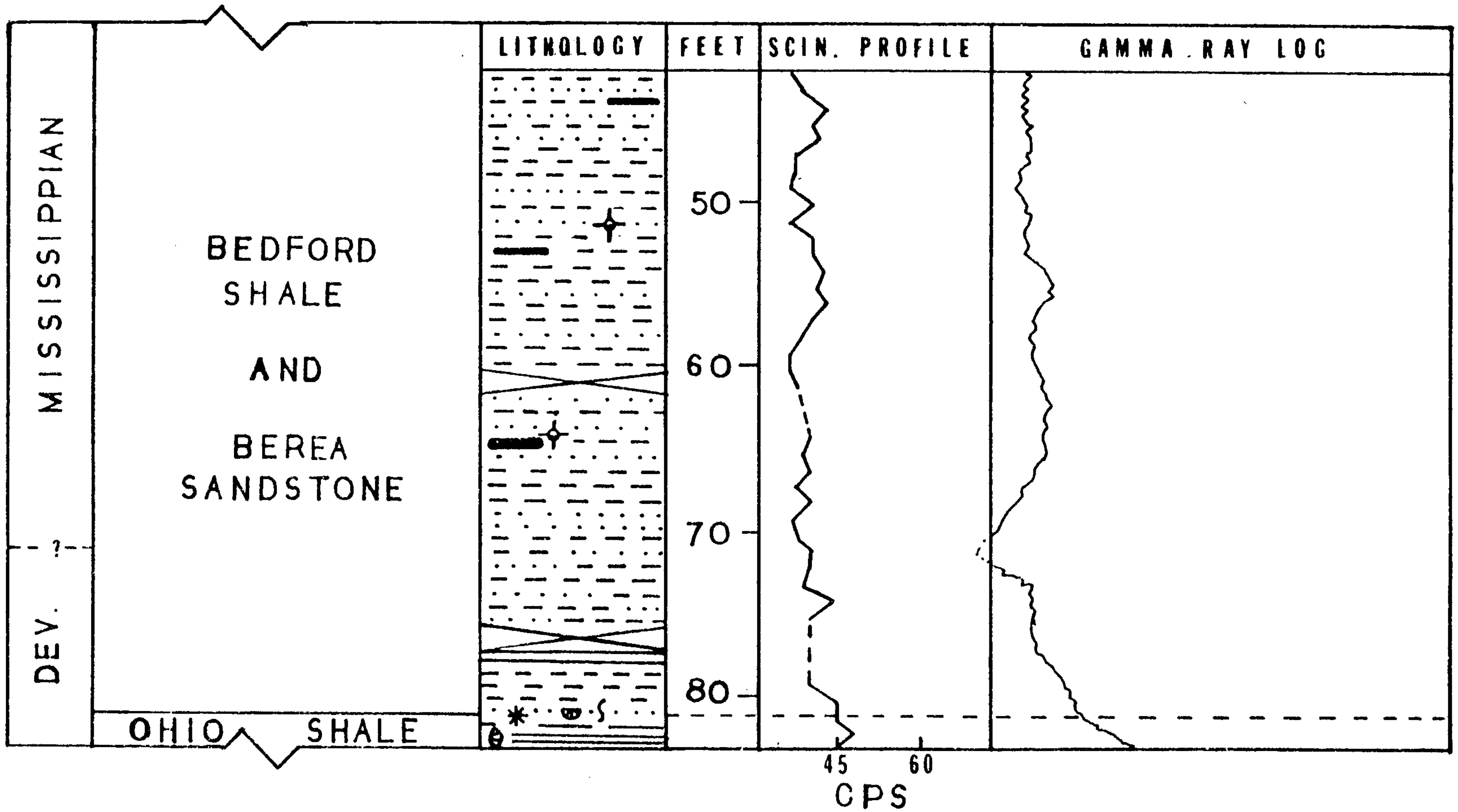
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
43.0-51.0	8.0	Shale, medium dark gray (N4) to dark gray (N3), occasional pyrite granules.
51.0-51.6	0.6	Shale, greenish gray (5GY 5/1) dry, glauconite grains in lowest 2-3 inches.
		Sunbury Shale
51.6-57.0	5.4	Shale, black (N1), finely laminated, bituminous, fissile, occasional pyrite laminae, blebs flattened parallel to bedding; rare green shale burrows and/or blebs extend down two feet from the upper contact.
57.0-59.0	2.0	Sample Removed.
59.0-68.4	9.4	Shale, as above; good lag zone at 67.9 contains Lingula, Orbiculoidae, fish fragments.
		Bedford and Berea
68.4-69.2	0.8	Siltstone, medium bluish gray (5B 5/1) to greenish gray (5G 6/1), argillaceous, calcareous at bottom; pyritic, micaceous.
69.2-81.0	11.8	Siltstone, medium light gray (N6), dry, to greenish gray (5GY 6/1), wet, 60% planar and wavy laminated and bedded, with most beds <.05' thick; some graded-bedding; calcareous to non-calcareous; occasional pyrite laminae and nodules; Shale, dark greenish gray (5GY 4/1) wet, 40%, silty, laminae usually less than .03' thick; planar to wavy laminated; bioturbated, sphalerite occupies center of pyrite nodule at 78.8.
81.0-91.0	10.0	Siltstone and shale, as above, in equal amounts; micro cross-lamination in siltstone; rare siderite bands.

Core #2, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford and Berea cont'd.
91.0-103.7	12.7	Shale, as above, approx. 70%; rare siderite bands or nodules; siltstone, as above, approx. 30%; occasionally oil-stained.
103.7-105.7	2.0	Sample Missing.
105.7-111.0	5.3	Shale, as above, 50%; occasional siderite bands or nodules; siltstone, as above, 50%; oil stained.
111.0-111.3	0.3	Shale and siltstone, as above; rare thin black shale laminae; grades to siltstone below.
111.3-112.3	1.0	Siltstone, light olive gray (5Y 6/1) oil stained, medium gray (N5) where not stained; contorted bedding 111.3-111.5; planar-bedded and finely laminated 111.5-112.3.
112.3-113.7	1.4	Siltstone, medium gray (N5), oil stained at bottom to light olive gray (5Y 6/1); planar-bedded and finely laminated.
113.7-119.0	5.3	Siltstone, medium gray (N5) interbedded and interlaminated with shale, dark greenish gray (5GY 4/1), fine, wavy laminated.
119.0-121.0	2.0	Sample Missing.
121.0-121.3	0.2	Shale, dark greenish gray (5GY 4/1) and black (N1), finely laminated.
121.3-121.8	0.5	Shale, black (N1), finely laminated, bituminous, fissile; glauconite green shale lamina at 121.6 contains *Lingula*.
121.8-123.2	1.4	Shale, dark greenish gray (5GY 4/1) some widely contorted bedding, some planar lamination.
123.2-123.6	0.4	Siltstone, dark greenish gray (5GY 4/1); burrowed, glauconitic at basal contact; contains few articulate brachiopods.
		Ohio Shale
123.6-		Shale, black (N1), finely laminated, bituminous, fissile, *Lingula* near upper contact.



CORE #2, 2-W-73 LEWIS COUNTY, KY.


MISSISSIPPIAN
?
DEV.
BEDFORD
SHALE
AND
BEREA
SANDSTONE
OHIO SHALE
LITHOLOGY
FEET
50
60
70
80
SCIN. PROFILE
45
60
CPS
GAMMA RAY LOG

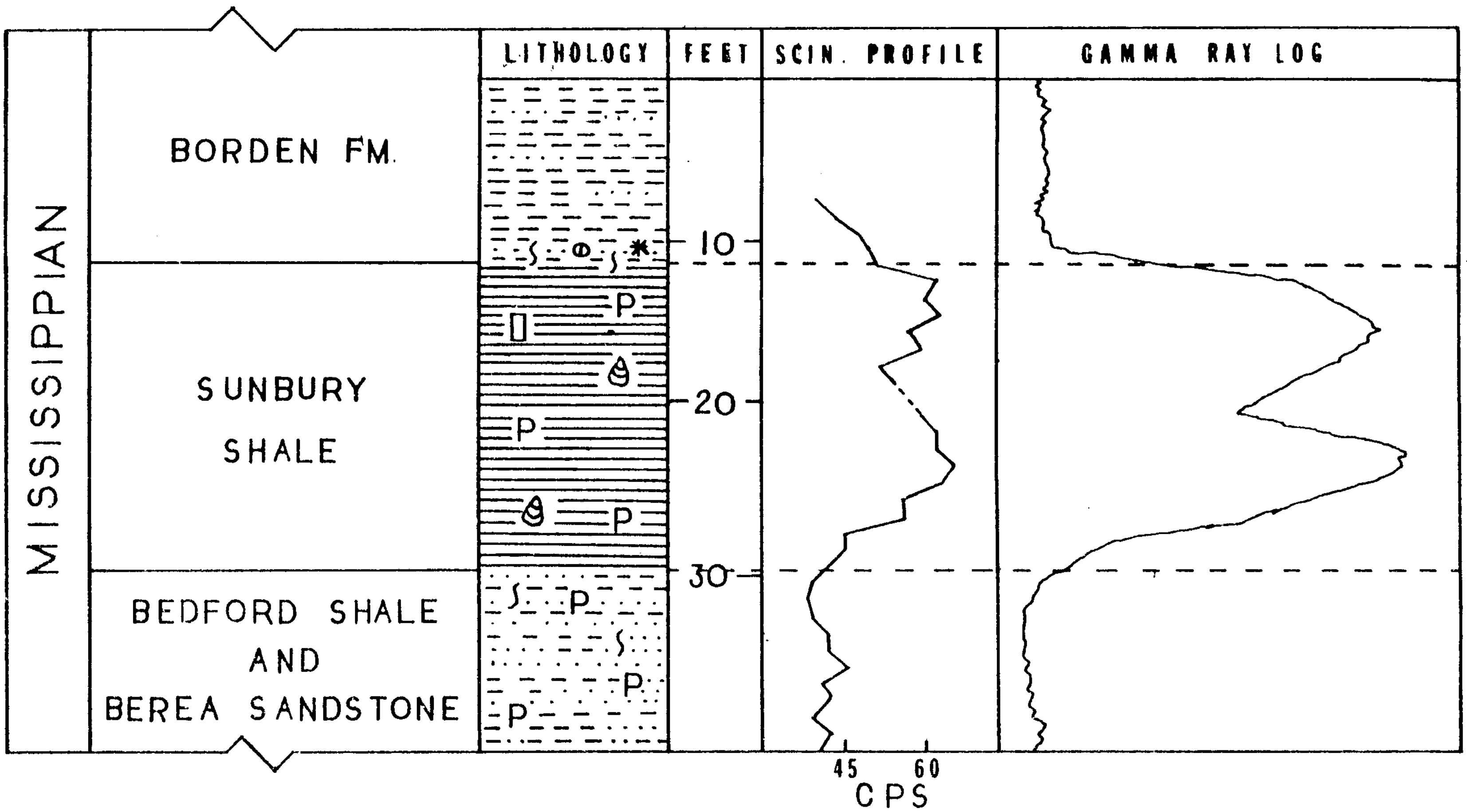
CORE # 2, CONTD.

Core #3 (IMMR Core Kep #4)
3-W-72, 2900' FSL x 1600' FEL
Burtonville Quadrangle, Fleming County, KY
Elevation 1088 Background Rad. 38 cps.

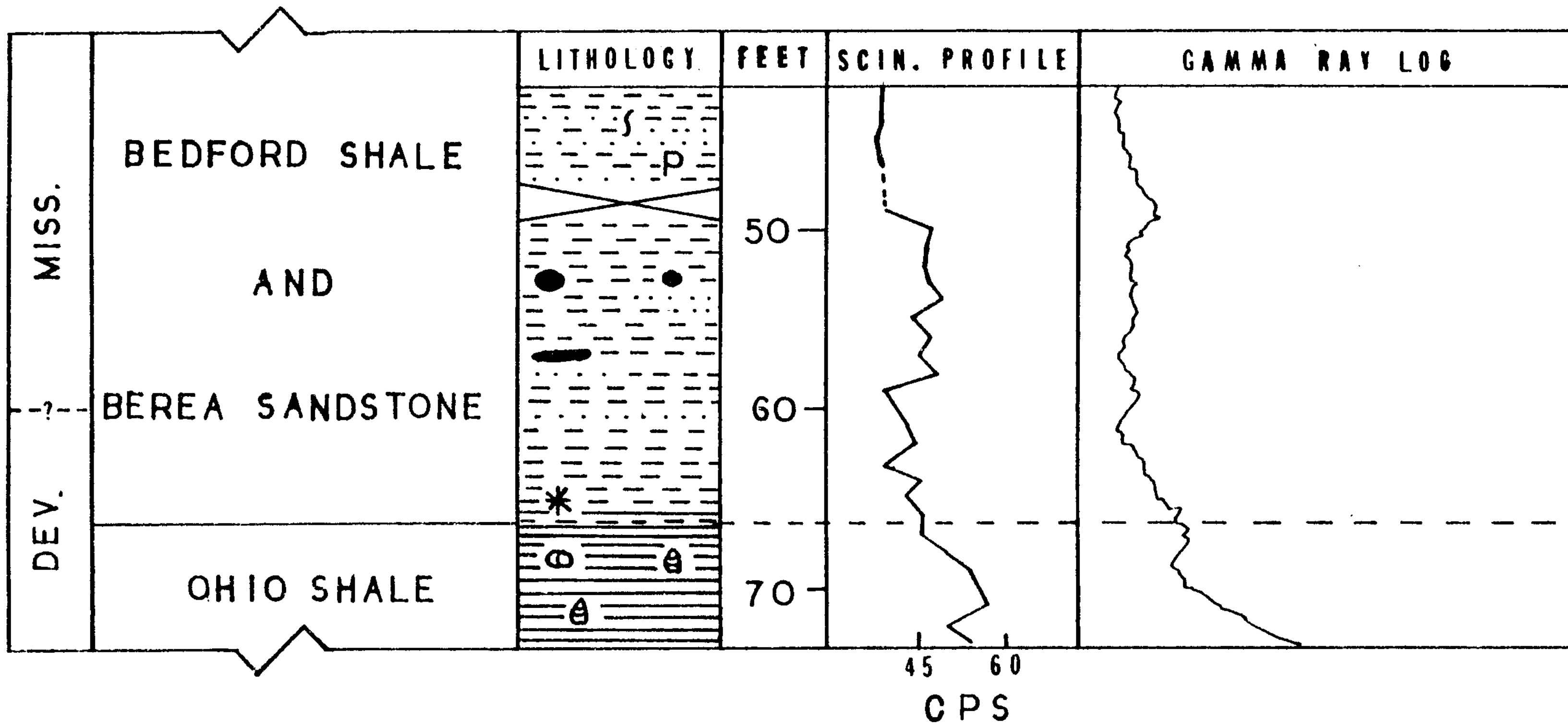
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
54.2-62.0	7.8	Shale, medium gray (N5), silt laminae a few mm thick.
62.0-64.2	2.2	Shale, medium olive gray (5Y 5/1) to medium dark gray (N4).
64.2-64.5	0.3	Shale, dark greenish gray (5G 4/1), occasional glauconite grains.
64.5-65.0	0.5	Siltstone, dark greenish gray (5G 4/1), argillaceous, occasional glauconite grains; phosphatic nodule.
65.0-65.3	0.3	Shale, dark greenish gray (5G 4/1), bioturbated, occasional glauconite grains.
		Sunbury Shale
65.3-83.8	18.5	Shale, black (N1) to olive black (5Y 2/1) in basal foot, finely laminated, bituminous, bioturbated green shale in uppermost two inches; fissile, occasional Lingula fragments; vitrinite bands with rare plant fossils; pyrite blebs and laminae common; fracture surfaces bear hydrous iron minerals.
		Bedford and Berea
83.8-93.0	9.2	Siltstone, medium light gray (N6), 60%, wavy laminated and cross-laminated, discontinuous; rarely calcareous; shale, medium dark gray (N4), 40%, burrowed (some pyrite); abundant pyrite; rare hydrous iron minerals.
93.0-100.0	7.0	Shale, as above, 50-70%; siltstone, as above 30-50%.
100.0-102.0	2.0	No Sample.

Core #3, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford and Berea Shale cont'd.
102.0-112.0	10.0	Shale, as above, 80-90%; siltstone, as above, 10-20%, in laminae less than 3 mm thick; fine dark gray shale laminae; occasional siderite bands or nodules; no pyrite.
112.0-113.7	1.7	Shale, as above; dark gray shale laminae nore numerous.
113.7-114.3	0.6	Siltstone, medium olive gray (5Y 5/1) to medium gray (N5), argillaceous, wavy-bedded, non-calcareous, micaceous.
114.3-121.1	6.8	Shale, medium dark gray (N4), fine dark gray shale laminae increase thickness in lowest 1.7 feet to beds; rarely glauconitic.
		Ohio Shale
121.1-127.5	6.4	Shale, brownish black (5YR 2/1) to black (N1), finely laminated, bituminous, fissile, *Lingula* common; occasional medium gray phosphate nodules appear to displace shale laminae (possibly due to compaction?); greenish gray shale laminae in uppermost 2 feet.



CORE # 3, 3-W-72 FLEMING COUNTY, KY.


LITHOLOGY
FEET
SCIN. PROFILE
GAMMA RAY LOG
MISS.
?
DEV.
BEDFORD SHALE
AND
BEREA SANDSTONE
OHIO SHALE
50
60
70
45
60
CPS

CORE # 3, CONTD.

Core #4 (IMMR Core Kep #6)
21-W-71, 5400' FSL x 225' FEL
Plummers Landing Quadrangle, Fleming County, KY
Elevation 1100 Backround Rad. 41 cps

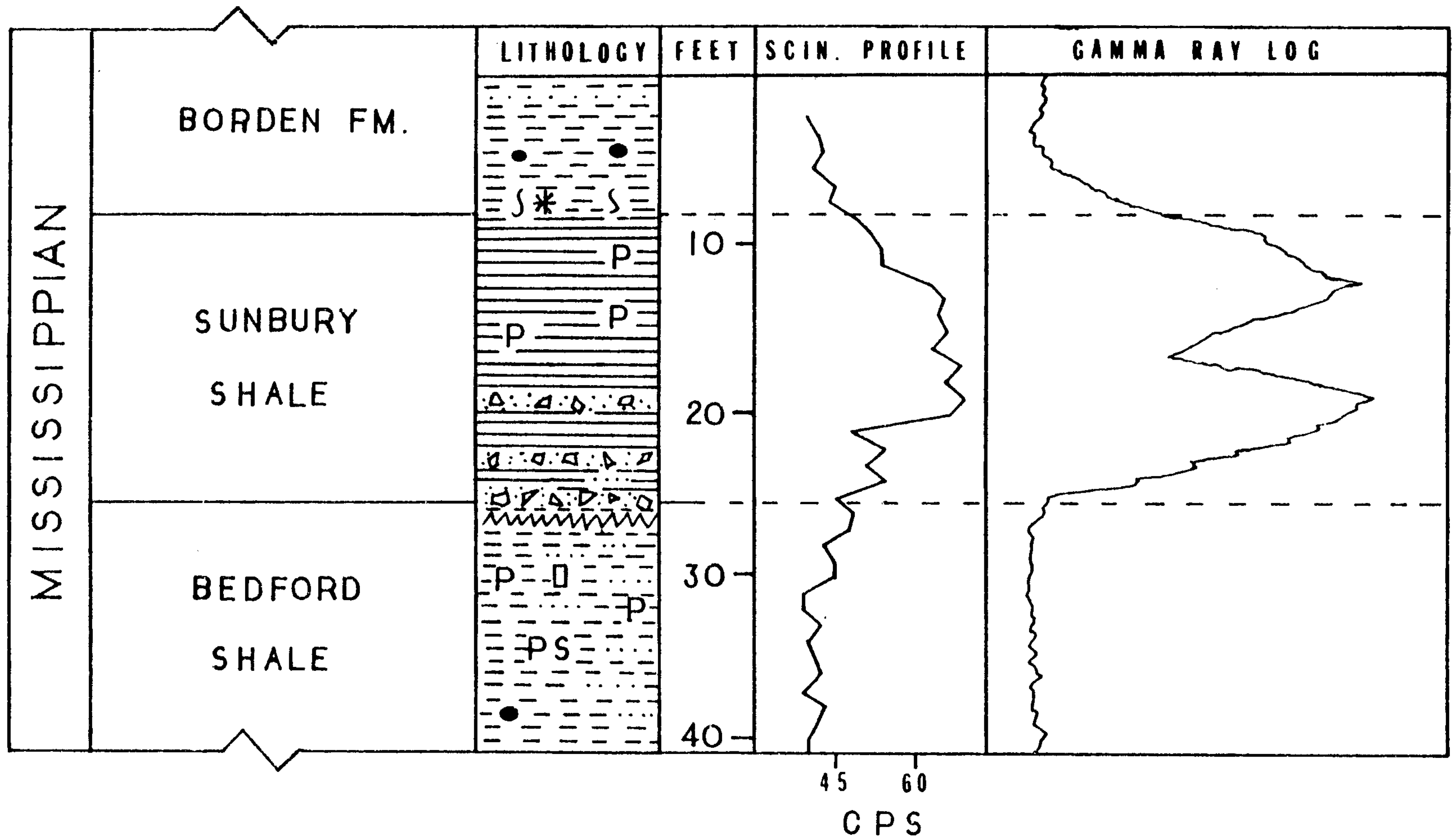
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
		Shale, medium dark gray (N5) to greenish gray (5G 5/1) dry.
19.6-19.9	0.3	Siltstone, medium gray (N5), bioturbated, non-calcareous.
19.9-27.0	7.1	Shale, medium dark gray (N5) to greenish gray (5G 5/1) dry, bioturbated, glauconite grains in burrows in lowest 3-4 inches; occasional siderite bands or nodules.
		Sunbury Shale
27.0-41.9	14.9	Shale, black (N1) to grayish black (N2), silty, finely laminated, bituminous, fissile, fossils in silty lag zone at 38.1 include conodonts, fish fragments; lag zone at 41.9 contains Lingula, conodonts, possible Orbiculoidea; pyrite common in grains, nodules, laminae.
41.9-43.9	2.0	Shale, black (N1), with more non-calcareous silt laminae; occasional fossils include Lingula, Orbiculoidea, conodonts, fish fragments.
43.9-44.0	0.1	Shale, olive gray (5Y 3/2) dry, abundant fossil fragments in silty lag zone; phosphate nodule at base.
44.0-44.5	0.5	Shale, black (N1), finely laminated, bituminous, fissile, three silty lag zones contain Lingula, Orbiculoidea, conodonts, fish fragments.
		Bedford Shale
44.5-44.7	0.2	Shale, grayish green (10GY 5/2) to dark greenish gray (5C 4/1), 70%; organic (plant)? fragments common; abundant granular and nodular pyrite; siltstone, medium light gray (N6), wavy-interlamimated with shale; calcareous to non-calcareous; abundant pyrite.

Core #4, Continued

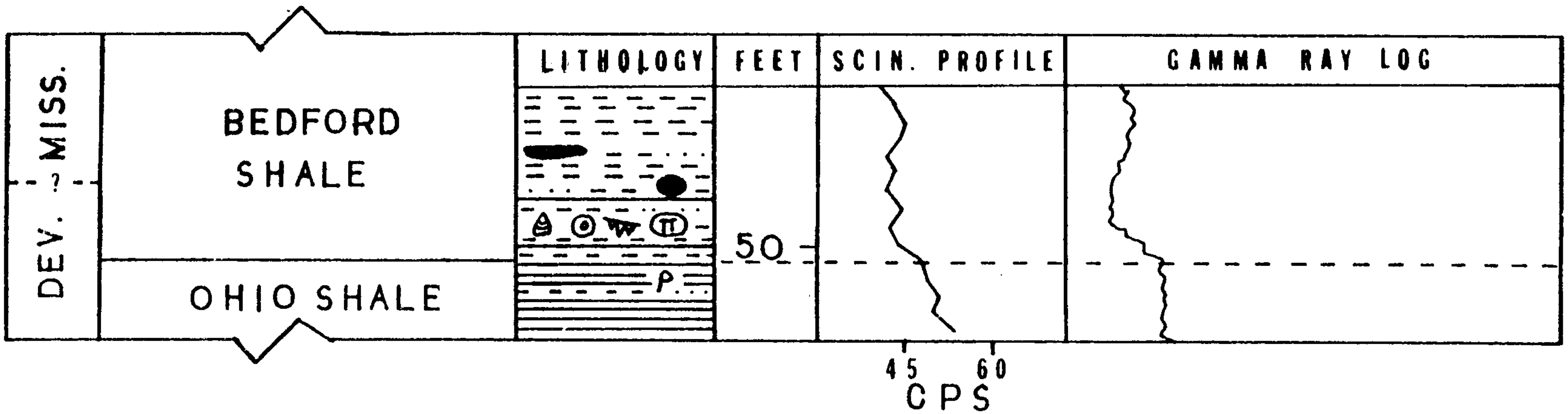
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
44.7-44.8	0.1	Limestone, medium light gray (N6); cone-in-cone.
44.8-51.0	6.2	Shale, grayish green (10GY 5/2) to dark greenish gray (5G 4/1), 70%; organic (plant)? fragments common; pyrite common; siltstone, medium light gray (N6) 30%; wavy-laminated, calcareous to non-calcareous, abundant granular and nodular pyrite.
51.0-61.0	10.0	Shale and siltstone, as above; siltstone less than 20%; pyrite locally abundant; pyrite nodule at 52.3 surrounds sphalerite; siderite bands or nodules, light olive gray (5Y 5/2) at 56.4, 60.4.
61.0-68.1	7.1	Shale and siltstone, as above; siltstone less than 10%; pyrite less common; siderite more common in 1/2 inch to 1 inch bands or nodules.
68.1-68.2	0.1	Shale, brownish black (5YR 2/1), finely laminated, bituminous, fissile.
68.2-70.6	2.4	Shale, dark greenish gray (5G 4/1); silty, finely laminated; silty lag zones contain Lingula, Orbiculoidea, conodonts, fish fragments.
70.6-70.9	0.3	Shale, brownish-black (5YR 2/1), finely laminated, fissile, bituminous.
70.9-71.2	0.3	Shale, dark greenish gray (5G 4/1), finely interlaminated with shale, black (N1).
		Ohio Shale
71.2-72.6	1.4	Shale, brownish black (5YR 2/1) to black (N1), finely laminated, bituminous, fissile, locally pyritic.
72.6-72.7	0.1	Shale, greenish gray (5GY 5/1); silty, planar top contact, irregular lower contact.
72.7-75.7	3.0	Shale, brownish-black (5YR 2/1) to black (N1), finely laminated, bituminous, fissile.

Core #4, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Ohio Shale cont'd.
72.7-75.7	3.0	Shale, brownish-black (5YR 2/1) to black (N1), finely laminated, bituminous, fissile.



CORE #4, 21-W-71 FLEMING COUNTY, KY.


MISS.
?
DEV.
BEDFORD SHALE
OHIO SHALE
LITHOLOGY
FEET
SCIN. PROFILE
GAMMA RAY LOG
50
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45
60
CPS

CORE #4, CONTD.

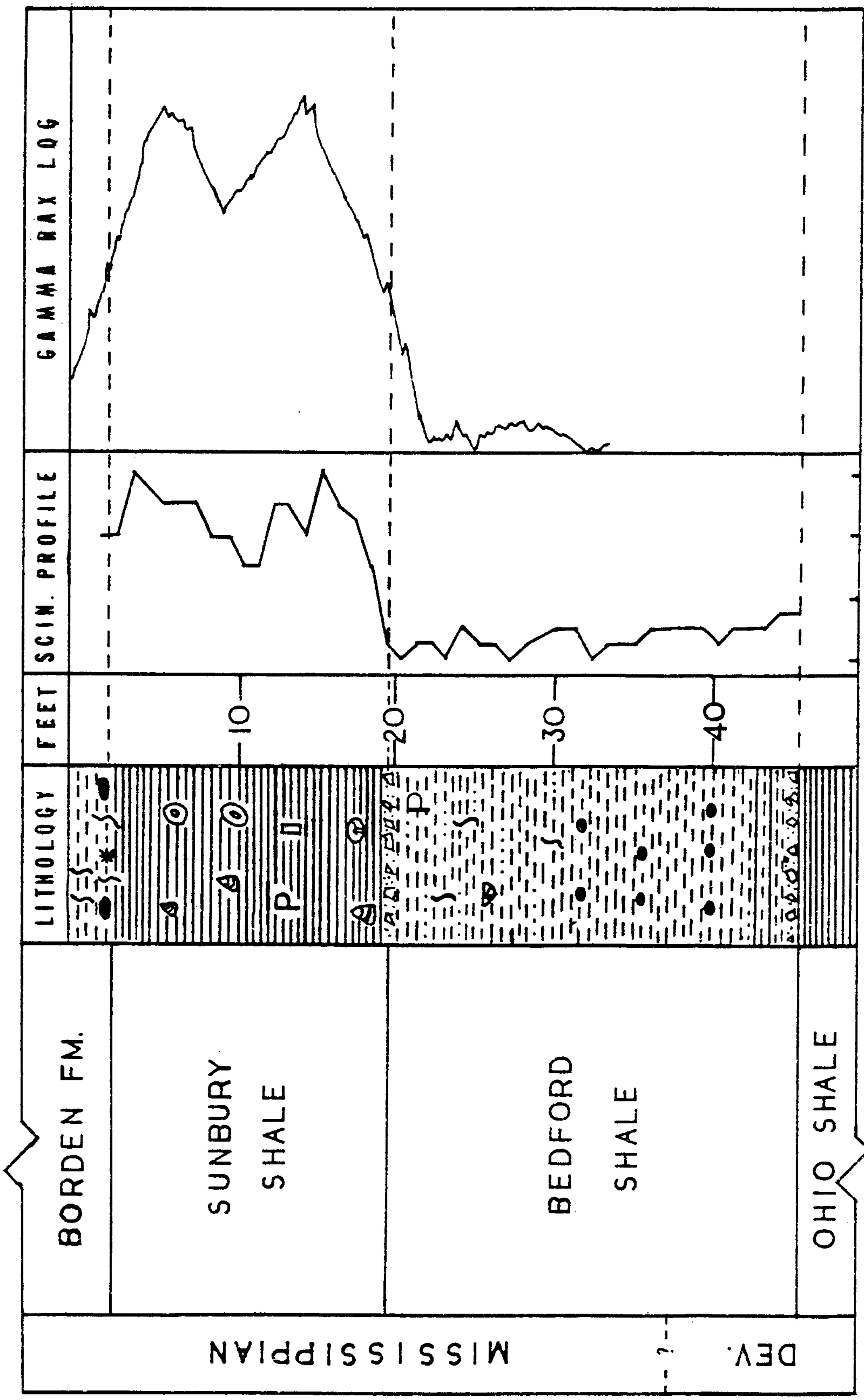
Core #5, (Core UA-4, SW corner of V-72)

Maxey Flats, Fleming County, KY
Elevation approx. 900' Background Rad. 35 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm. (Henley Bed)
80.0-82.7	2.7	Shale, greenish gray (5G 6/1), bioturbated, siderite nodules, glauconite at base (sometimes filling burrows).
		Sunbury Shale
82.7-84.6	1.9	Shale, grayish black (N2), dry, finely laminated, occasionally bioturbated, bituminous, fissile, occasional pyrite grains.
84.6-85.2	0.6	Sample Missing.
85.2-85.4	0.2	Shale, as above, with framboidal pyrite.
85.4-86.4	1.0	Sample Missing.
86.4-100.4	14.0	Shale, as above; fossils occasional to locally abundant in silty lag zones, including Lingula, Orbiculoidea, fish scales; vitrinite laminae associated with plant cast and mold; subtle color changes from black to greenish tint occur 86'-92'.
		Bedford Shale
100.4-111.8	11.4	Shale, dark greenish gray (5GY 4/1), bioturbated, rare articulate brachiopods; brown plant matter common; granular and nodular pyrite common; siltstone, medium gray (N5); wavy to irregularly-laminated, bioturbated, rarely calcareous, nodular pyrite common.
111.8-123.0	11.2	Shale, as above; siltstone laminae, as above, decrease in number and thickness; siderite bands common up to 1 inch thick; pyrite nodules, sometimes oxidized, decrease downward.
123.0-125.2	2.2	Shale, as above; interlaminated with black shale; laminae highly contorted; siltstone laminae rare.

Core #5, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
125.2-126.0	0.8	Shale, black (N1), finely laminated, bituminous, fissile, interlaminated with sparse argillaceous green shale, gently contorted.
126.0-126.6	0.6	Shale, dark greenish gray (5GY 4/1), indistinct bedding, lag zone with *Lingula* at 126.3
		Ohio Shale
126.6-130.0	3.4	Shale, black (N1), finely laminated, bituminous, fissile, pyrite common.



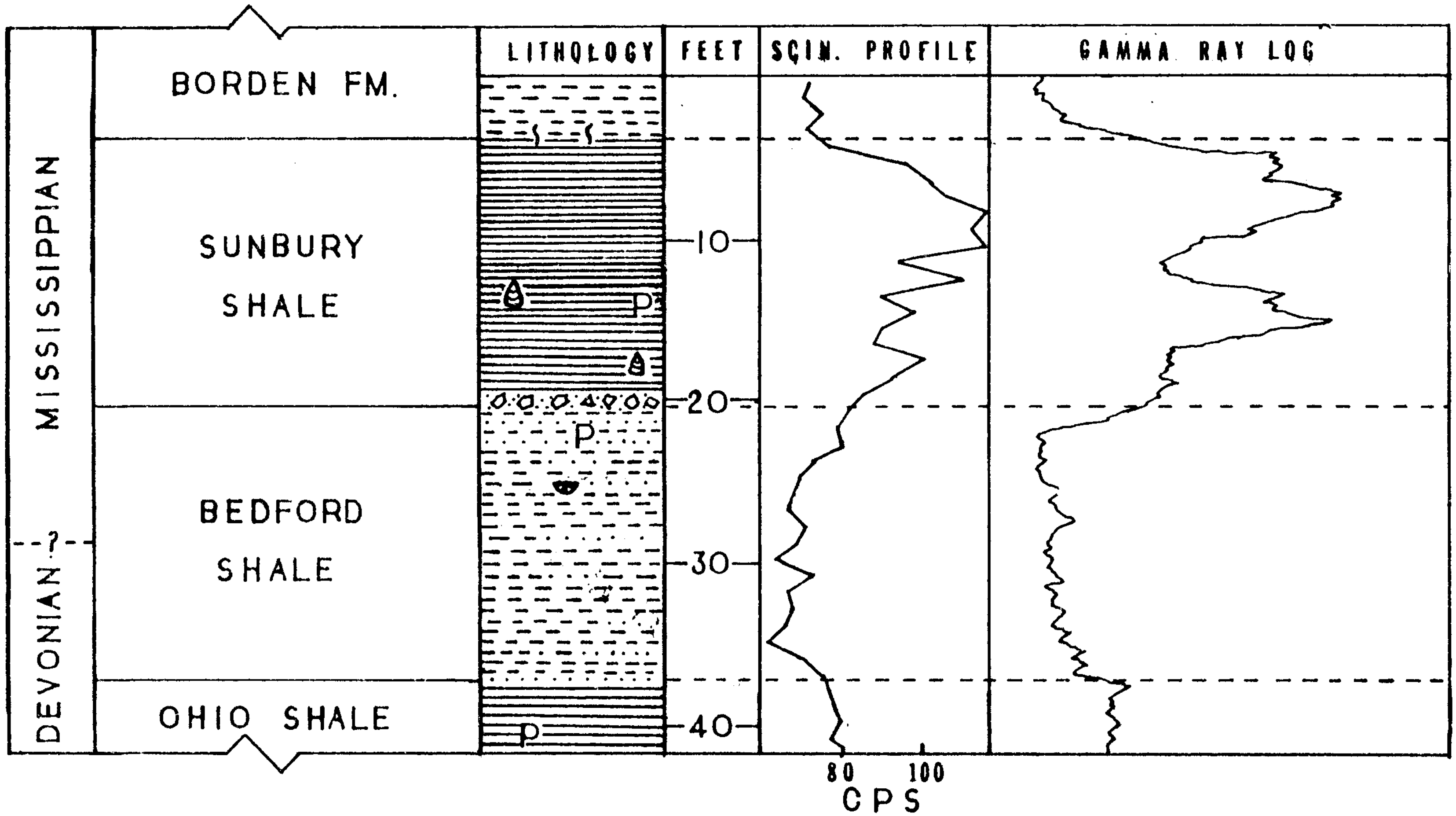
CORE #5, 24-V-72 FLEMING COUNTY, KY.

Core #6 (IMMR Core D-11)
15-U-72, 5200' FSL x 2750' FEL
Farmers Quadrangle, Rowan County, KY
Elevation 985' Full Core Background Rad. 56 cps

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm. (Henley Bed)
51.5-53.8	2.3	Shale, greenish gray (5G 6/1 to 5GY 6/1).
53.8-54.3	0.5	Shale, medium dark gray (N4).
54.3-55.5	1.2	Shale, greenish gray (5G 6/1 to 5GY 6/1), bioturbated.
		Sunbury Shale
55.5-55.6	0.1	Shale, dark gray (N3) and medium dark gray (N4) dry, to grayish black (N2) wet, finely laminated, sub-horizontal green shale burrows; bituminous.
55.6-55.9	0.3	Shale, dark gray (N3) to medium dark gray (N4), dry to grayish black (N2) wet; finely laminated, bituminous.
55.9-72.0	16.1	Shale, black (N1) to brownish black (5YR 2/1), finely laminated, bituminous, fissile, rare *Lingula*, fish fragments, lag zone containing *Lingula*, *Orbiculoidea*, conodonts, fish scales and bone fragments in lowest few mm; granular, nodular, and laminated pyrite is common
		Bedford Shale
72.0-72.2	0.2	Siltstone, greenish gray (5G 6/1) dry, to dark greenish gray (5G 4/1) wet, fine-grained, bioturbated, non-calcareous, hydrous iron minerals at contact.
72.2-73.1	0.9	Shale, greenish gray (5G 6/1) dry, to dark greenish gray (5G 4/1) wet, locally silty, wavy-bedded, interlaminated with siltstone, light gray (N7), locally calcareous; pyrite granules appear to displace silts and shales.
73.1-73.9	0.8	Shale, greenish-gray (5G 6/1) dry, dark greenish gray (5G 4/1) wet, silty, pyritized brachiopods (*Chonetes*?) at 73.9.

Core #6, Continued

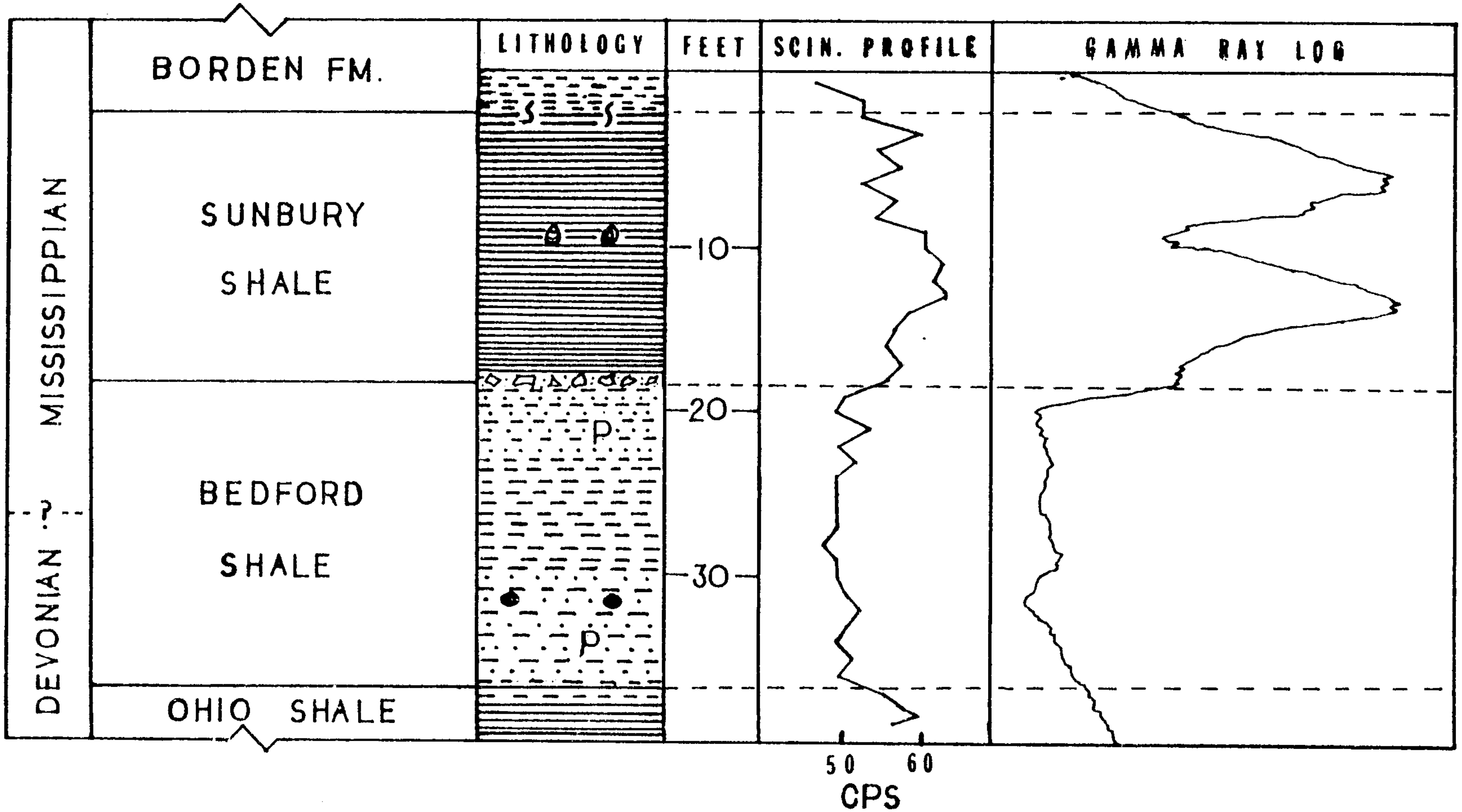
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
73.9-77.0	3.1	Shale, greenish gray (5G 6/1) dry to dark greenish gray (5G 4/1), with calcareous silt stringers; slightly wavy-bedded; occasional pyrite granules.
77.0-86.6	9.6	Shale, greenish gray (5G 6/1) dry, dark greenish gray (5G 4/1), with fewer calcareous silts stringers; slightly wavy-bedded.
86.6-86.7	0.1	Siltstone, light greenish gray (5GY 4/1), fine-grained.
86.7-87.3	0.6	Shale, greenish gray (5G 6/1) dry, dark greenish gray (5G 4/1), with few calcareous silt stringers; slightly wavy-bedded.
87.3-88.1	0.8	Shale, greenish gray (5G 6/1) dry, dark greenish gray, dark gray and brownish black, finely laminated, pyrite granules.
88.1-88.9	0.8	Siltstone, greenish gray (5G 6/1) to dark greenish gray (5GY 4/1), fine to medium-grained; indistinct bedding (burrowed?), non-calcareous, thin green clay shale at base.
		Ohio Shale
88.9-93.5	4.6	Shale, brownish-black (5YR 2/1) to black (N1), finely laminated, bituminous, fissile, occasional pyrite grains.



CORE #6, 15-U-72 ROWAN COUNTY, KY.

Core #7 (IMMR Core D-1)
25-U-72, 3150' FSL x 525' FEL
Farmers Quadrangle, Rowan County, KY
Elevation 924'   Background Rad. 45 cps.

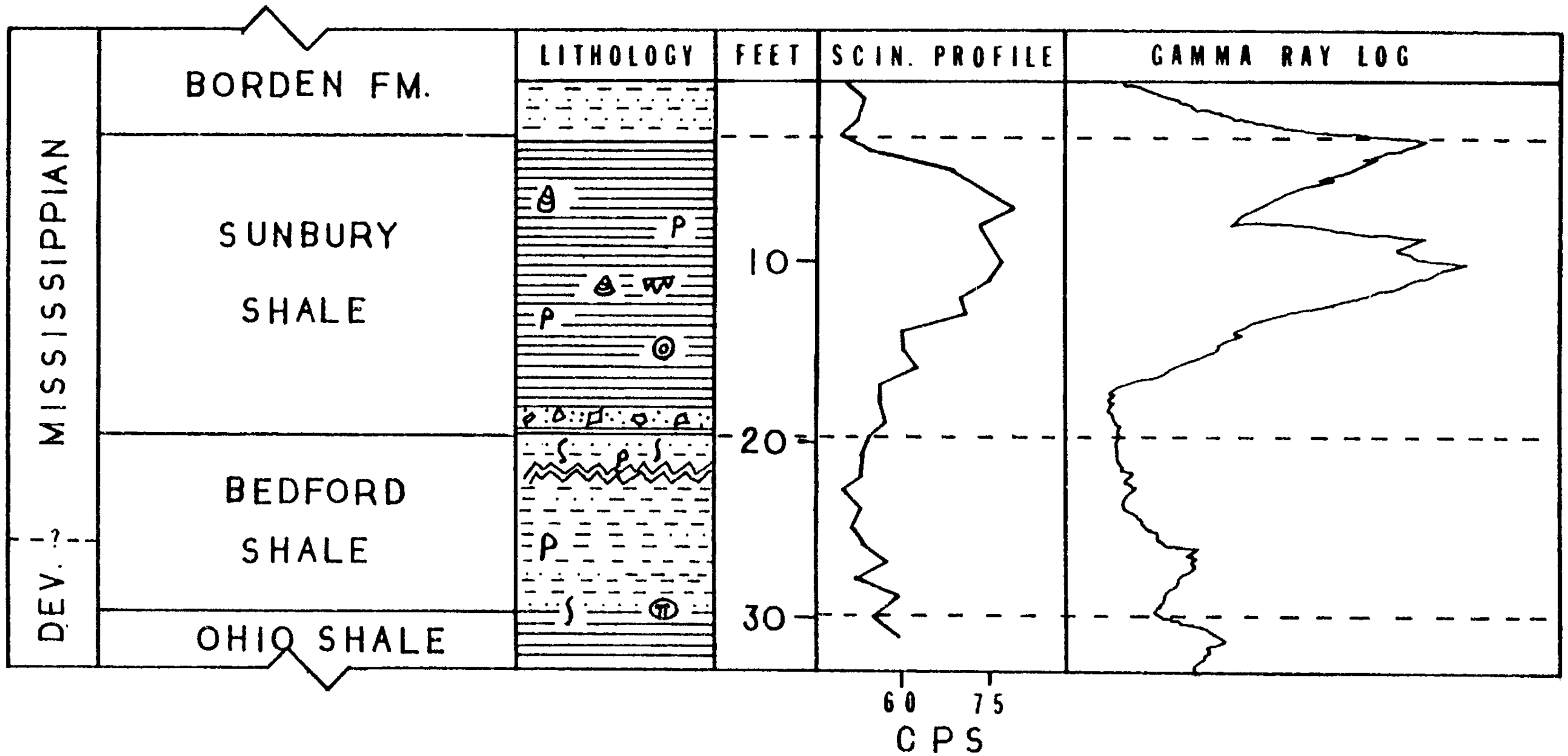
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm. (Henley Bed)
50.0-52.1	2.1	Shale, grayish olive green (5GY 3/2) to greenish-black (5GY 2/1) near base, bioturbated, glauconitic in basal few inches.
		Sunbury Shale
52.1-68.7	16.7	Shale, black (N1) finely laminated, bituminous, green shale burrows in uppermost few inches; fissile, minor lag zone with *Lingula*, *Orbiculoidea* at 59.7; ocasional disseminated pyrite.
68.7		Good lag zone containing *Lingula*, *Orbiculoidea*, fish fragments, conodonts.
		Bedford Shale
68.7-73.0	4.3	Shale, dark greenish gray (5G 4/1) interlaminated with siltstone, light gray (N7), rarely calcareous, pyrite common.
73.0-80.0	7.0	Shale, as above; siltstone as above, laminae increase in size and number.
80.0-87.0	7.0	Shale, dark greenish gray (5G 4/1) to greenish black (5GY 2/1), with occasional siderite nodules; siltstone, as above; laminae increase in size and number.
		Ohio Shale
87.0-87.3	0.2	Shale, black (N1), finely laminated, earthy, bituminous, fissile.
87.3-87.5	0.2	Shale, grayish olive green (5GY 3/2) clayey.
87.5-		Shale, black (N1), finely laminated, earthy, bituminous, fissile.



CORE #7, 25-U-72. ROWAN COUNTY, KY.

Core #8 (IMMR Core D-2)
14-T-71, 1500' FSL x 1550' FEL
Olympia Quadrangle, Bath County, KY
Elevation 758' Background Rad. 46 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
22.5-25.5	3.0	Siltstone, medium gray (N5), medium-grained well-sorted, interbedded with shale, greenish gray (5GY 4/1) weathered.
		Sunbury Shale
25.5-40.2	14.7	Shale, black (N1) to grayish-black (N2), finely laminated, earthy, bituminous, fissile, occasional *Lingula*, *Orbiculoidae*, conodonts, fish fragments; good lag zone at 39.5; occasional framboidal and rare bedded pyrite.
		Bedford Shale
40.2-40.4	0.2	Siltstone, fine to medium grained, greenish-gray (5G 6/1) to dark greenish gray (5G 4/1), mottled, bioturbated, burrows occasionally pyrite-filled.
40.4-40.6	0.2	Shale, dark greenish gray (5G 4/1).
40.6-40.7	0.1	Limestone, light gray (N7) cone-in-cone.
40.7-48.8	8.1	Shale, dark greenish gray (5G 4/1), clayey and silty, occasional calcareous silt laminae, wavy-bedded, occasional granular pyrite.
48.8-50.0	1.2	Siltstone grayish olive green (5GY 3/2), fine-grained, bioturbated, common fish fragments near bottom.
		Ohio Shale
50.0-53.0	3.0	Shale, black (N1), finely laminated, earthy, bituminous, fissile.



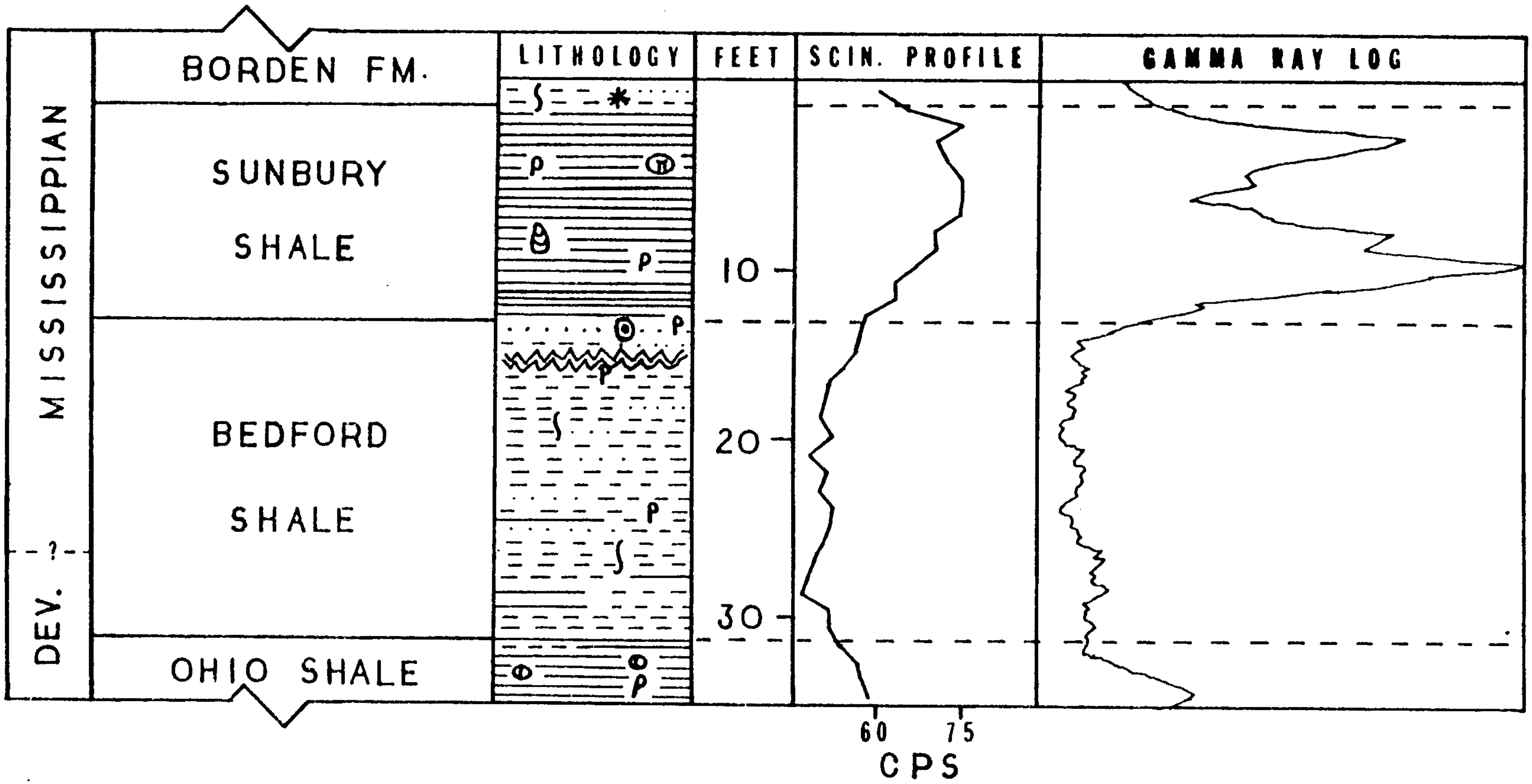
CORE #8, 14-T-71 BATH COUNTY, KY.

Core #9 (IMMR Core D-3)
8-S-71, 2300' FSL x 1200' FEL
Salt Lick Quadrangle, Bath County, KY
Elevation 815' Background Rad. 48 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm. (Henley Bed)
37.0-38.3	1.3	Shale, dark grayish green (5GY 3/2), locally silty, bioturbated, glauconitic; black shale globules in basal few inches.
		Sunbury Shale
38.3-43.0	4.7	Shale, black (N1) to olive black (5Y 2/1), finely laminated, earthy, bituminous, fissile, occasional pyrite.
43.0-50.8	7.8	Shale, as above; fine silty laminae near base, *Lingula*, fish scales at 43.0, 50.0.
		Bedford Shale
50.8-51.2	0.4	Siltstone, greenish gray (5G 6/1) to dark greenish gray (5GY 4/1), bedding indistinct, bioturbated, *Orbiculoidea* at 51.0; bedded pyrite at upper contact, granular pyrite throughout.
51.2-51.3	0.1	Shale, dark greenish gray (5GY 4/1, 5G 4/1) interbedded with siltstone, as above.
51.3-51.5	0.2	Limestone, light bluish gray (5B 7/1) cone-in-cone; minor interbedded shale dark greenish gray shale (5G 4/1).
51.5-54.0	2.5	Shale, dark greenish gray (5GY 4/1, 5G 4/1), framboidal pyrite common.
54.0-64.8	10.8	Shale, as above, with common silt laminae; rare black shale laminae; burrowed locally; pyrite framboids common.
64.8-65.0	0.2	Shale, black (N1).
65.0-67.9	2.9	Shale, dark greenish gray (5GY 4/1), interbedded with shale, black (N1), finely laminated, minor silt laminae.
67.9-68.3	0.4	Shale, as above; minor contorted bedding, micro cross-laminated.

Core #9, Continued

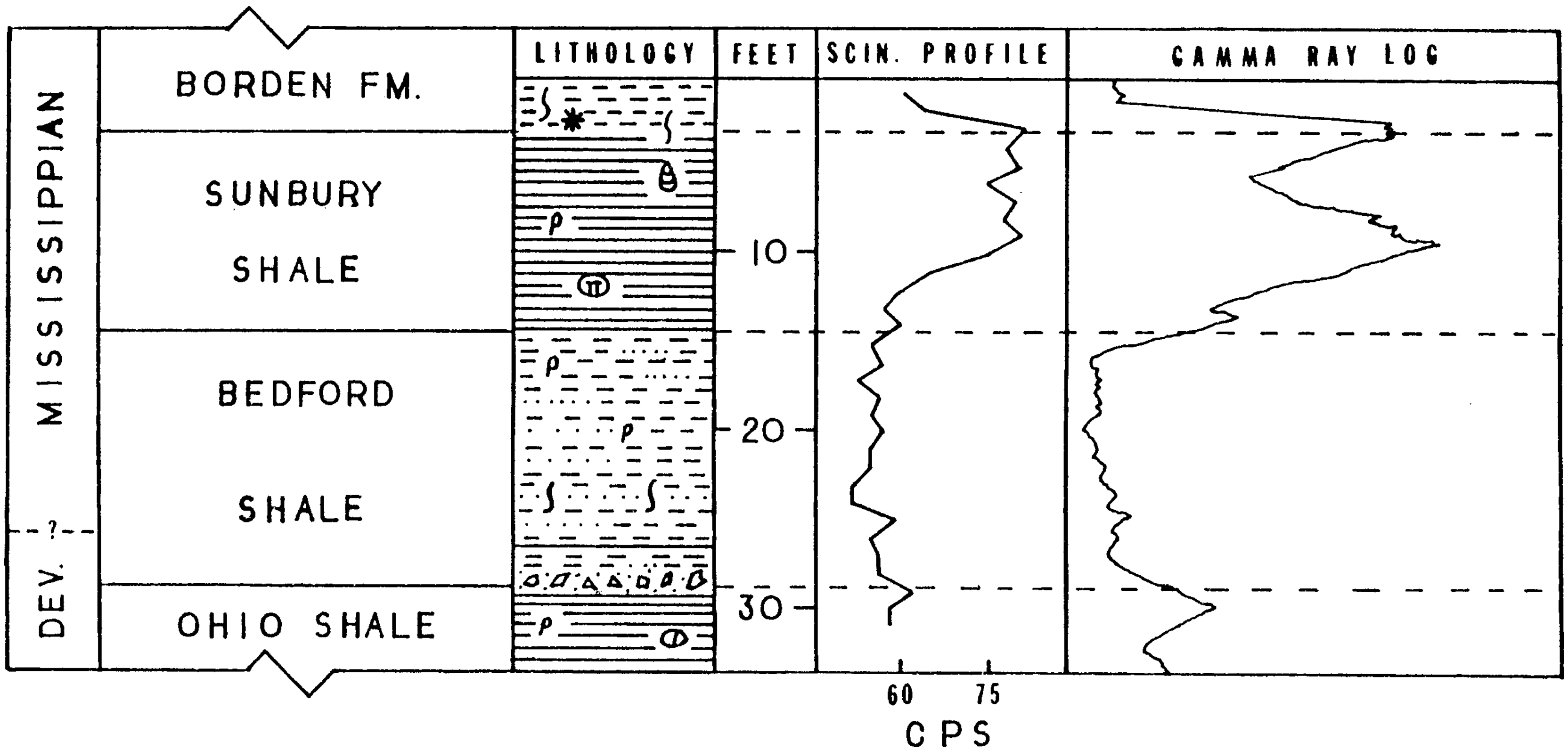
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
68.3-69.9	1.6	Shale, dark greenish gray (5G 4/1), wavy-laminated.
		Ohio Shale
69.9-73.0	3.1	Shale, black (N1), finely laminated, earthy, bituminous, fissile, common phosphatic nodules appear to displace laminations; minor green shale laminae in top most inch; pyritic



CORE #9, 8-S-71 BATH COUNTY, KY.

Core #10 (IMMR Core D-4)
17-S-70, 3775' FSL x 3300' FEL
Olympia Quadrangle, Bath County, KY
Elevation 867' Background Rad. 52 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
34.0-37.0	3.0	Shale, grayish green (10GY 5/2), clayey, burrowed, glauconitic in basal few inches.
		Sunbury Shale
37.0-48.5	11.5	Shale, black (N1), finely laminated, earthy, bituminous, earthy, green shale burrows in uppermost few inches; Lingula and fish scales rare; pyrite rare except for nodular bodies at 42.0.
		Bedford Shale
48.5-57.8	9.3	Shale, olive black (5Y 2/1), occasional thin beds and laminae of silt; micro cross-bedded; pyrite blebs and granules common.
57.8-58.3	0.5	Siltstone, dark greenish gray (5G 4/1), indistinct bedding; bioturbated, rare pyritic burrows; calcareous.
58.3-60.8	2.5	Shale, dark greenish gray (5GY 4/1); siltstone, thin-bedded, displaced by pyrite granules, decreasing downward.
60.8-61.0	0.2	Shale, brownish black (5Y 2/1); green shale blebs parallel to bedding.
61.0-62.5	1.5	Shale, dark greenish gray (5GY 4/1); siltstone, thin-bedded, displaced by pyrite granules, decreasing downward.
62.5-63.4	0.9	Shale, greenish gray (5G 6/1), dark greenish gray (5G 4/1), brownish-black (5Y 2/1), finely laminated, rare silt laminae; lag zone contains Lingula, fish scales at base.
		Ohio Shale
63.4-67.4	4.0	Shale, black (N1), fine laminae displaced by pyrite, phosphate nodules, bituminous, fissile.



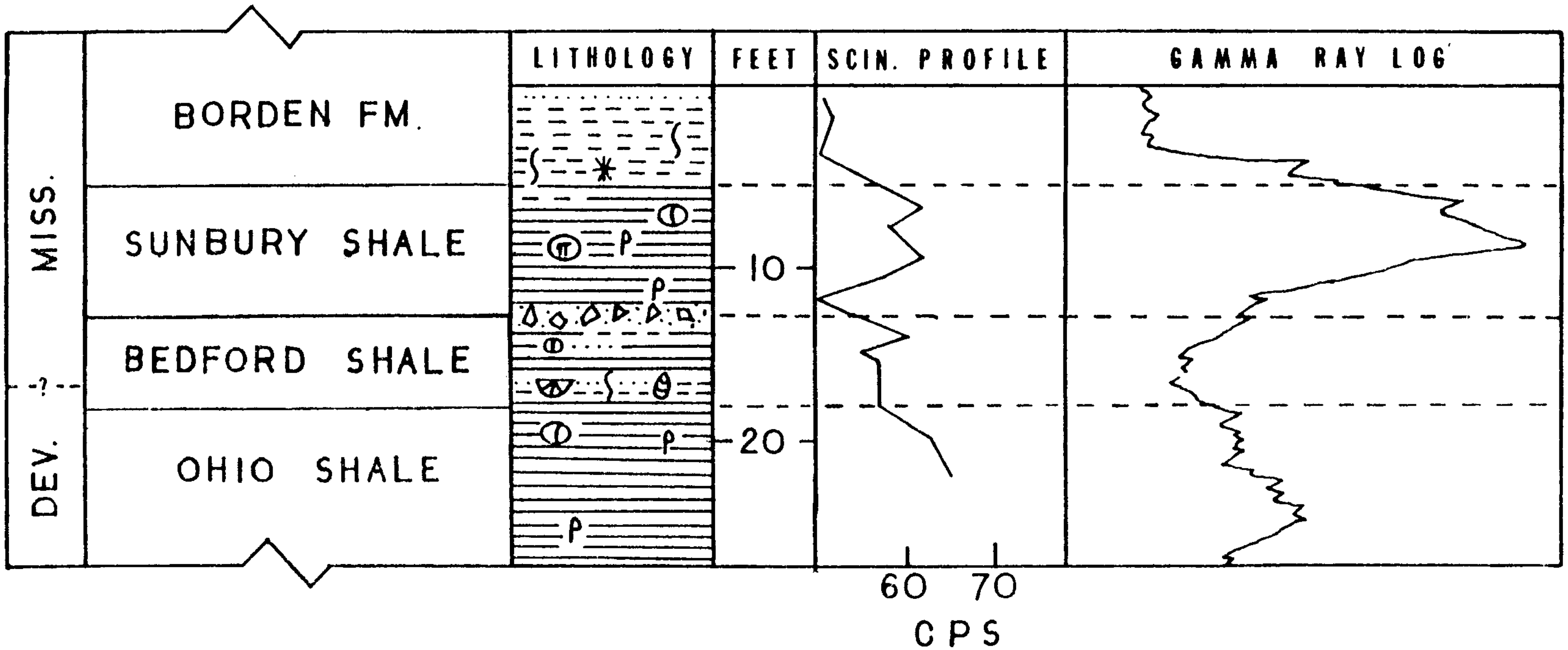
CORE #10, 17-S-70 BATH COUNTY, KY.

Core #11 (IMMR Core D-5)
13-R-69, 2100' FSL x 4000' FEL
Means Quadrangle, Montgomery County, KY
Elevation 850' Background Rad. 52.0 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
15.0-15.7	0.7	Siltstone, medium light gray (N6).
15.7-15.85	0.15	Siltstone, grades downward from olive gray (5Y 3/2) to dark gray (N3).
15.85-20.5	4.65	Shale, greenish gray (5G 6/1), clayey, burrowed, glauconitic.
		Sunbury Shale
20.5-27.0	6.5	Shale, black (N1), finely laminated, earthy, bituminous, fissile, green shale blebs and one laminae within 1 inch of upper contact; occasional fish fragments; pyrite blebs flattened parallel to bedding; phosphatic nodule at 22.5; gypsum, hydrous iron minerals along joints.
27.0-27.7	0.7	Shale, black (N1), finely laminated, earthy, bituminous, fissile, fine light gray silt laminae; burrows contain pyrite; good lag zones at 27.2 and 27.5 contain abundant *Lingula* and *Orbiculoidea*, fossils otherwise occasional.
27.7-27.9	0.2	Shale, dark gray (N3) dry, earthy, pyrite abundant.
27.9-30.1	2.2	Shale, black (N1), earthy, bituminous, fissile, with fine calcareous silt laminae, phosphatic nodule at 28.1.
		Bedford Shale
30.1-30.6	0.5	Siltstone, greenish black (5G 2/1) to dark greenish gray (5G 4/1), fine-grained, argillaceous; burrowed; articulate brachiopod at 30.4; inarticulate brachiopod at 30.5.
30.6-34.4	3.8	Shale, black (N1) to dark gray (N3), finely laminated, earthy; bituminous, slightly lighter in color near upper contact, pyrite stringers and blebs; phosphatic nodule at 34.0.

Core #11, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
34.4-34.6	0.2	Shale, medium dark gray (N4) dry, finely laminated, slightly clayey, semi-fissile, bituminous.
34.6-40.0	5.4	Shale, black (N1) wet to dark gray (N3) dry, earthy, bituminous, fissile.



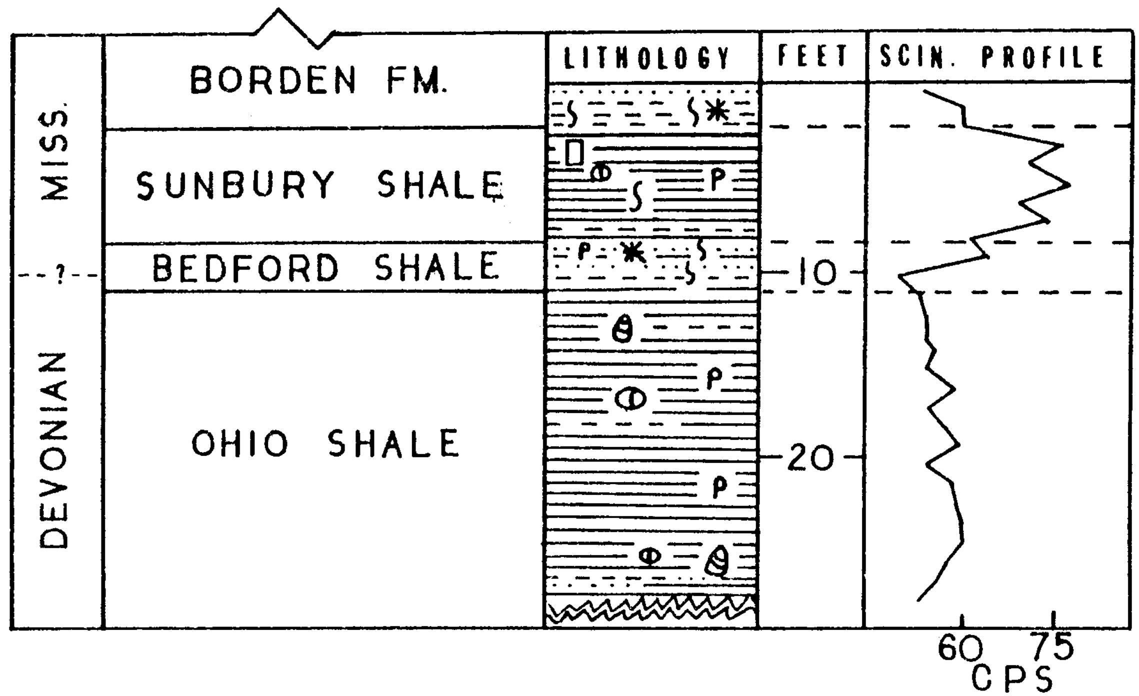
CORE #11, 13-R-69 MONTGOMERY COUNTY, KY.

Core #12 (IMMR Core D-6)
16-R-68, 1700' FSL x 150' FEL
Levee Quadrangle, Montgomery County, KY
Elevation 860' Background Rad. 54 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
17.5-19.7	2.2	Shale, greenish gray (5GY 6/1, 5G 6/1), clayey, burrowed, glauconitic burrows near base; siltstone, light gray (N7).
		Sunbury Shale
19.7-25.2	5.5	Shale, black (N1) wet to brownish-black (5Y 2/1) dry, finely laminated, bituminous, occasional granular pyrite; vitrinite plant fragment at 20.7; rare pyritic burrows; phosphatic nodules common at 22.2-22.5.
25.2-25.4	0.2	Shale, dark gray (N3) to medium dark gray (N4), silty, finely laminated, pyritic.
25.4-25.8	0.4	Shale, black (N1), finely laminated, bituminous, occasional granular pyrite.
		Bedford Shale
25.8-26.0	0.2	Siltstone, medium bluish gray (5B 5/1) to greenish gray (5G 6/1) dry, mottled (bioturbated?), silt-size grains of glauconite and pyrite.
26.0-26.1	0.1	Shale, medium bluish gray (5B 5/1), silty; grades to black shale.
26.1-26.5	0.4	Shale, black (N1), slightly silty, finely laminated.
26.5-26.7	0.2	Siltstone, medium bluish gray (5B 5/1) to greenish gray (5G 6/1) dry, mottled (burrowed?), silt-size grains of glauconite and pyrite.
26.7-27.25	0.55	Shale, medium bluish gray (5B 5/1) to greenish gray (5G 6/1) dry, silty, fissile, thin black shale laminae in basal few inches.

Core #12, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
27.25-43.0	15.75	Shale, black (N1) wet to dark gray (N3) dry, finely laminated, earthy, bituminous, fissile; shale, medium dark gray (N4) dry, clayey, finely laminated, semi-fissile, occasional Lingula fragments; phosphate nodules at 33.5; 41.4 laminar and nodular pyrite.
43.0-46.25	3.25	Shale, as above, with minor fluctuations in color to dark gray - dark brown shades; thin calcareous silt laminae at 46.2; phosphatic nodules at 43.3, 44.4.
46.25-46.35	0.1	Limestone, medium gray (N5), in part cone-in-cone.



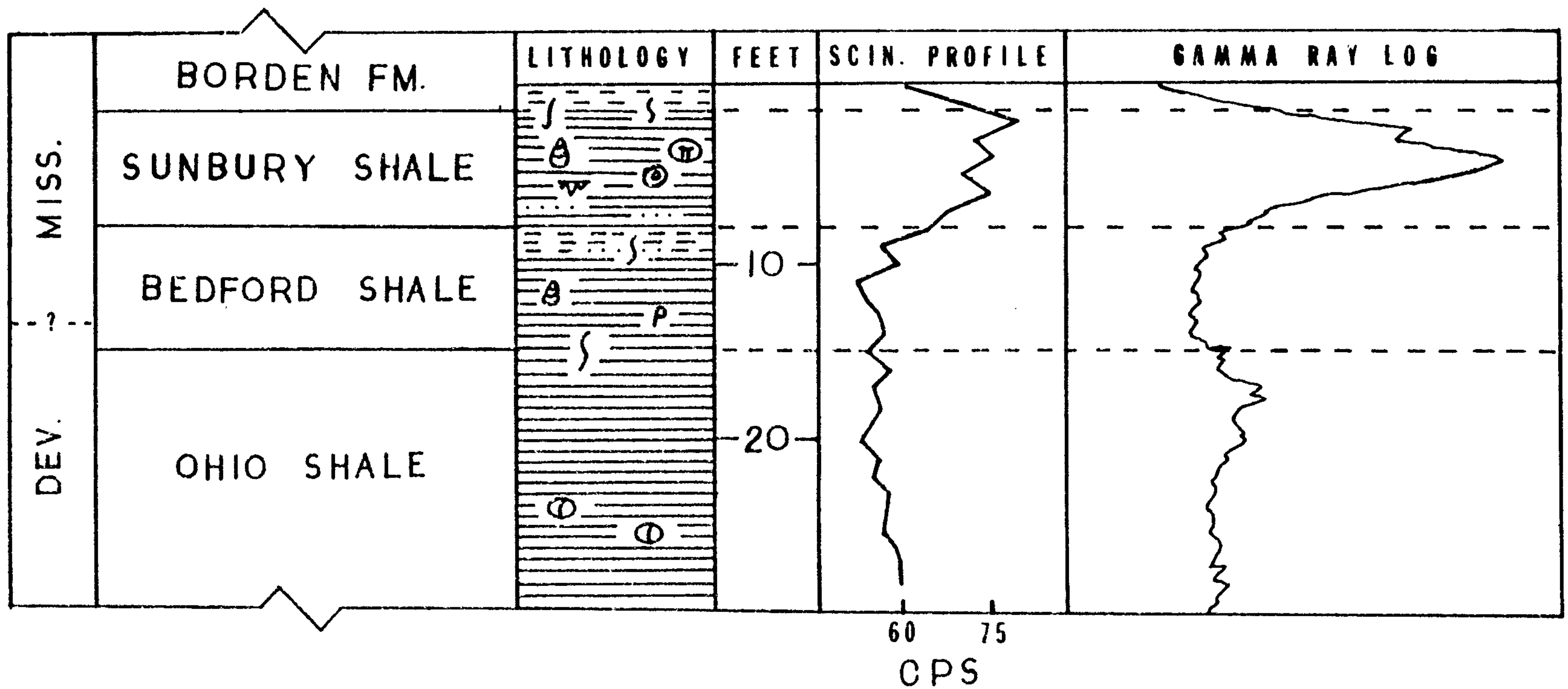
CORE #12, 16-R-68 MONTGOMERY COUNTY, KY.

Core #13 (IMMR Core D-7)
20-Q-68, 5300' FSL x 4450' FEL
Stanton Quadrangle, Powell County, KY
Elevation 662' Background Rad. 55 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
16.0-17.3	1.3	Shale, greenish gray (5GY 6/1), clayey, weathered (poor sample).
		Sunbury Shale
17.3-17.4	0.1	Shale, black (N1), interlaminated with green shale laminae, green shale burrows.
17.4-22.4	5.0	Shale, black (N1), finely laminated, earthy, bituminous, fissile, fossils locally abundant, including *Lingula*, *Orbiculoidea*, conodonts, fish fragments.
22.4-22.5	0.1	Shale, as above; calcareous silt laminae associated with pyrite.
22.5-22.7	0.2	Shale, black (N1), finely laminated, earthy, bituminous, fissile.
22.7-22.8	0.1	Shale, as above; calcareous silt laminae associated with pyrite.
22.8-23.0	0.2	Shale, black (N1), as above.
23.0-23.3	0.3	Shale, olive black (5Y 2/1), slightly silty.
23.3-23.9	0.6	Shale, black (N1), finely laminated, bituminous, fissile.
23.9-24.0	0.1	Shale, black (N1), interlaminated with green shale.
		Bedford Shale
24.0-24.1	0.1	Shale, dark greenish gray (5G 4/1), silty, grades to siltstone.
24.1-24.2	0.1	Siltstone, dark greenish gray (5G 4/1), argillaceous.
24.2-24.5	0.3	Siltstone, dark greenish gray (5G 4/1), argillaceous near bottom; wavy-bedded, non-calcareous, burrowed (some pyritic).

Core #13, Continued

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Ohio Shale
24.5-28.5	4.0	Shale, black (N1) dark gray (N3) dry; finely laminated, earthy, bituminous, fissile, *Lingula* common, occasional small pyrite blebs parallel to bedding, rare pyritic laminae.
28.5-33.0	4.5	Shale, as above, with subtle color variations of brown and gray shades in laminae and thin beds; thin light gray calcareous silt laminae.
33.0-37.0	4.0	Shale, black (N1) dark gray (N3) dry, finely laminated, earthy, bituminous, fissile, large pyrite nodular at 36.2 connected to vertical pyritized burrow, which displaces lamination.
37.0-45.4	8.4	Shale, as above, with minor changes to brown and gray shales in laminae and thin beds; phosphatic nodules at 39.9, 40.3, 40.7.
45.4-45.5	0.1	Limestone, light gray (N5) wet, partly, cone-in-cone, interlaminated with black shale; gypsum on parting plane.



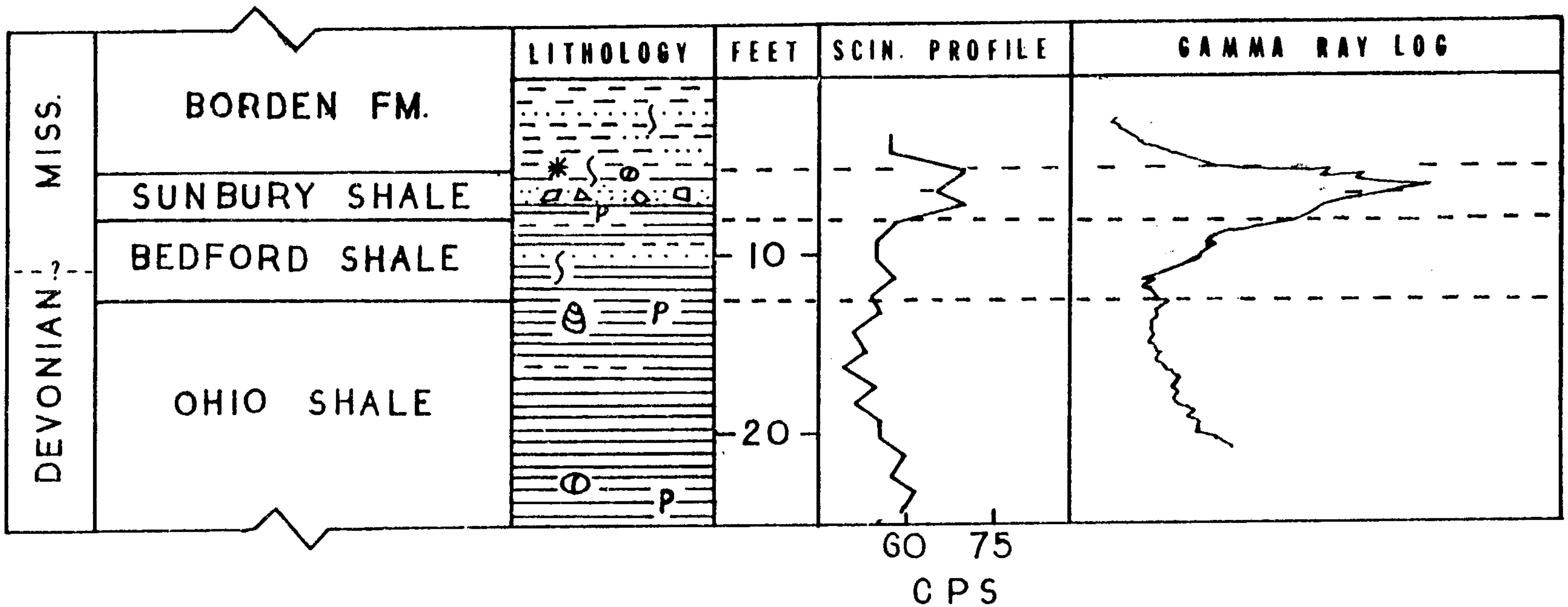
CORE #13, 20-Q-68 POWELL COUNTY, KY.

Core #14 (IMMR Core D-8)
6-P-68, 2775' FSL x 400' FEL
Clay City Quadrangle, Powell County, KY
Elevation 725' Background Rad. 50 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
Washed Out	Depths Uncertain	<u>Borden Fm.</u>
20.0		Shale, greenish gray (5G 6/1), dark greenish gray (5G 4/1), slightly silty, bioturbated, glauconitic burrows near base; siltstone, greenish gray (5GY 6/1), finely laminated, non-calcareous, weathered.
		<u>Sunbury Shale</u>
24.9-27.0	2.1	Shale, black (N1), finely laminated, bituminous, locally bioturbated, fissile, green shale burrows in top few inches; lag zone contains <u>Lingula</u>, conodonts, fish scales at 26.9; phosphate nodule at 25.1; pyritized burrow at 25.6.
27.0-27.3	0.3	Shale, grayish black (N2) to medium dark gray (N4) dry, silty, thin wavy calcareous silt laminae from 21.0 to 27.1; <u>Lingula</u>, <u>Orbiculoidea</u> common; granular pyrite common.
27.3-28.4	1.1	Shale, black (N1), finely laminated, bituminous, fissile; rare fine silt laminae.
28.4-28.7	0.3	Shale, dark gray (N3) to grayish black (N2), interlaminated with brownish black to black shale.
28.7-29.3	0.6	Shale, black (N1), finely laminated, bituminous, fissile.
		<u>Bedford Shale</u>
29.3-29.5	0.2	Siltstone, dark greenish gray (5G 4/1 to 5GY 4/1) wet, argillaceous near top and bottom; burrowed, non-calcareous; possible glauconitic and pyrite granules.
29.5-45.0	15.5	Black (N1) to brownish-black (5YR 2/1), dark gray (N3), finely laminated, bituminous, fissile, occasional <u>Lingula</u>, rare small green shale blebs parallel to lamination; clay-rich laminae at 33.5, 36.4, are

Core #14 Continued

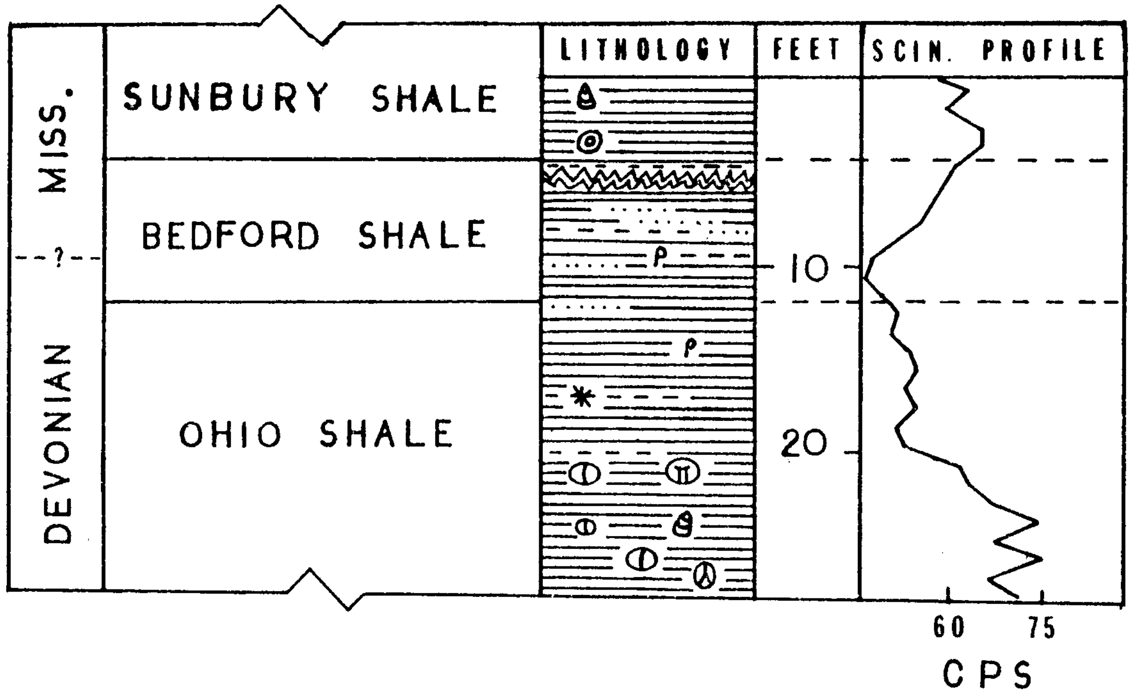
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
29.5-45.0 (continued)	15.5	slightly lighter gray color, semi-fissile; rare calcareous silt laminae; phosphatic nodule at 43.0; occasional pyrite blebs parallel to lamination and nodular pyrite.



CORE #14, 6-P-68 POWELL COUNTY, KY.

Core #15 (Core ENW-GNC #3)
5-P-67
Estill County, KY
Elevation Background Rad. 40 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Sunbury Shale
7.5-11.8	4.3	Shale, black (N1), earthy, bituminous, fissile, Lingula at 11.3, Orbiculoidea at 9.5, 11.6; hydrous iron minerals, gypsum along partings, joints.
		Bedford Shale
11.8-11.95	0.15	Shale, dark greenish gray (5G 4/1), clayey.
11.95-12.00	0.05	Shale, as above, with silt laminae, contorted, flaser-bedding, calcareous; interlaminated with brownish-black shale.
12.00-12.25	.25	Limestone, medium gray (N5), cone-in-cone, interlaminated with black shale.
12.25-17.1	4.85	Shale, grayish-black (N2), fissile, interlaminated with siltstone, very light gray (N8), contorted, with micro cross-laminae and flaser-bedding; calcareous; thin beds of pyrite common.
17.1-17.5	0.4	Shale, as above; siltstone laminae, as above, decrease in number and size; local beds of dark gray (N3) shale; occasional laminae, framboids of granular pyrite.
17.5-22.9	5.4	Shale, as above; siltstone lamina as above, continue to decrease in number and size.
22.9-25.3	2.4	Shale, black (N1), earthy, fissile, occasional blebs of green shale throughout sometimes glauconitic, flattened parallel to lamination, two phosphatic nodules in lowest few inches.
25.3-28.7	3.4	Shale, as above; occasional fish scales; occasional phosphatic nodules 1-2 inches diameter; gypsum on partings.



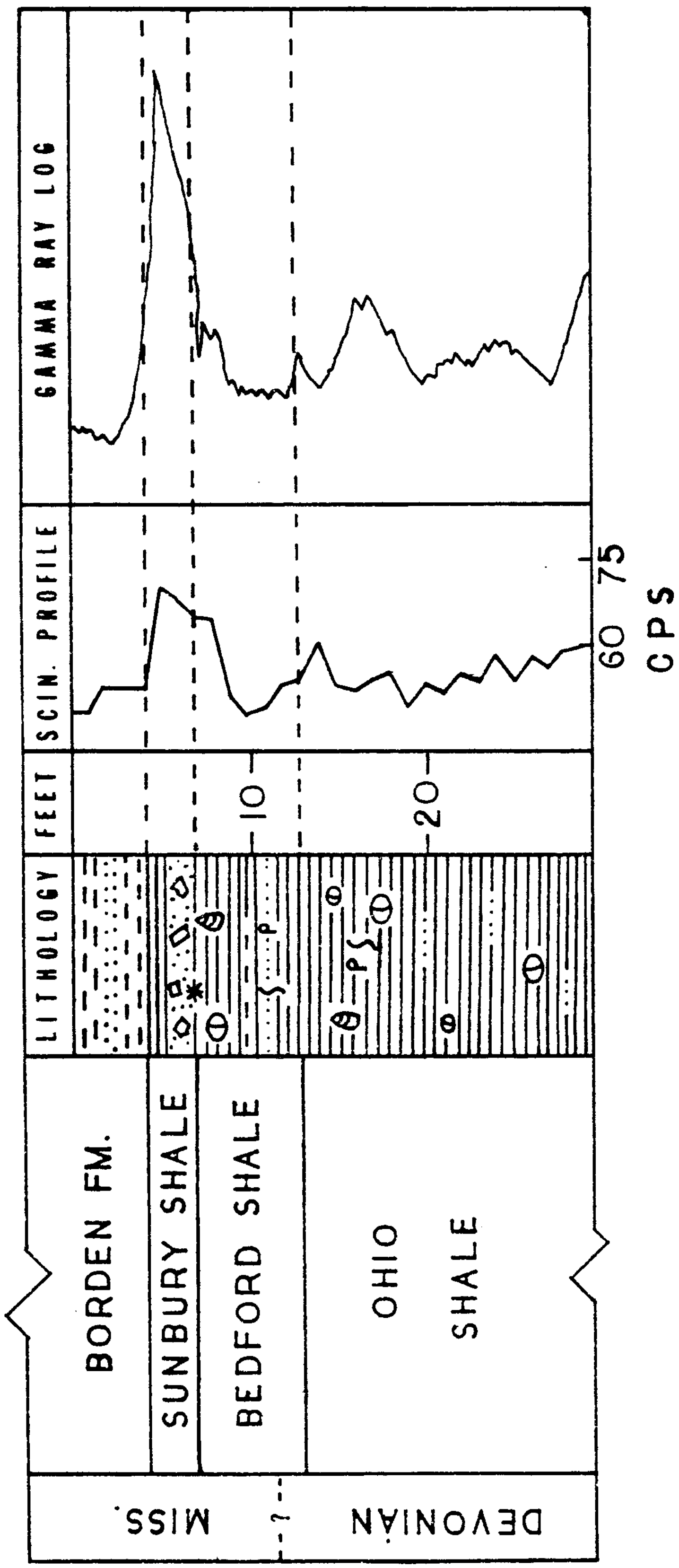
CORE #15, 5-P-67 ESTILL COUNTY, KY.

Core #16 (IMMR Core D-9)
15-0-68, 2700' FSL x 3000' FEL
Irvine Quadrangle, Estill County, KY
Elevation 675' Background Rad. 50 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
Washed out	Depths Uncertain	Borden Fm.
		Shale, medium gray (N5) dry to greenish gray (5G 6/1) and dark greenish gray (5G 4/1) wavy-laminated, highly weathered.
		Sunbury Shale
31.0-32.5	1.5	Shale, black (N1) to brownish black (5YR 2/1), finely laminated, bituminous, fissile.
32.5-33.1	0.6	Shale, dark gray (N3), finely laminated, bituminous, fissile, occasional calcareous silts; minor lag zones contain *Lingula*, *Orbiculoidea*; glauconite pellets.
33.1-36.0	2.9	Shale, black (N1); finely laminated, fissile, bituminous, occasional fine calcareous silts; laminae displaced by occasional phosphatic nodules; occasional fossils include *Lingula*.
36.0-36.2	0.2	Shale, dark gray (N3) to grayish black (N2), finely laminated, bituminous, rare non-calcareous silt laminae; rare laminated pyrite.
36.2-36.8	0.6	Shale, brownish-black (5YR 2/1) to black (N1), finely laminated with rare dark gray liminae, bituminous, fissile.
		Bedford Shale
36.8-37.15	0.35	Siltstone, dark greenish gray (5G 4/1 to 5GY 4/1), wavy laminated, argillaceous near top and bottom: bioturbated, pyrite granules common, sometimes within burrows.
37.15-46.0	8.85	Shale, black (N1) wet, dark gray (N3) to grayish black (N2) dry, finely laminated, fissile, bituminous, subtle color changes to brown and gray in some laminae; *Lingula* fragments common; phosphatic nodules common from 42.5-43.3; small

Core #16 Continued

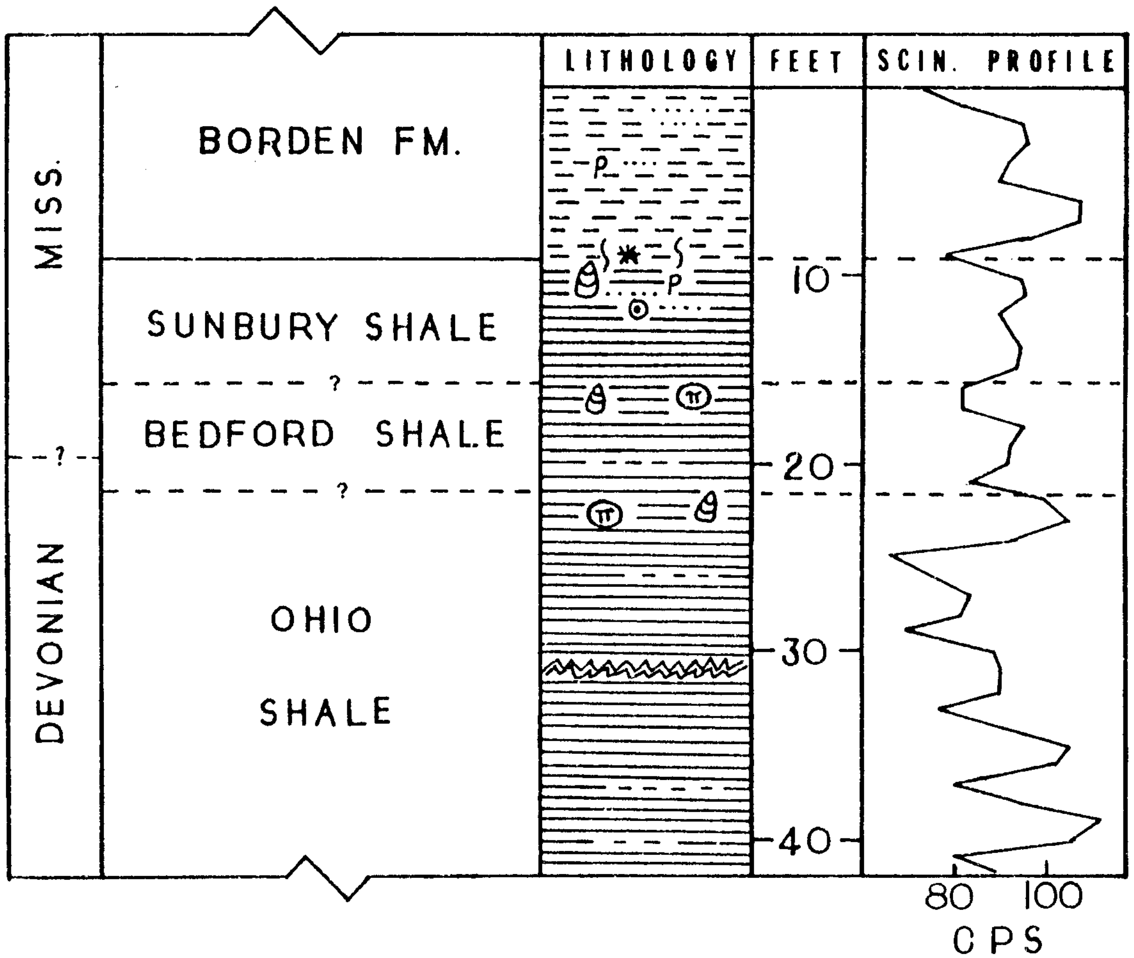
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
37.15-46.0 continued	8.85	pyrite blebs parallel to bedding and laminae common; pyritic vertical burrow at 41.2-41.4.
46.0-56.0	10.0	Shale, as above; rare thin light gray calcareous silt laminae; phosphatic nodules at 47.9, 51.3, 51.5.



CORE #16, 15-0-68 ESTILL COUNTY, KY.

Core #17 (KGS-Soil Conservation Service Core DH-5)
18-0-67, 2950' FSL x 1200' FEL
Estill County, Kentucky
Background Rad. 50 cps

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		<u>Borden Fm.</u>
14.0-33.7	19.7	Weathered horizon
33.7-42.7	9.0	Shale, dark greenish gray (5GY 4/1), locally silty, finely laminated, bioturbated, clayey, semi-fissile, locally pyritic; glauconitic in basal few inches; glauconitic burrows 42.6-42.7.
		<u>Sunbury Shale</u>
42.7-43.9	1.2	Shale, black (N1), finely laminated, bituminous, fissile, *Lingula* fragments locally common; occasional granular pyrite.
43.9-44.5	0.6	Shale, as above; interlaminated with calcareous siltstone medium dark gray (N4), flaser-bedded, *Lingula*, *Orbiculoidea* fragments common on parting planes.
44.5-62.5	18.0	Shale, black (N1) wet, finely laminated, bituminous, fissile, interlaminated with subtly lighter shades of gray and brown shale, clayey, occasional fish scales, *Lingula*.
62.5-76.4	13.9	Shale, black (N1) wet, dark gray (N3) dry, finely laminated, bituminous, fissile, subtle lighter shades of brown and gray in shale; rare, thin limestone laminae, medium gray (N5).



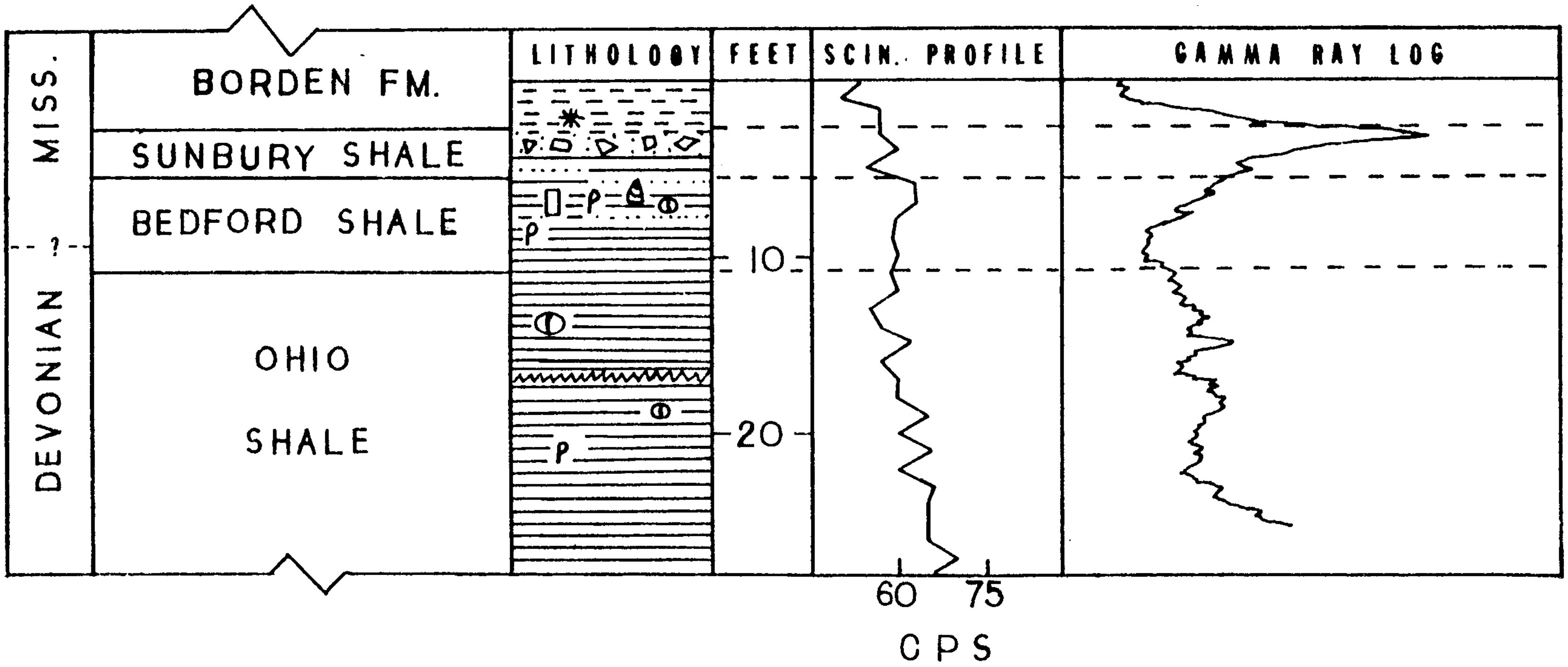
CORE #17, 18-0-67 ESTILL COUNTY, KY.

Core #18 (IMMR Core D-10)
20-N-67, 4550' FSL x 4675' FEL
Leighton Quadrangle, Estill County, Kentucky
Elevation 630' Background Rad. 57 cps.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
34.5-37.4	2.9	Shale, greenish black (5G 2/1) to medium dark gray (N4), clayey, glauconitic in lowest few inches.
		Sunbury Shale
37.4-38.4	1.0	Shale, black (N1), finely laminated, bituminous, fissile, good lag zone at 37.5 contains abundant Lingula, Orbiculoidea, conodonts, and fish fragments.
38.4-38.7	0.3	Shale, as above; siltstone, medium gray (N5), increasing to 50%; wavy and cross-laminated; fossil fragments common; vitrinite-band.
38.7-39.0	0.3	Siltstone, light gray (N6) dry, wavy and cross-bedded and laminated; calcareous, common fossils include fish fragments, Lingula; shale black (N1), bituminous, fissile.
39.0-40.7	1.7	Shale, black (N1), finely laminated, bituminous, fissile, occasional phosphatic nodules; occasional trace of vitrinite; occasional calcareous silt laminae often displaced by common pyrite nodules.
40.7-40.8	0.1	Shale, grayish black (N2), slightly silty, finely laminated, pyrite granules common.
40.8-41.3	0.5	Shale, black (N1), finely laminated, bituminous, fissile, pyrite common.
		Bedford Shale
41.3-41.55	0.25	Siltstone, dark greenish gray (5G 4/1) to greenish black (5G 2/1) argillaceous, wavy-laminated, calcareous to non-calcareous, abundant pyrite.
41.55-41.75	0.20	Shale, greenish black (5G 2/1) to olive black (5Y 2/1), silty, wavy and cross-laminated, calcareous, abundant pyrite.

Core #18 Continued

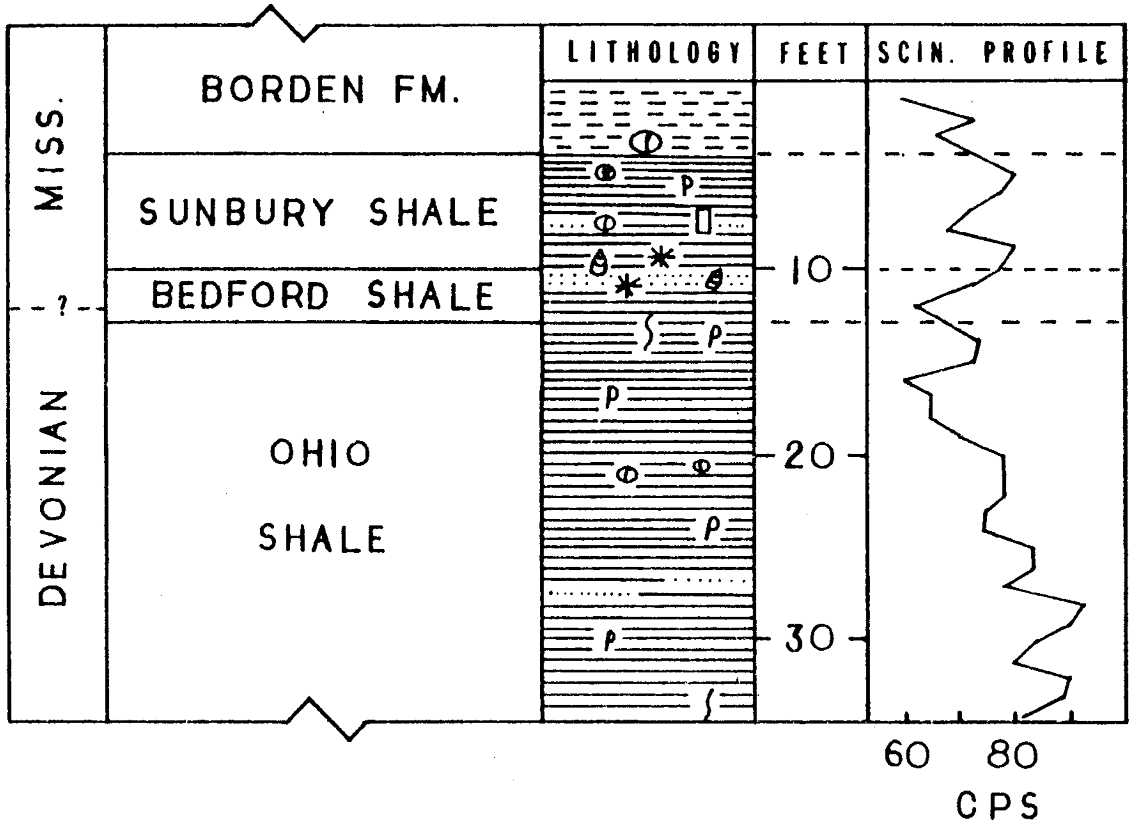
CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Bedford Shale cont'd.
41.75-		Shale, black (N1), finely laminated, bituminous, fissile, occasional phosphatic nodules; rare thin limestone beds, dark gray (N3).



CORE #18, 20-N-67 ESTILL COUNTY, KY.

Core #19
3-M-64
Madison County, Kentucky
Elevation 910' Core angled 15° from Vertical.

CORE DEPTH (Feet)	THICKNESS (Feet)	LITHOLOGIC DESCRIPTION
		Borden Fm.
5.3-9.1	3.8	Shale, light gray (N7) dry, weathered, iron-stained phosphate nodule at base.
		Sunbury Shale
9.1-10.0	0.9	Shale, black (N1), but highly weathered; gypsum, hydrous iron minerals on partings.
10.0-15.7	5.7	Shale, black (N1) to medium dark gray (N4) dry, finely laminated, bituminous, fissile, rare fish scales, Lingula, rare calcareous silt laminae; pyritic common; phosphate nodule at 12.7, vitrain band at 12.8; occasional glauconitic shale blebs, 15.3-15.7.
		Bedford Shale
15.7-16.3	0.6	Siltstone, light greenish gray (5GY 6/1) dry, argillaceous, bioturbated, calcareous, occasional Lingula, articulate brachiopods; abundant glaucontic green shale blebs.
16.3-30.0	13.7	Shale, black (N1) finely laminated, bituminous, fissile; abundant pyrite in grains, nodules, and laminae; occasional phosphatic nodules.
30.0-30.3	0.3	Shale, as above; common thin calcareous silt laminae, contorted.
30.3-40.2	9.9	Shale, as above; rare calcareous silt laminae; possible bioturbation.



CORE # 19, 3-M-64 MADISON COUNTY, KY.

APPENDIX B

SCINTILLOMETER MEASURED OUTCROP LOCATIONS

1. GARRARD COUNTY SECTION

The section is poorly exposed 0.25 miles east of U.S. 27, on the south flank of Burdette Knob, in the Bryantsville Quadrangle, Garrard County, Kentucky. Carter coordinate location: 24-O-59, 1250' FNL x 1500' FWL. The section was measured with a scintillometer on May 27, 1981 by Vincent Nelson, Frank Ettensohn and Tim Elam.

2. CASEY COUNTY SECTION

The section is exposed on the west side of U.S. Highway 127, 0.2 miles north of Liberty, in the Liberty Quadrangle, Casey County, Kentucky. Carter coordinate location: 25-K-56, 500' FSL x 2250' FWL. The section was measured with a scintillometer on May 5, 1981, by Frank Ettensohn and Tim Elam.

3. PULASKI COUNTY SECTION

The section is exposed on the southwest side of Ringgold Road, 4.2 miles of West Somerset in the Delmer Quadrangle, Pulaski County, Kentucky. Carter coordinate location: 19-H-58, 2850' FSL x 2400' FEL. The section was measured with a scintillometer on May 5, 1981, by Frank Ettensohn and Tim Elam.

4. RUSSELL COUNTY SECTION #1

The section is exposed on the west side of Kentucky 1058, 2.2 miles north of Creelsboro in the Creelsboro Quadrangle, Russell County, Kentucky. Carter coordinate location: 2-E-52, 2250' FNL x 400' FWL. The section was measured with a scintillometer on April 4, 1981, by Frank Ettensohn, Lance Barron, and Tim Elam.

5. RUSSELL COUNTY SECTION #2

The section is exposed on the southeast side of Kentucky Highway 1730, 2.65 miles northwest of its intersection with U.S. Highway 127, in the Creelsboro Quadrangle, Russell County, Kentucky. Carter coordinate location: 14-E-53, 800' FNL x 150' FWL. The section was measured with a scintillometer on April 4, 1981, by Frank Ettensohn, Lance Barron, and Tim Elam.

6. CUMBERLAND COUNTY SECTION

The section is exposed on the north side of Kentucky Highway 90, 2.5 miles east of Burkesville, in the Burkesville Quadrangle, Cumberland County, Kentucky. Carter coordinate location: 21-D-50, 1250' FNL x 1400' FWL. The section was measured with a scintillometer on April 4, 1981, by Frank Ettensohn, Lance Barron, and Tim Elam.

APPENDIX C

(Figures 16-20, Oversized illustrations -

See separate volume)

APPENDIX D

(Figures 21-25, Oversized Illustrations -

See separate volume)

REFERENCES CITED

Alvord, D. C., 1971, Geologic map of the Hellier quadrangle, Kentucky-Virginia, and part of the Clintwood quadrangle, Pike County, Kentucky: U.S. Geol. Survey Geologic Quadrangle 950, scale 1:24,000.

Alvord, D. C., and R. L. Miller, 1972, Geologic map of the Elkhorn City quadrangle, Kentucky-Virginia, and part of the Harman quadrangle, Pike County, Kentucky: U.S. Geol. Survey Geologic Quadrangle 951, scale 1:24,000.

Ammerman, M. L., and G. R. Keller, 1979, Delineation of Rome trough in eastern Kentucky by gravity and deep drilling data: AAPG Bull., v. 63, p. 341-353.

Barron, L. S., and F. R. Ettensohn, 1981, Paleoecology of the Devonian-Mississippian black-shale sequence in eastern Kentucky with an atlas of some common fossils: U.S. Dept. of Energy-Morgantown Energy Technology Center, 75 p.

Butts, C. F., 1922, The Mississippian series of eastern Kentucky: Kentucky Geol. Survey, series VI, v. 7, p. 4-27.

Byers, C. W., 1977, Biofacies patterns in euxinic basins: a general model: SEPM Spec. Pub. 25, p. 1-25.

Campbell, Guy, 1946, New Albany Shale: Geol. Soc. America Bull., v. 57, p. 828-908.

Caspers, H., 1957, Black Sea and Sea of Azov, <u>in</u> J. W. Hedgepeth, ed., <u>Treatise on marine ecology and paleoecology</u>: Geol. Soc. America Mem. 67, v. 1, p. 801-889.

Cattermole, J. M., 1963, Geology of the Waterview quadrangle, Kentucky, U.S. Geol. Survey Geologic Quadrangle 286, scale 1:24,000.

Chaplin, J. E., 1979, The Devonian-Carboniferous boundary <u>in</u> F. R. Ettensohn and G. R. Dever, eds., Carboniferous Geology from the Appalachian Basin to the Illinois Basin through eastern Ohio and Kentucky: Ninth Intl. Cong. of Carb. Strat. and Geol., field trip no. 4, p. 152-163.

Chaplin, J. E., and C. E. Mason, 1978, Geologic map of the Garrison quadrangle, Kentucky-Ohio, and part of the Pond Run quadrangle, Lewis County, Kentucky: U.S. Geol. Survey Geologic Quadrangle 1490, scale 1:24,000.

Clarke, M. K., 1969, The Farmers Siltstone: a flysch-like deposit in northeastern Kentucky: unpub. M.S. thesis, Univ. of Kentucky, Lexington, 69 p.

Conant, L. C., and V. E. Swanson, 1961, Chattanooga Shale and related rocks of central Tennessee and nearby areas: U.S. Geol. Survey Prof. Paper 357, 91 p.

Conkin, J. E., and B. M. Conkin, 1975, The Devonian-Mississippian and Kinderhookian-Osagean boundaries in east-central United States are paracontinuities: Univ. of Louisville Studies in Paleontology and Stratigraphy, no. 4, 55 p.

Conkin, J. E., B. M. Conkin, and L. Z. Lipchinsky, 1980, Devonian black shale in the eastern U.S.: Part I - southern Indiana, Kentucky, northern and eastern Highland Rim of Tennessee, and central Ohio: Univ. of Louisville Studies in Paleontology and Stratigraphy, no. 12, 63 p.

Cooper, G. A., and others, Correlation of the Devonian sedimentary formations of North America: Geol. Soc. America Bull., v. 53, p. 1729-1793.

Csejtey, B., Jr., 1970, Geologic map of the Nolansburg quadrangle, southeastern Kentucky: U.S. Geol. Survey Geologic Quadrangle 868, scale 1:24,000.

Curtis, C. D., and D. A. Spears, 1968, The formation of sedimentary iron minerals: Economic Geology, v. 63, p. 257-270.

Denny, C. S., 1964, Geology of the Brushart quadrangle, Kentucky: U.S. Geol. Survey Geologic Quadrangle 324, scale 1:24,000.

de Witt, 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.

de Witt, W., Jr., and L. W. McGrew, 1979, The Appalachian Basin region, in L. C. Craig and C. W. Conner, coord., Paleotectonic investigations of the Mississippian System in the United States: U.S. Geol. Survey Prof. Paper 1010-C, 48 p.

de Witt, W., Jr., G. V., Cohee, and L. W. McGrew, 1979, Oil and gas in Mississippian rocks in part of the eastern United States, in L. C. Craig and C. W. Conner, coord., Paleotectonic investigations of the Mississippian System in the United States: U.S. Geol. Survey Prof. Paper 1010-U, p. 441-455.

Dillman, S. B., 1980, Subsurface geology of the Upper Devonian-Lower Mississippian black-shale sequence in eastern Kentucky: unpub. M.S. thesis, Univ. of Kentucky, Lexington, 72 p.

Dohm, F. P., 1963, The Lower Mississippian of the northern Paint Creek uplift, Kentucky: unpub. M.S. thesis, Univ. of Kentucky, Lexington, 106 p.

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

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

Ettensohn, F. R., 1979a, Generalized description of Carboniferous stratigraphy, structure, and depositional environments in east-central Kentucky, in F. R. Ettensohn and G. R. Dever, eds., Carboniferous geology from the Appalachian Basin to the Illinois Basin through eastern Ohio and Kentucky: Ninth Intl. Cong. of Carb. Strat. and Geol., field trip no. 4, p. 64-77.

Ettensohn, F. R., 1979b, Radioactive stratigraphy at the Devonian-Carboniferous boundary, in F. R. Ettensohn and G. R. Dever, eds., Carboniferous geology from the Appalachian basin to the Illinois basin through eastern Ohio and Kentucky: Ninth Intl. Cong. of Carb. Strat. and Geol., field trip no. 4, p. 166-170.

Ettensohn, F. R., 1980, An alternative to the barrier-shoreline model for deposition of Mississippian and Pennsylvanian rocks in northeastern Kentucky: Geol. Soc. America Bull., v. 91, part II, p. 934-1056.

Ettensohn, F. R., and L. S. Barron, 1981, Depositional model for the Devonian-Mississippian black-shale sequence of North America: a tectono-climatic approach: U.S. Dept. of Energy-Morgantown Energy Technology Center, 80 p.

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, part II, p. 828-849.

Froelich, A. J., 1973, Geologic map of the Louellen quadrangle, southeastern Kentucky: U.S. Geol. Survey Geologic Quadrangle 1060, scale 1:24,000.

Fulton, L. P., 1979, Structure and isopach map of the New Albany-Chattanooga-Ohio Shale (Devonian and Mississippian) in Kentucky: eastern sheet: Kentucky Geol. Survey, series XI, scale 1:250,000.

Glover, Lynn, 1959, Stratigraphy and uranium content of the Chattanooga Shale in northeastern Alabama, northwestern Georgia, and eastern Tennessee: U.S. Geol. Survey Bull. 1087-E, p. 113-168.

Hard, E. W., 1931, Black shale deposition in central New York: AAPG Bull., v. 15, p. 165-181.

Harris, L. D., W. de Witt, Jr., and G. W. Colton, 1978, What are possible stratigraphic controls on gas fields in eastern black shale?: The Oil and Gas Journal, v. 76, no. 14, p. 162-165.

Hass, W. H., 1956, Age and correlation of the Chattanooga Shale and the Maury Formation: U.S. Geol. Survey Prof. Paper 286, 47 p.

Haught, O. L., 1959, Oil and gas in southern West Virginia: West Virginia Geol. Survey Bull., no. 17, 34 p.

Heckel, P. H., 1977, Origin of phosphatic black shale facies in Pennsylvanian cyclothems of mid-continent North America: AAPG Bull., v. 61, p. 1045-1068.

Heyl, A. V., 1972, The 38th parallel lineament and its relationship to ore deposits: Economic Geology, v. 67, p. 879-894.

Hicks, L. E., 1878, The Waverly Group in central Ohio: American Jour. Science, 3rd series, v. 16, p. 216-220.

Hoover, K. V., 1960, Devonian-Mississippian shale sequence in Ohio: Ohio Geol. Survey Information Circ., no. 27, 154 p.

Howard, J. D., 1975, The sedimentological significance of trace fossils, in R. D. Frey, ed., The study of trace fossils: New York, Springer-Verlag, p. 131-146.

Hülsemann, J., and K. O. Emery, 1961, Stratification in recent sediments of Santa Barbara basin as controlled by organism and water character: Jour. of Geology, v. 69, p. 279-290.

Hunter, C. D., 1935, Natural gas in eastern Kentucky, in H. A. Ley, ed., Geology of natural gas: Tulsa, OH., AAPG, p. 915-947.

Hyde, J. E., 1911, Stratigraphy of the Waverly formations in central and southern Ohio: Jour. of Geology, v. 23, p. 655-682, 757-779.

Hyde, J. E., 1963, Mississippian formations of central and southern Ohio, in M. F. Marple, ed., Ohio Geol. Survey Bull. 51, 335 p.

Jillson, W. R., 1931, Structural geologic map of Kentucky: Kentucky Geol. Survey, series VI, scale 1:500,000.

Kentucky Geological Survey, anonymous, 1980, Devonian black shale study of western Kentucky: Final Status Rept., prepared for U.S. Dept. of Energy, contract no. EW-78-S-21-8215, 110 p.

Kepferle, R. C., P. E. Potter, and W. A. Pryor, 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.

Larese, R. E., 1974, Petrology and stratigraphy of the Berea Sandstone in the Cabin Creek and Gay-Fink trends, West Virginia: unpub. Ph. D. dissertation, West Virginia Univ., Morgantown, 387 p.

Maughan, E. K., 1976, Geologic map of the Roxana quadrangle, Letcher and Harlan counties, Kentucky: U.S. Geol. Survey Geologic Quadrangle 1299, scale 1:24,000.

Maynard, J. B., 1980, Sulfur isotopes of iron sulfides in Devonian-Mississippian shales of the Appalachian basin; control by rate of sedimentation: American Jour. Science. v. 280, no. 8, p. 772-786.

McDowell, R. C., 1976, Geologic map of the Colfax quadrangle, east-central Kentucky: U.S. Geol. Survey Geologic Quadrangle 1332, scale 1:24,000.

Merkel, R. H., 1979, Well log formation evaluation: AAPG Continuing Education Course Note Series, no. 14, 82 p.

Miller, M. L., 1978, A petrographic study of the Upper Devonian-Lower Mississippian black shales in eastern Kentucky: unpub. M.S. thesis, Univ. of Kentucky, Lexington, 108 p.

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

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

Morse, W. C., and A. F. Foerste, 1909b, The Bedford fauna at Indian Fields and Irvine, Kentucky: Ohio Naturalist, v. 9, no. 7, p. 515-523.

Morse, W. C., and A. F. Foerste, 1912, Preliminary report on the Waverlain formation of east-central Kentucky: Kentucky Geol. Survey, Bull. 16, series no. 19, 76 p.

Negus-de Wys, J., 1979, The Eastern Kentucky Gas Field: Ph. D. dissertation, West Virginia Univ., Morgantown, 199 p.

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

Pepper, J. F., D. F. Demarest, C. W. Merrels, II, and W. de Witt, Jr., 1946, Map of the Berea sand of southern Ohio, eastern Kentucky, and southwestern West Virginia: U.S. Geol. Survey Oil and Gas Prelim. Map no. 69, scale 1:189,700.

Philley, J. C., 1978, Geologic Map of the Salt Lick quadrangle, east-central Kentucky: U.S. Geol. Survey Geologic Quadrangle 1499, scale 1:24,000.

Potter, P. E., 1978, Structure and isopach map of the New Albany-Chattanooga-Ohio Shale (Devonian-Mississippian) in Kentucky, central sheet: Kentucky Geol. Survey, series X, scale 1:250,000.

Potter, P. E., J. B. Maynard, and W. A. Pryor, 1980, Final report of special geological, geochemical, and petrological studies of the Devonian shales in the Appalachian basin: (Eastern Gas Shales Project; U.S. Dept. of Energy): Cincinnati, University of Cincinnati, 86 p.

Potter, P. E., J. B. Maynard, and W. A. Pryor, 1981, Sedimentology of gas-bearing Devonian shales of the Appalachian basin: U.S. Dept. of Energy-Morgantown Energy Technology Center, 43 p.

Provo, L. J., 1977, Stratigraphy and sedimentology of the radioactive Devonian-Mississippian shales of the central Appalachian Basin: unpub. Ph.D. dissertation, Univ. of Cincinnati, 177 p.

Provo, L. J., R. C. Kepferle, and P. E. Potter, 1978, Division of black Ohio Shale in eastern Kentucky: AAPG Bull., v. 62, p. 1703-1713.

Ray, E. O., 1968, Shale stimulation-a new approach, in Proc. of the Tech. Sessions, Kentucky Oil and Gas Assoc., 30th and 31st meetings: Kentucky Geol. Survey, series X, Spec. Pub. 15, p. 35-42.

Rhoads, D. C., and J. W. Morse, 1971, Evolutionary and ecologic significance of oxygen-deficient marine basins: Lethaia, v. 4, p. 413-428.

Rice, C. L., 1973, Geologic map of the Jenkins West quadrangle, Kentucky-Virginia: U.S. Geol. Survey Geologic Quadrangle 1126, scale 1:24,000.

Rice, C. L., and D. Wolcott, 1973, Geologic map of the Whitesburg quadrangle, Kentucky-Virginia, and part of the Flat Gap quadrangle, Letcher County, Kentucky: U.S. Geol. Survey Geologic Quadrangle 1119, scale 1:240,000.

Robl, T. L., and others, 1980, Resource assessment of oil-bearing shales in Lewis and Fleming counties, Kentucky: Vol. 1-Project Report: prepared for the Davy-McKee Corp. by the Institute for Mining and Minerals Research, Univ. of Kentucky, Lexington, 87 p.

Roen, J. B., R. L. Miller, and J. W. Huddle, 1964, The Chattanooga Shale (Devonian and Mississippian) in the vicinity of Big Stone Gap, Virginia: U.S. Geol. Survey Prof. Paper 501-B, p. B43-B48.

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

Schlumberger, 1972, Log interpretation-volume I-principles: New York, Schlumberger Limited, 114 p.

Schmoker, J. W., 1978, the relationship between density and gamma-ray intensity in the Devonian shale sequence, Lincoln County, West Virginia: in Proc. of First Eastern Gas Shales Symposium: U.S. Dept. of Energy-Morgantown Energy Tech. Center, p. 355-360.

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

Swager, D. R., 1978, Stratigraphy of the Upper Devonian-Lower Mississippian shale sequence in eastern Kentucky outcrop belts: unpub. M.S. thesis, Univ. of Kentucky, Lexington, 116 p.

Thomas, R. N., 1951, Devonian shale gas production in the central Appalachian area: Kentucky Geol. Survey, series IX, Reprint 4.

Thomas, R. N., and J. B. Lauffer, 1964, Completion techniques and results of recent Berea sand development in Pike County, Kentucky: Kentucky Geol. Survey, series X, Spec. Pub. 8, p. 83-89.

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

Walls, R. A., 1975, Late Devonian-Early Mississippian sub-aqueous deltaic facies in a portion of the southeastern Appalachian basin, in M. L. Broussard, ed., Deltas: Houston Geol. Society, p. 359-367.

Webb, E. J., 1969, Geologic history of the Cambrian system in the Appalachian basin: Kentucky Geol. Survey, series X, Spec. Pub. no. 18, p. 7-15.

Weir, G. W., 1967, Geologic map of the Berea quadrangle, east-central Kentucky: U.S. Geol. Survey Geologic Quadrangle 649, scale 1:240,000.

Wilson, E. N., and J. S. Zafar, 1978, Wireline logs and sample studies in stratigraphy and gas occurrence of the Devonian shales along the Southern Tie section in eastern Kentucky and vicinity, in Proc. of First Eastern Gas Shales Symposium: U.S. Dept. of Energy-Morgantown Energy Technology Center, p. 145-165.

Wilson, W. J., 1950, Sub-aqueous flow marking in the Lower Mississippian strata of south-central Ohio and adjacent parts of Kentucky: unpub. M.S. thesis, Univ. of Cincinnati, 37 p.

Wood, E. B., and Walker, F. H., 1954, Preliminary oil and gas map of Kentucky: Kentucky Geol. Survey, series IX, scale 1:507,000.

Woodward, H. P., 1961, Preliminary subsurface study of southeastern Appalachian interior plateau: AAPG Bull., v. 45, p. 1634-1655.

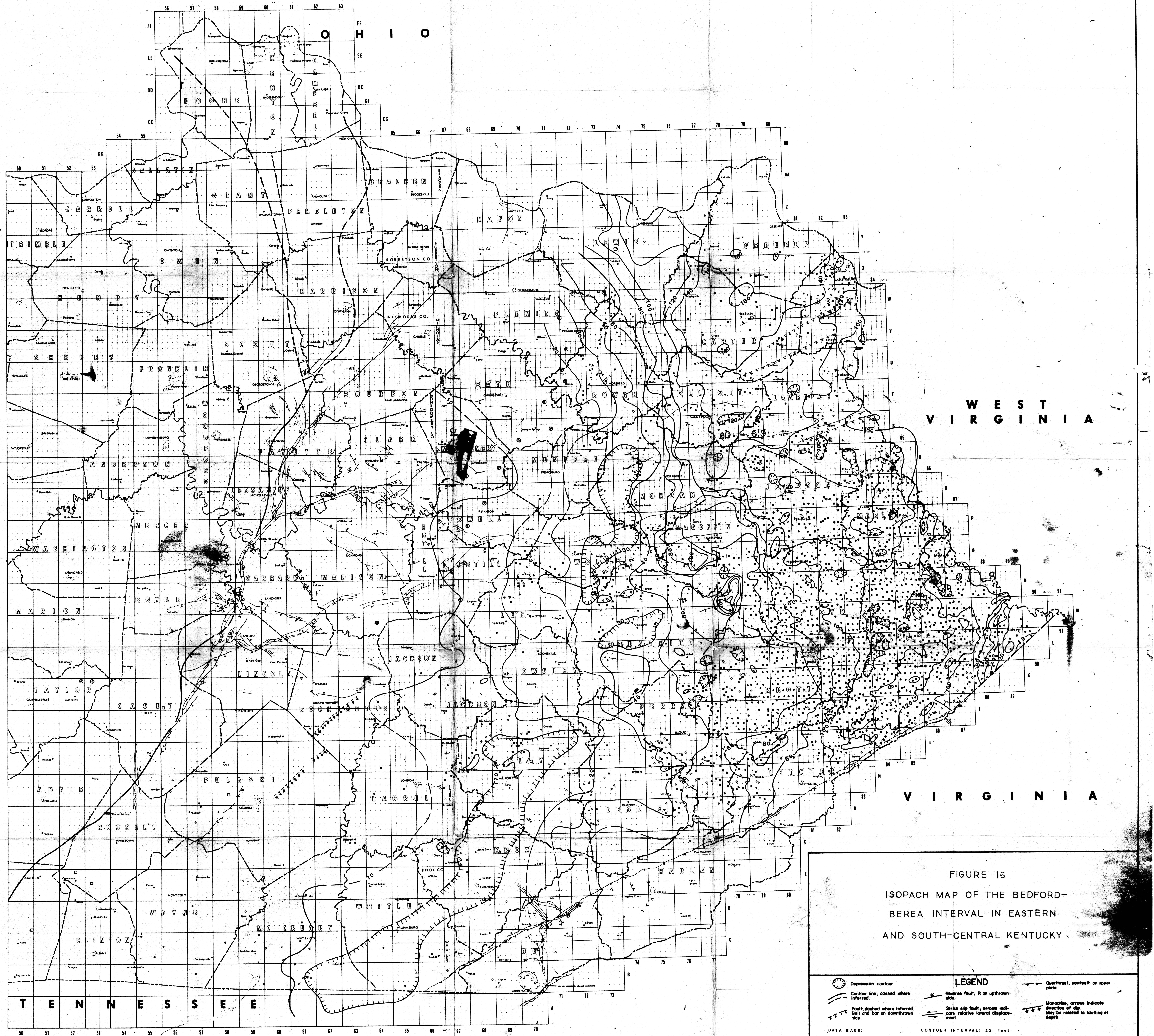


FIGURE 16

ISOPACH MAP OF THE BEDFORD–BEREA INTERVAL IN EASTERN AND SOUTH-CENTRAL KENTUCKY

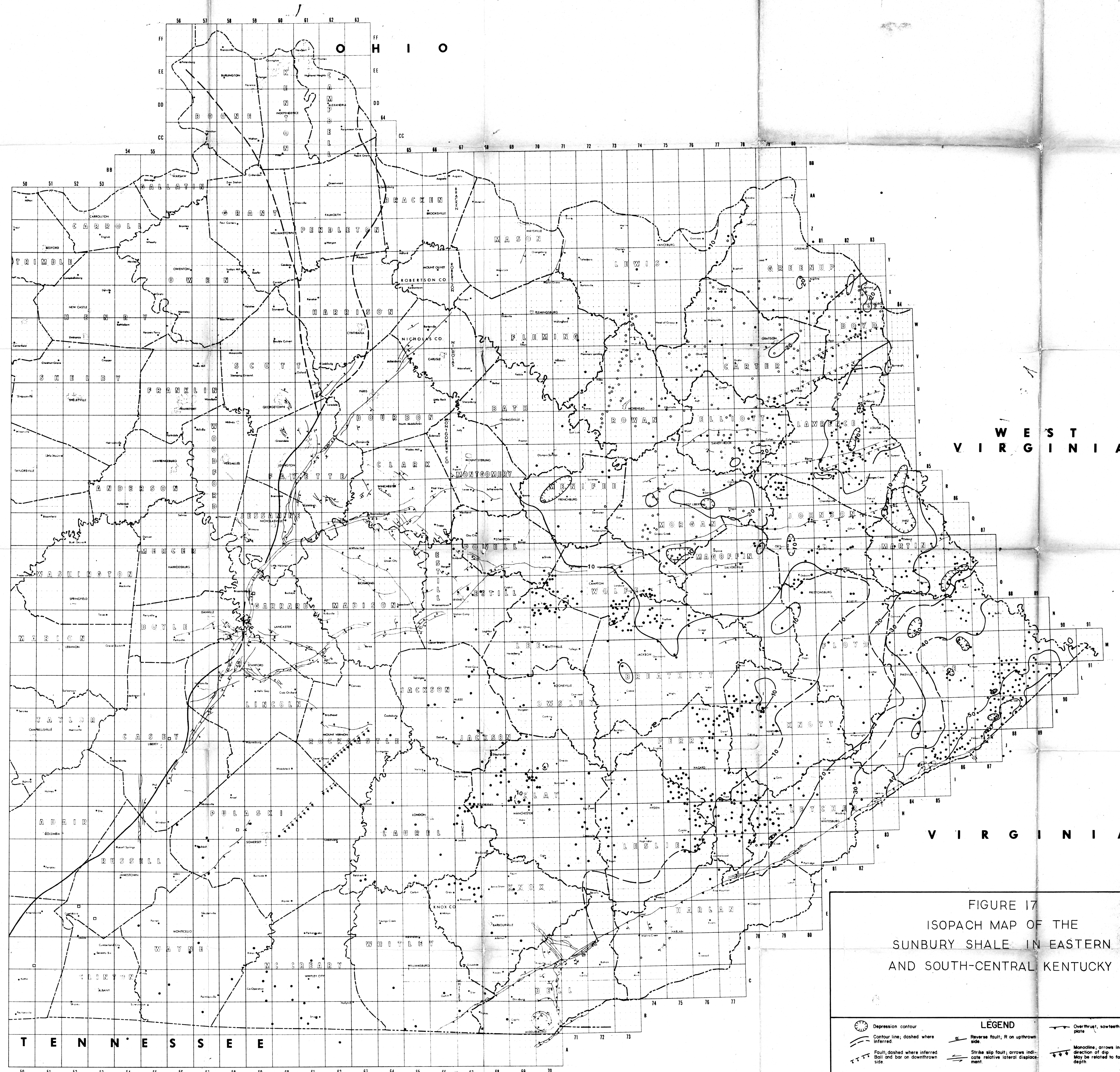


FIGURE 17
ISOPACH MAP OF THE
SUNBURY SHALE IN EASTERN
AND SOUTH-CENTRAL KENTUCKY

LEGEND

- Depression contour
- Contour line; dashed where inferred.
- Fault; dashed where inferred. Ball and bar on downthrown side.
- Reverse fault; R on upthrown side.
- Strike slip fault; arrows indicate relative lateral displacement.
- Overthrust, sawteeth on upper plate
- Monocline; arrows indicate direction of dip. May be related to faulting at depth

DATA BASE:

- ● gamma-ray log
- driller's log
- △ geol. quad. elevation
- ◎ core
- □ scintillated outcrop

CONTOUR INTERVAL: 10 feet

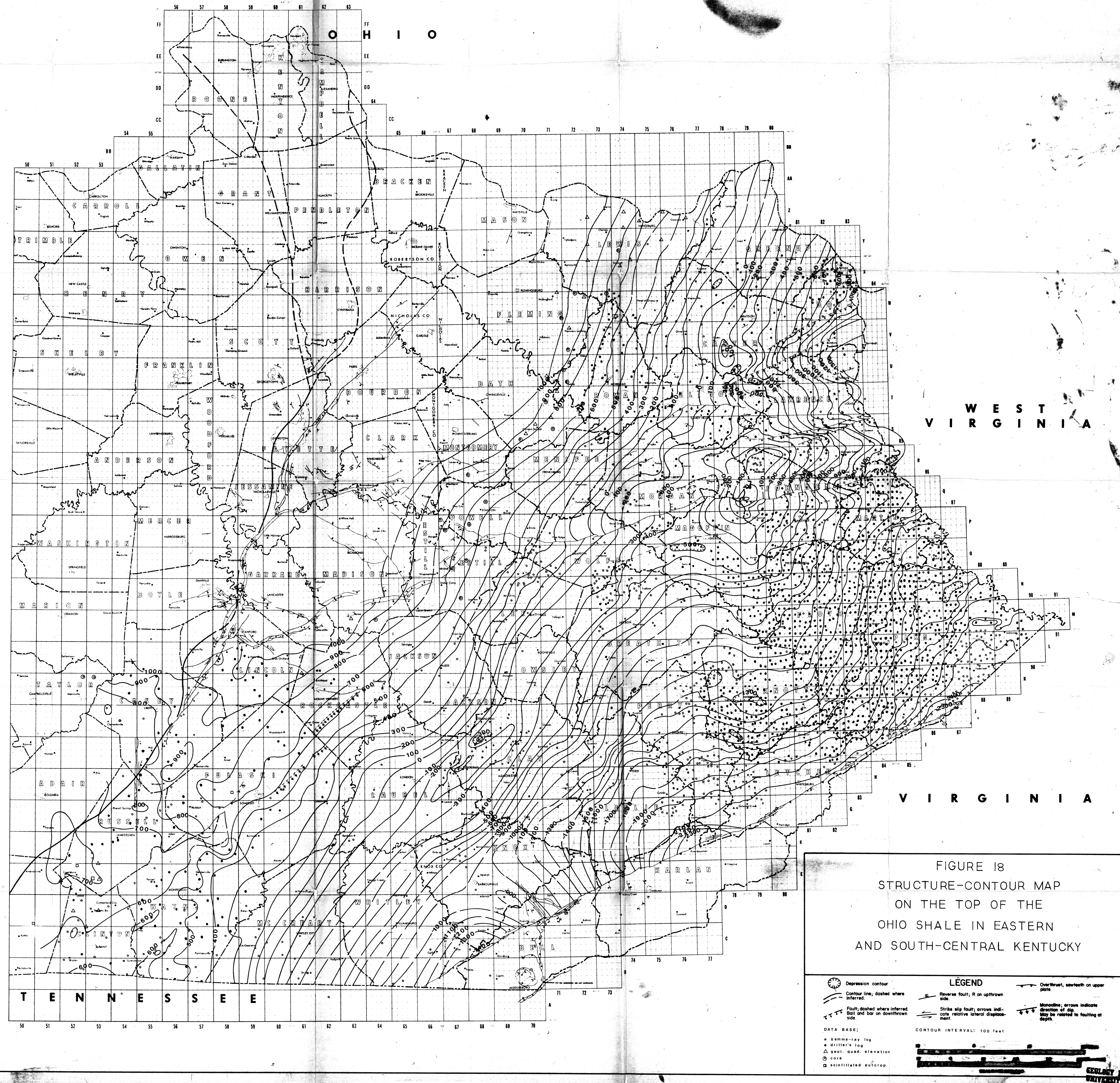


FIGURE 18
STRUCTURE-CONTOUR MAP
ON THE TOP OF THE
OHIO SHALE IN EASTERN
AND SOUTH-CENTRAL KENTUCKY

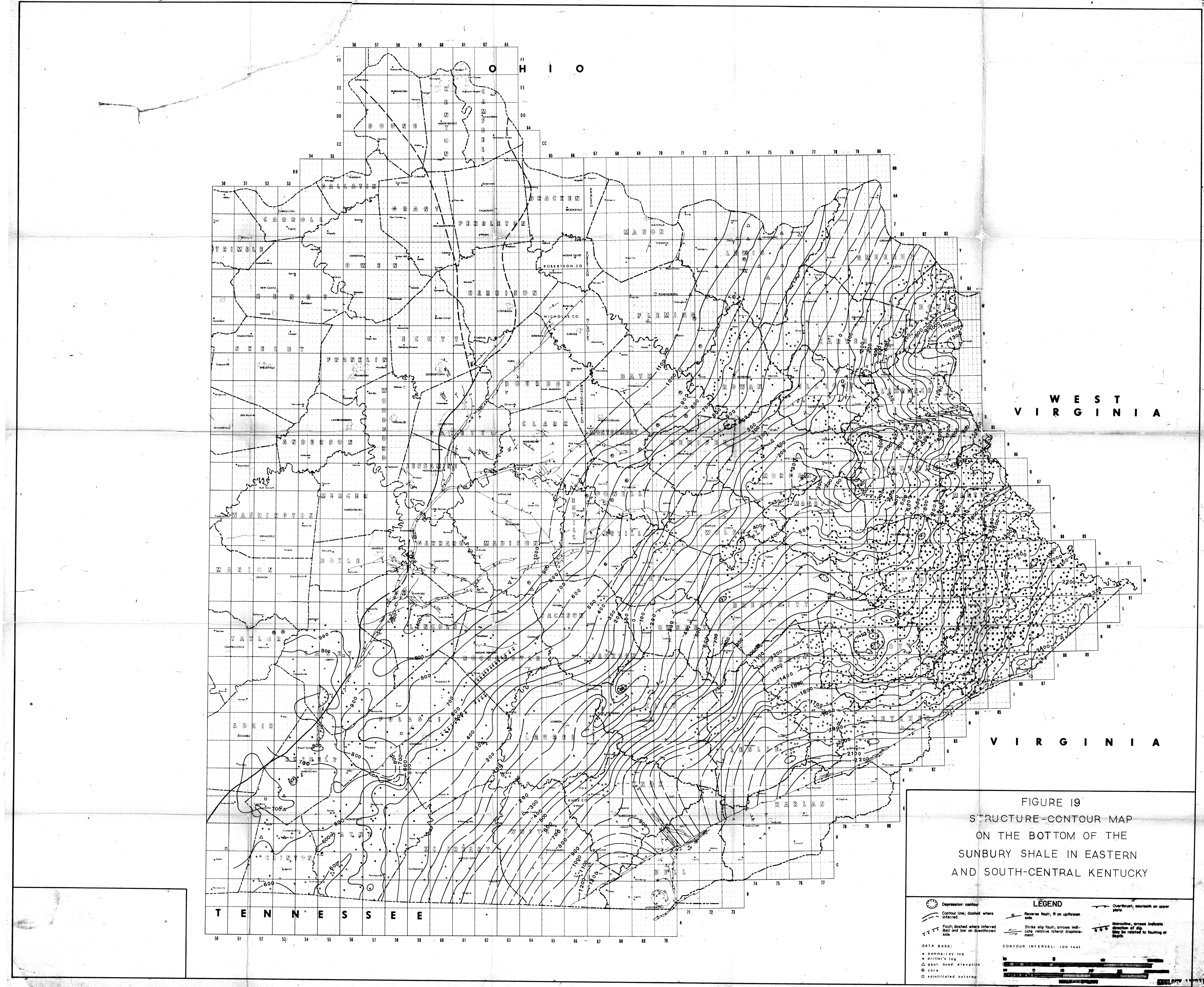


FIGURE 19

STRUCTURE-CONTOUR MAP ON THE BOTTOM OF THE SUNBURY SHALE IN EASTERN AND SOUTH-CENTRAL KENTUCKY

LEGEND

- Depression contour
- Contour line; dashed where inferred.
- Fault; dashed where inferred. Ball and bar on downthrown side.
- Reverse fault; R on upthrown side.
- Strike slip fault; arrows indicate relative lateral displacement.
- Overthrust; sawteeth on upper plate.
- Monocline; arrows indicate direction of dip. May be related to faulting at depth.

DATA BASE:

- gamma-ray log
- driller's log
- geol. quad. elevation
- core
- scintillated outcrop

CONTOUR INTERVAL: 100 feet

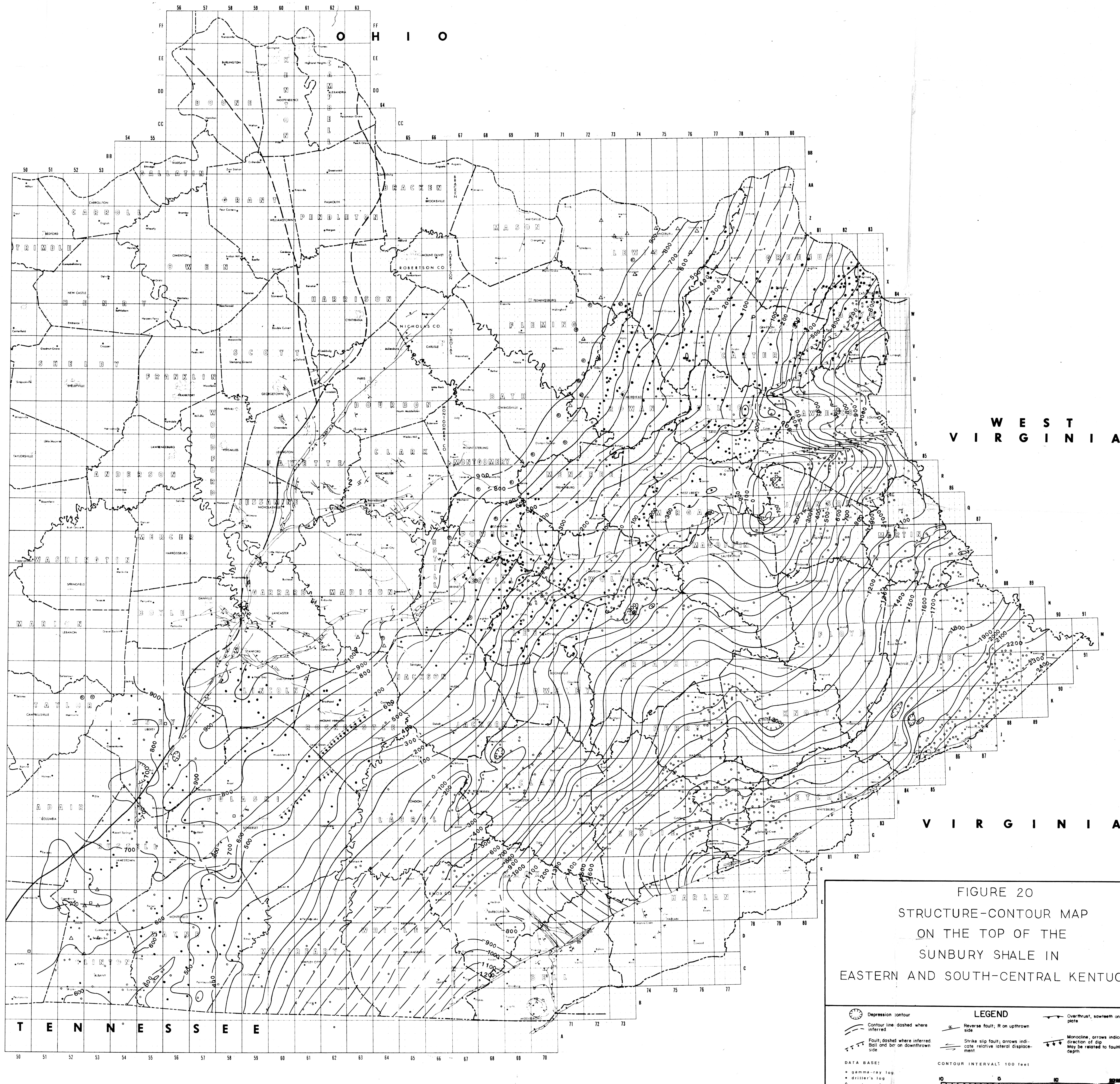


FIGURE 20
STRUCTURE-CONTOUR MAP
ON THE TOP OF THE
SUNBURY SHALE IN
EASTERN AND SOUTH-CENTRAL KENTUCKY

LEGEND

- Depression contour
- Contour line dashed where inferred
- Fault; dashed where inferred. Ball and bar on downthrown side
- Reverse fault; R on upthrown side
- Strike slip fault; arrows indicate relative lateral displacement
- Overthrust, sawteeth on upper plate
- Monocline; arrows indicate direction of dip. May be related to faulting at depth

DATA BASE:

- gamma-ray log
- driller's log
- geol. quad. elevation
- core
- scintillated outcrop

CONTOUR INTERVAL: 100 feet

SCALE = 1:370,000

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Thesis 1981

FIGURE 211

CROSS-SECTION A–B (GAMMA RAY LOGS)

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FIGURE 22

CROSS-SECTION C-D (OUTCROP SCINTILLOMETER PROFILES)

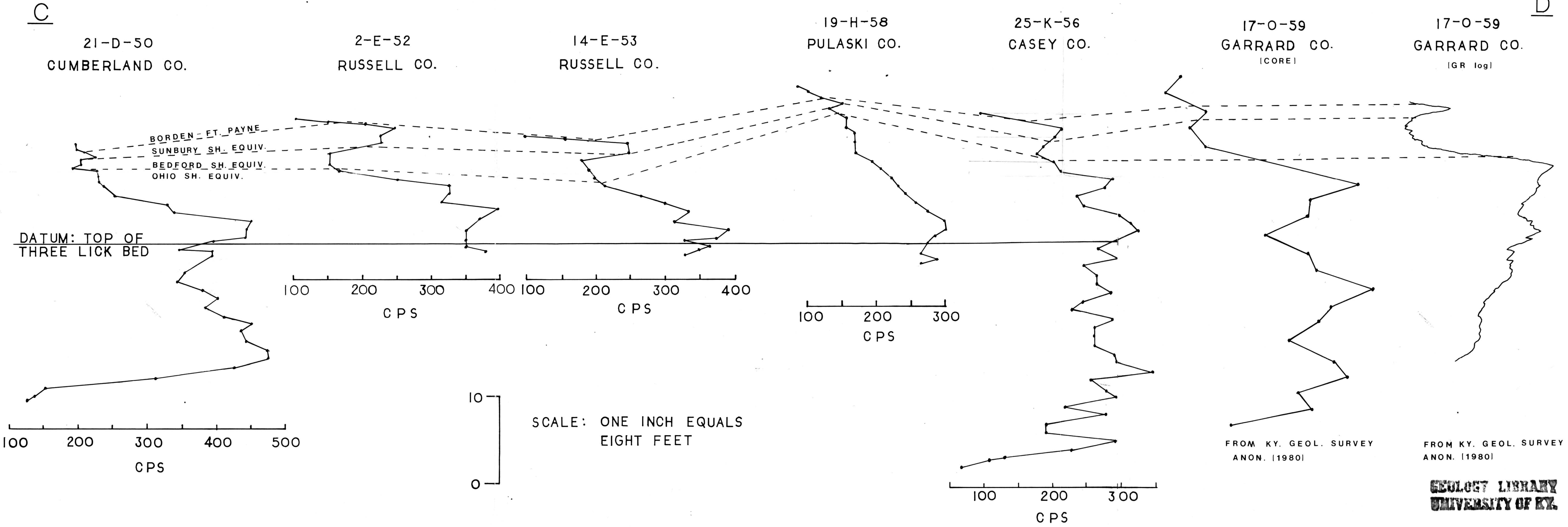

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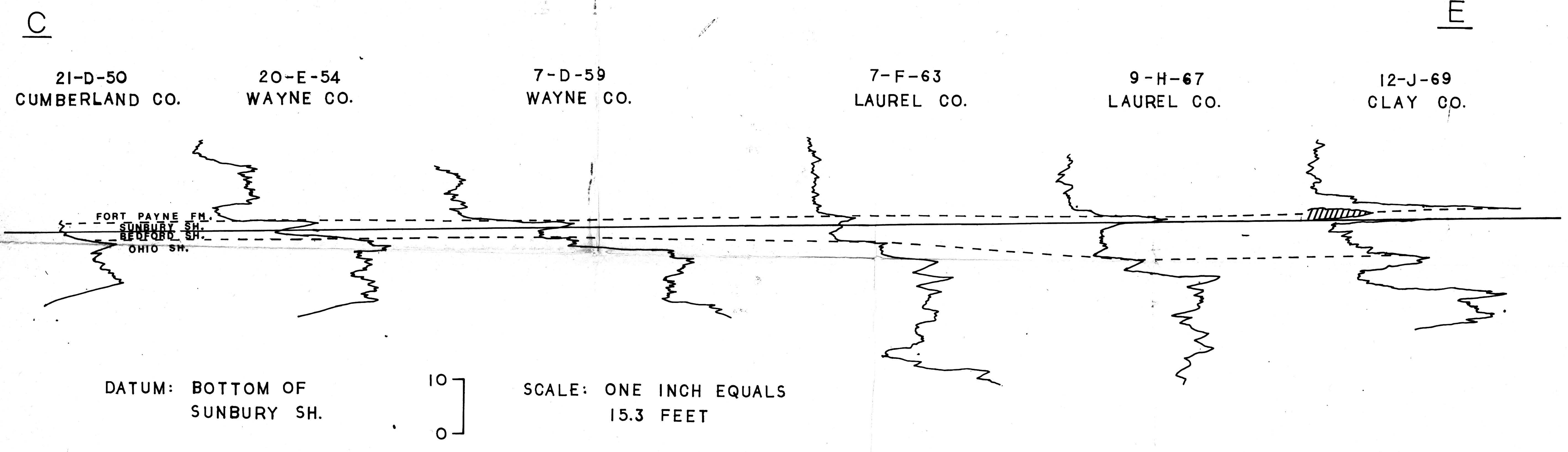
FIGURE 23

CROSS-SECTION C-E (GAMMA RAY LOGS)



DATUM: BOTTOM OF SUNBURY SH.

SCALE: ONE INCH EQUALS 15.3 FEET

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THESIS 1981

FIGURE 24
CROSS-SECTION - E-F (GAMMA RAY LOGS)

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THESIS 1981

FIGURE 25

CROSS-SECTION G-H (GAMMA RAY LOGS)