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OF THE CENTRAL APPALACHIAN BASIN.

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STRATIGRAPHY AND SEDIMENTOLOGY
OF RADIOACTIVE DEVONIAN-MISSISSIPPIAN SHALES
OF THE CENTRAL APPALACHIAN BASIN

A dissertation submitted to the
Division of Graduate Studies
of the University of Cincinnati
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requirements for the degree of

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in the Department of Geology
of the Graduate School of Arts and Sciences

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entitled Stratigraphy and Sedimentology of Radiactive Devonian-Mississippian Shales of the Central Appalachian Basin

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

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ABSTRACT

In eastern Kentucky and nearby, the Ohio Shale -- a radioactive, black, organic-rich shale of Late Devonian age -- consists of two dominant lithologic types, which occur in a distinctive stratigraphic sequence. These two lithologies are brownish-black, organic-rich shale and greenish-gray, organic-poor shale and mudstone. Five to seven stratigraphic subunits can be recognized easily in both the subsurface and outcrop and are traceable over most of eastern Kentucky and into parts of Ohio, West Virginia, and Tennessee. In descending order, these seven units are the Cleveland Shale, Three Lick Bed, Upper, Middle, and Lower Huron Shales, Olentangy Shale, and Marcellus(?) Shale. The first five of these units are correlatable with members of the Ohio Shale in Ohio and with members of the Chattanooga Shale of Tennessee. Correlations are less clear in West Virginia, because facies changes obscure the gamma ray definition of these stratigraphic subunits.

Black shale within the Ohio Shale in Kentucky typically contains 30 ppm uranium, while lighter-colored, organic-poor shale contains only 15 ppm. Uranium content of samples from five stratigraphic subunits in Kentucky ranges from 6 to 74 ppm; average content is 27.7 ± 3.2 ppm at 90 percent confidence limits. The amount of uranium varies with lithology and geographically, with those richest in uranium being black shales from Tennessee and Alabama. In Kentucky, the Ohio Shale is estimated to contain 6.28×10^{12} tons of uranium.

During Late Devonian time, two conditions were necessary for accumulation of black, organic-rich muds: production and preservation of abundant organic matter. Locally, a stratified water mass, a high rate of organic productivity, and a possible algal mat favored deposition of black mud. In the central Appalachian Basin, deposition of black shale as distal facies of turbidites and as shallow, cratonic deposits occurred in response to episodes of deltaic progradation and marine transgression associated with development of the Catskill delta. Transgressive and regressive pulses, in turn, were controlled by tectonism marginal to the North American craton and related to movement of continental plates.

Black shales of Late Devonian age have a widespread geographic distribution in North America and on three other continents, where depositional settings are much like those described for North America. In addition, in Europe black shale may also occur as basinal facies associated with reefs.

KEY WORDS: Devonian black shale, internal stratigraphy, subsurface mapping, uranium reserves, sedimentology, paleogeography, and worldwide equivalents.

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INTRODUCTION

Shales are the most abundant of all the sedimentary rocks, occur in every geologic period, and are estimated to comprise as much as approximately 80 percent of the sedimentary column. Color, because it is the most easily observed property of shales, is commonly used to describe and differentiate shales. Typical shale colors include gray, green, red, brown, and black. Black shales and muds are known from Precambrian sequences, such as the Nonesuch Shale of Michigan, as well as from recent sedimentary basins like the Black Sea.

One black shale in particular, the Upper Devonian-Lower Mississippian black shale of the eastern interior of the United States, has particularly interested many North American geologists. Those who live in areas where the shale crops out are impressed by its appearance, especially its blackness, its fissility, and its large concretions. Its petroliferous odor and its resemblance to coal have led to attempts to exploit the black shale for fuel.

Stratigraphers have recognized the importance of this black shale as "the geologist's plane of reference" (Safford, 1869, p. 329) and have concerned themselves with its age and with its transgression of the Devonian-Mississippian systemic boundary. They have also noted the wide geographic distribution of black shale in the United States. Sedimentologists have recognized that the black shale represents unusual and extensively uniform conditions of deposition, but have not been able to agree upon a depositional model.

Questions about depositional setting, such as water depth, circulation, and bottom conditions, can sometimes be resolved by paleontology, but the black shale is characterized by a depauperate fauna consisting chiefly of conodonts, inarticulate brachiopods, and fish parts. Other fossil remains occasionally found in black shale include radiolaria, foraminifera, cephalopods, scolecodonts, articulate brachiopods, pelecypods, crinoids, and sponges (spicules). Fossil wood (Callixylon) and algae (Foerstia) have been observed in outcrop and subsurface samples. Fauna has been of limited usefulness in paleoecologic studies because of wide environmental tolerances of some species found most commonly in black shale, such as linguloid brachiopods. Other fossils, like conodonts, are not diagnostic of specific environments. Biostratigraphic zones have been delineated by conodont and spore assemblages which occur in the black shale. Biostratigraphers, however, have not yet precisely determined the position of the Devonian-Mississippian boundary, as different faunal assemblages give different dates for the boundary. Furthermore, the particular ammonoids which were successfully used to zone the Devonian and Carboniferous in Europe are missing from North American sections.

Another notable characteristic of this black shale as compared with other marine shales is its high radioactivity caused by greater than normal concentrations of uranium. The nature of the uraniferous compounds, their mode of occurrence, and their origin are problems of interest to economic geologists and geochemists. Near the close of World War II, research projects to evaluate the potential of black

shale as a source of uranium were organized. Although the amount of uranium in marine black shales is very large -- some samples contain over 100 ppm -- it was concluded that the availability of other, higher-grade sources of uranium made mining of such shales unprofitable at present. In conjunction with studies of uranium, the unusually high organic content of black shales and their oil yields were investigated with the hope that processes used to extract uranium would also yield oil through distillation.

Although the organic content of these Devonian-Mississippian shales is high and ranges from one to twenty percent, they are not normally regarded as oil shales. Natural gas, however, has been produced for at least sixty years from the fields of eastern Kentucky, generally from wells with a low but remarkably continuous flow of gas. Exactly why these black shales produce gas remains an unsolved problem for geologists and explorationists. Because gas occurrence is perhaps controlled by joints and fractures, research programs to determine the specific properties of the shales which relate to gas production and to devise ways to stimulate production from currently nonproductive zones are now in progress.

Despite the numerous studies on nearly every aspect of the Devonian-Mississippian black shales, there obviously remain many unanswered questions about this unusual formation. Even before any specific questions about these shales can be answered, one must decide how to do a basin analysis of a shale. How can paleocurrents in shales be measured? Is it possible to determine the source of muds which

filled the basin? Can shales be separated into distinct depositional facies? How do shales respond to tectonism within or near a basin? Clearly, the usual techniques of basin analysis of coarser clastic basin fill must be modified for study of shales.

When approached from the point of view of basin analysis, additional specific questions relating to the Devonian-Mississippian shales of the Appalachian Basin should be asked. For example, what is the internal stratigraphy of this shale sequence, which in the eastern parts of the Appalachian Basin is over 2,000 feet (610 m) thick, and yet only 150 miles (241 km) to the west is as thin as 25 feet (7.6 m)? What depositional facies are represented by individual stratigraphic units? What depositional setting(s) best describes these black shales? Why were such conditions so widespread in North America during that period of geologic time? Where else may similar Devonian-Mississippian black shales be found? What was the history of development of the Appalachian Basin? Was its development similar to that of other black shale basins? Does a modern analogue for the black shale exist, or are areally extensive, organic-rich radioactive shales a phenomenon of only the Late Devonian or Late Paleozoic? What are the differences and similarities between these shales and organic-rich, black shales of other geologic periods? How many different basin models for black shale are known?

Closely related to these questions about depositional environment of black shale are paleontologic problems. Of what significance to the depositional environment are the fauna and flora of black shale? What

may be inferred about Devonian-Mississippian climate from paleontology and paleoecology? Are there any faunal assemblages which may be used to establish the position of the Devonian-Mississippian boundary, or any other time plane within the unit? Are the Ohio Shale and its correlatives entirely Devonian in age or transitional across the systemic boundary?

Geochemistry of the depositional environment controlled, in part, composition and paleontologic assemblages of the black shale. But what were the geochemical conditions during black shale deposition, and can any geochemical facies be recognized? Do geochemical facies correspond to depositional or lithologic facies? What is the source and nature of the organic material in the shale? What is the relationship between organic matter and uranium?

In a larger framework, the sedimentology of black shale possibly depends on tectonics. What is the character of the shelf-to-basin transition of these black shales and what does it mean? Does deposition of black shale represent a singular tectonic event? In the context of plate tectonic theory, where in time and space are black shales found with respect to former positions of continental masses? Can tectonics be used to explain the occurrences of Devonian-Mississippian shales worldwide?

Finally, economic geologists may raise questions of a more applied nature with regard to gas production from the Devonian-Mississippian shales. What are the economic constituents of these organic shales and how may they be exploited most advantageously?

Where does natural gas occur? By what techniques may productivity be increased? Are there economically important quantities of uranium in these shales? Perhaps before these questions are asked, basic geologic questions should be answered. For instance, what geologic controls determine present producing fields? Are fractures or more porous silty zones responsible for production? Which of these parameters most influences production: thickness? structure? tectonics? How is stratigraphy of the black shale related to uranium concentration?

All of these questions constitute a comprehensive, integrated program of study of Devonian-Mississippian black shales. Answering some of these questions will be accomplished in this study by dividing it into two parts. The first is a basin analysis of these shales in the subsurface and in outcrop from the central Appalachian Basin, where they are best developed. This part will lead to an understanding of the stratigraphy, clastic and chemical sedimentology, and tectonic setting of this unusual formation. The second part is larger in scope and consists of locating black shales of Devonian-Mississippian age worldwide. In this way, black shales of the Appalachian Basin may be compared to those from other North American basins and from other continents in terms of geologic and tectonic settings. These comparisons will offer insights into the megasedimentology of radioactive, organic-rich black shales from around the world and from other geologic times.

DEVONIAN-MISSISSIPPIAN BLACK SHALE
IN THE CENTRAL APPALACHIAN BASIN -- CHARACTERIZATION

Location and Formations

The Devonian-Mississippian shale sequence in the central Appalachian Basin was studied from its exposure on the western margin of the basin in Kentucky eastward into the subsurface of West Virginia and Virginia (Figure 1). The Ohio Shale and its equivalents, the Chattanooga and New Albany Shales, were also studied in northernmost Tennessee and southeastern Ohio. Ten outcrop sections were measured and described (Figure 2 and Appendix A), and over 900 wells were examined for subsurface mapping of the Ohio Shale (Figure 3). Approximately half of these wells have wire-line logs (Figure 3). In addition, 28 sets of well samples and one core were described (Figure 3).

Review of Previous Studies

The Devonian-Mississippian shale sequence of the central Appalachian Basin has been studied by many stratigraphers and paleontologists who generally limited their investigations to the area of a single state or less. Conant and Swanson (1961) provided a detailed stratigraphy of the Devonian-Mississippian shale sequence in Tennessee and suggested that some of their stratigraphic units were traceable into southern Kentucky (their fig. 11). Stratigraphy of Devonian-Mississippian shales in Ohio was clarified and restated by Hoover (1960). The history of stratigraphic studies of the Ohio Shale, however, goes back to the early Twentieth Century when Prosser (1903, 1912, 1913)

FIGURE 1.--Location map of samples analyzed for uranium oxide and area of subsurface study. Area underlain by Devonian black shale is lightly stippled.

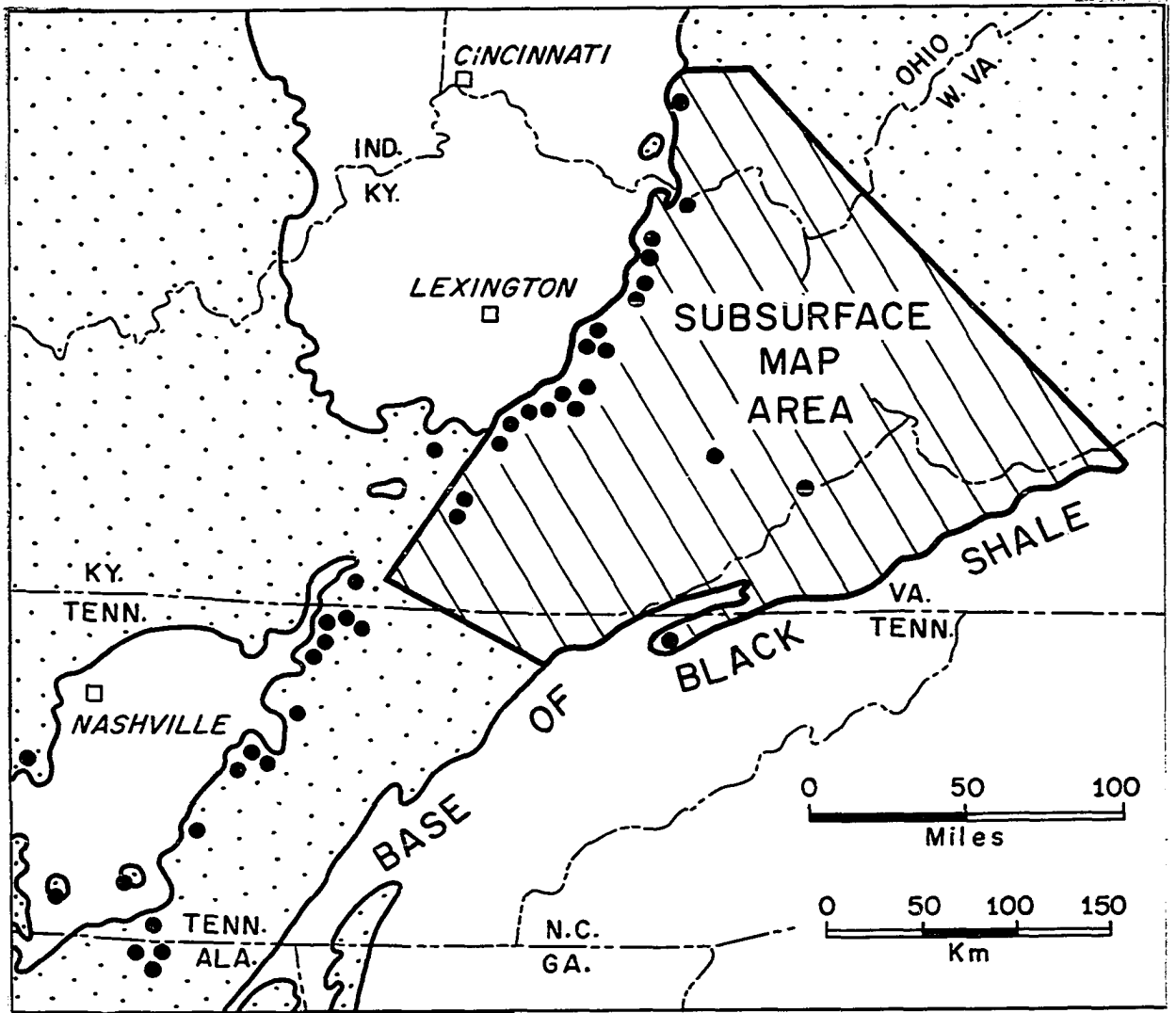
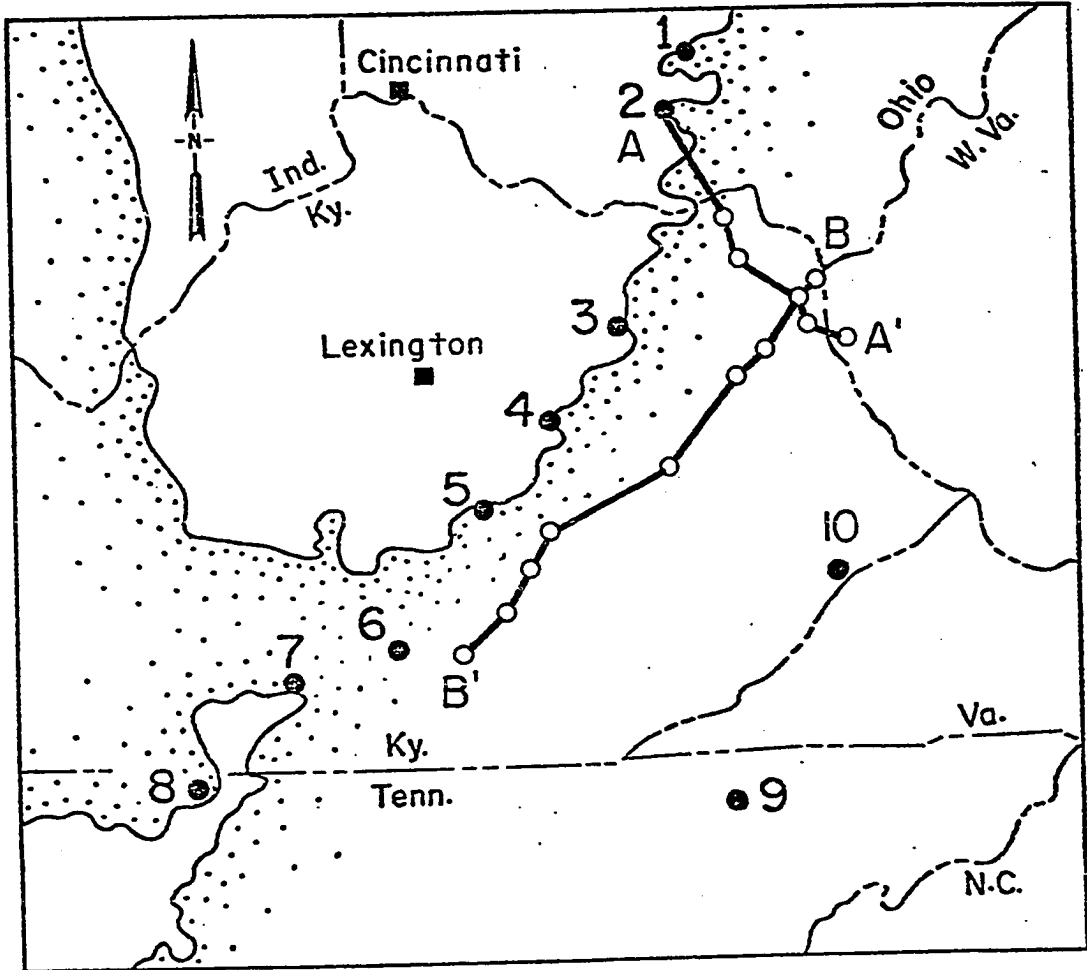
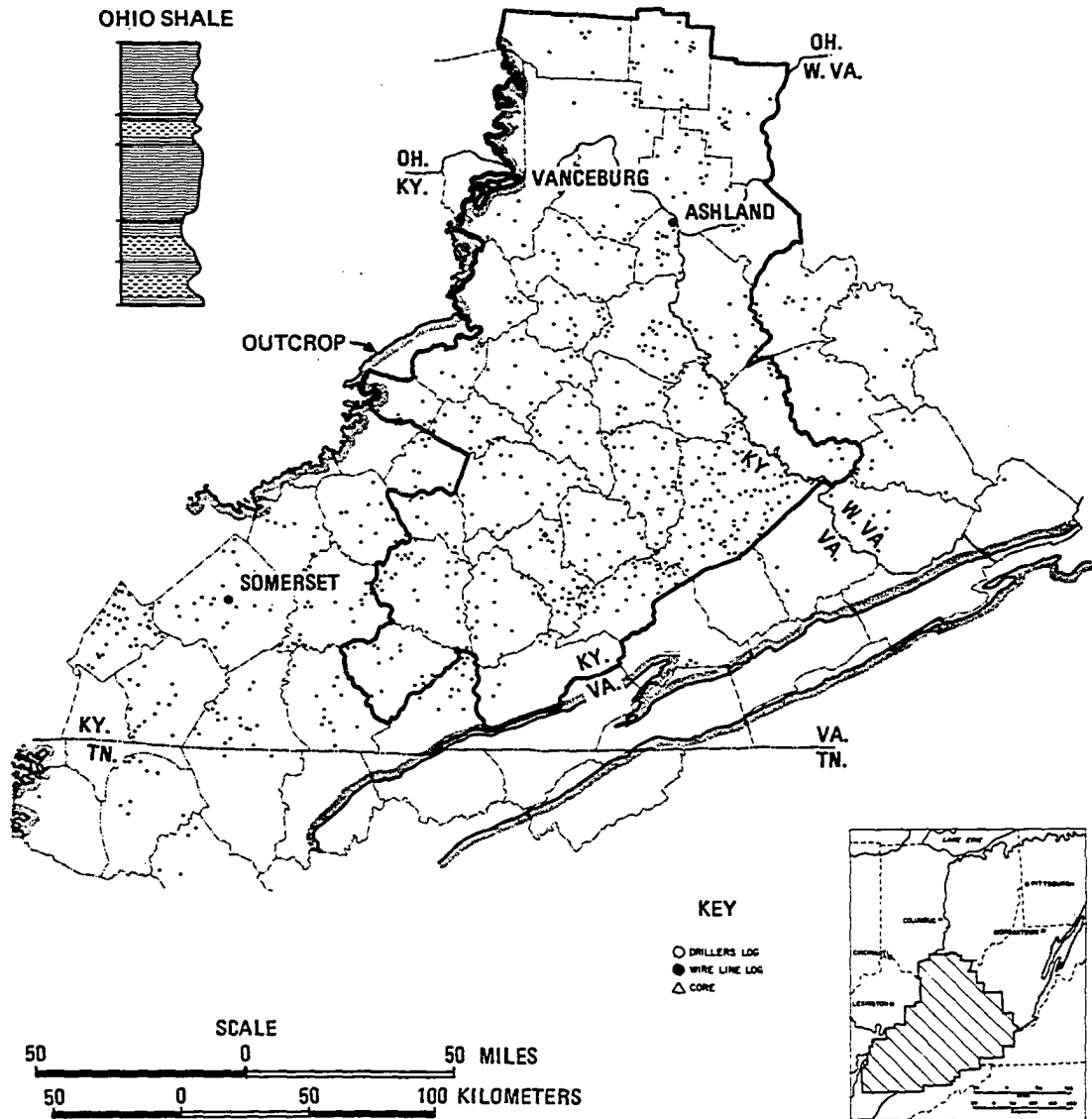


FIGURE 2.--Location map of ten outcrop sections and lines of section for cross sections of Figure 15.



● Measured Outcrop ○ Well

FIGURE 3.--Well control map, showing counties where five to seven subunits of Devonian shale sequence are recognizable.



published several lengthy articles on Devonian-Mississippian formations of Ohio.

For Kentucky, there is only one stratigraphic study which is comparable in detail to those of Tennessee and Ohio. Campbell (1946) defined five stratigraphic units in the New Albany Shale in southern Indiana and extended them southeastward into central Kentucky. Devonian-Mississippian black shales, of course, were recognized by other Kentucky stratigraphers such as Savage (1930a) and Freeman (1951), but only as a single, indivisible unit.

As the Devonian-Mississippian shale sequence of the central Appalachian Basin is traced eastward into Virginia, West Virginia, and Pennsylvania, less and less information about its stratigraphy is available, largely because of lack of surface exposures. Until recently, the only mention of rocks equivalent to the Ohio Shale occurred in basin-wide correlation charts and on large-scale isopach maps such as those by Oliver and others (1967, 1969, 1971). Much progress in delineating stratigraphic units in Devonian-Mississippian shales in the central and eastern portions of the Appalachian Basin is currently being made, and the most up-to-date compilation of stratigraphic studies for West Virginia is a collection of papers presented at the Seventh Appalachian Petroleum Geology Symposium in 1976 (Patchen and Larese; Martin and Nuckols; Bagnall and Ryan). These authors defined three or four recognizable zones based on gamma ray characteristics and lithologies obtained from sample descriptions and traced these zones as far east as possible.

In addition to stratigraphy, the paleontology and age of the Devonian-Mississippian shale sequence have been studied. The unusual, if sparse, fauna of the Ohio Shale and its equivalents includes conodonts (Hass, 1947; 1958), radiolarians (Foreman, 1959; 1963), crinoids (Wells, 1941), fish (Dunkle and Schaeffer, 1973), and brachiopods (Campbell, 1946). The abundance of plant fossils from Devonian-Mississippian shales has resulted in numerous paleobotanical studies, some of which discuss flora of Devonian-Mississippian shales worldwide (Cross and Hoskins, 1951) or by formation (Read, 1936; Read and Campbell, 1939). Others deal with occurrence and significance of individual plant genera such as Foerstia (Schopf and Schwietering, 1970; Phillips and others, 1972), Callixylon (Wells, 1941; Romans, 1972), or groups like spores, chitinozoa, and acritarchs (Winslow, 1962; Bharadwaj and others 1971; Wicander, 1975).

Related to paleontological studies is the problem of the age of the Ohio and Chattanooga Shales, which are generally believed to contain the Devonian-Mississippian boundary. Those who have commented on the age of these shales include Swartz (1929), Savage (1930b), Savage and Sutton (1931), Keyes (1938), Hass (1956), and Conant and Swanson (1961).

Another aspect of Devonian-Mississippian shales -- one perhaps which has not been so thoroughly investigated -- is the geochemistry. For the Chattanooga Shale, Breger and Brown (1963) identified types of organic matter; Smith and Young (1967) made a similar study of Kentucky's New Albany Shale. Other geochemical studies deal with

black, organic-rich shales from all geologic periods and from many different basins, in addition to the Devonian shales of the Appalachian Basin (Vine, 1966, 1969; Vine and Tourtelot, 1969, 1970; Vine and others, 1969); Stevenson and Dickerson, 1969). The emphasis of these reports generally is on identification and distribution of trace elements, one of which (uranium) has been of particular interest (Kornfeld, 1964; Swanson, 1956, 1960a, 1960b; Conant and Swanson, 1961; Glover, 1961; Hickman and Lynch, 1967).

Finally, depositional environment of Appalachian black shales has long been a source of controversy, the arguments being primarily over water depth. Advocates of a deep-water environment (Rich, 1951) cite fine stratification, abundance of organic matter, presence of phosphate nodules, presumed slow sedimentation, and paleontology as evidence supporting water depths of several hundred feet. Rich (1951) suggested that deposition of the Ohio Shale and its equivalents occurred in deep, unaerated portions of an areally extensive marine basin characterized by a low rate of sediment supply. More recently, a deep-water origin for the uppermost portion of the Ohio Shale (the Cleveland Shale) was proposed (Lewis and Schwietering, 1971, p. 3482). These authors maintained that the Cleveland black shale is a distal deltaic facies which was deposited in deep, restricted areas of an inland sea. No specific water depths, however, were suggested.

A shallow-water origin for these same Devonian-Mississippian shales, however, is the more popular argument (Conant, 1956; Swanson, 1956; Glover, 1961; Conant and Swanson, 1961; Breger and Brown, 1963).

Among the early supporters of a shallow-water origin for Devonian-Mississippian shales were Grabau (1906, p. 612-613), who believed that black shale represented reworked residual soil derived from a peneplain, and Stockdale (1939, p. 38), who described the Chattanooga Shale of Tennessee and Kentucky as a shore or nearshore facies.

In more recent interpretations of the Chattanooga Shale, evidence of deposition in a shallow, epicontinental sea with water depths less than 100 feet includes: (1) presence of a basal unconformity; (2) shallow-water sedimentary features; (3) overlapping relations; (4) occurrence of linguloid brachiopods; (5) overlying strata of deeper water origin; (6) long history of shallow-water sedimentation in this part of the Appalachian Basin (Conant and Swanson, 1961, p. 60-62). In one reconstruction of the depositional environment of the Chattanooga Shale, sedimentation in Tennessee during late Devonian time is compared with that occurring in modern salt marshes in coastal Louisiana (Breger and Brown, 1963, p. 745) where black, organic-rich muds are now accumulating. A similar interpretation of depositional setting for the Chattanooga Shale is offered by Conant (1956, p. 466) and by Conant and Swanson (1961, p. 52 and 62; fig. 12), who suggest that black muds were deposited in shallow, almost land-locked embayments which eventually coalesced into a single epicontinental sea covering much of southern Kentucky, Tennessee, and northern Alabama.

Similarly, Lineback (1968, p. 1301-1303) has proposed that southern Indiana's New Albany Shale, an equivalent of the Ohio Shale,

was deposited in a quiet, widespread inland sea which received large amounts of organic matter from a floating algal mat ("flotant"). When the flotant was destroyed or disrupted, shales without organic matter were deposited. Most importantly, Lineback has suggested that water depth was not a factor controlling the origin of Devonian-Mississippian black shales and that locally deep areas were present within the basin. Although Lineback studied Devonian-Mississippian shales in the Illinois Basin, his ideas may also apply to the New Albany's lithologic and stratigraphic equivalents in the central Appalachian Basin.

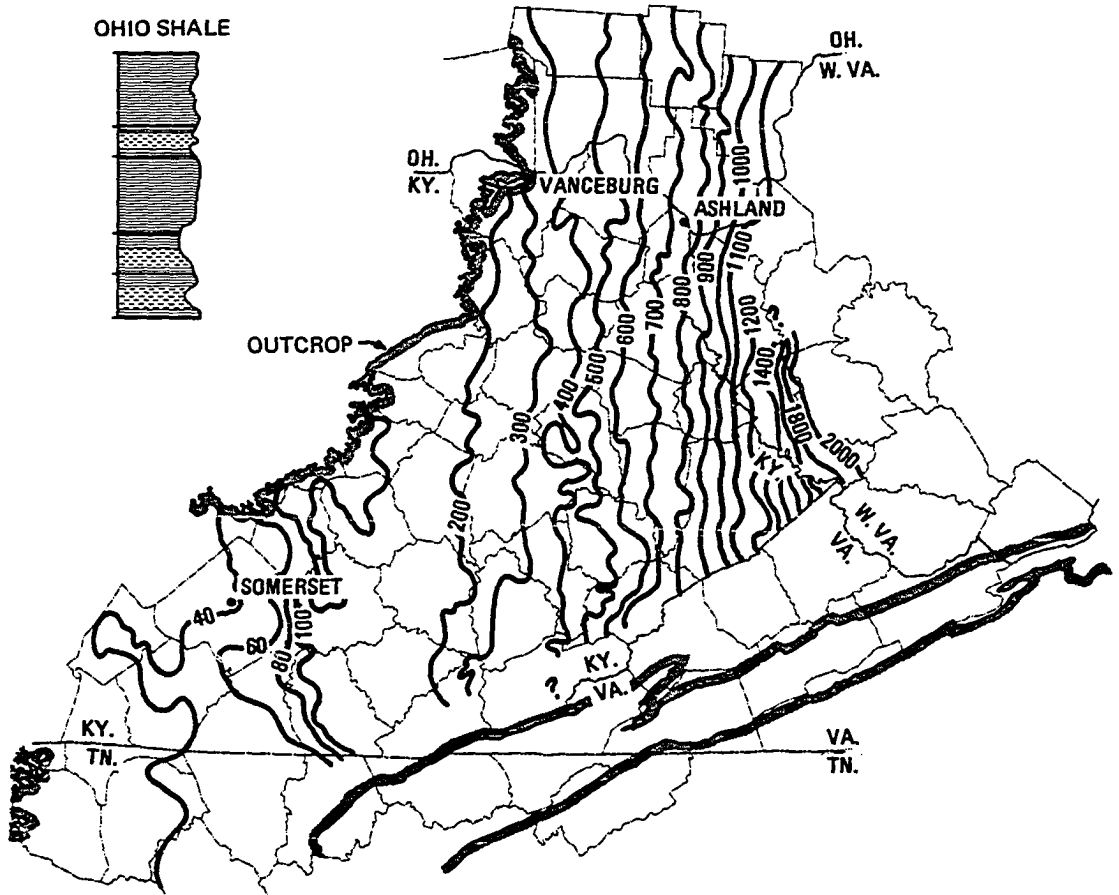
Extent and Thickness of Black Shale

The Ohio Shale and its equivalents are thinnest in the southwestern corner of the study area, where outcrop sections may be only 20 feet thick (Appendix A, section 8), and subsurface sections are typically 40 feet or less in thickness (Figure 4). The Devonian-Mississippian shale sequence thickens greatly to the east, attaining a maximum thickness of 2,500 feet (762 m) in West Virginia (Figure 4), and also to the north. In southern Ohio, outcrop thicknesses exceed 200 feet (61 m) (Appendix A, section 2) and subsurface sections may be more than 1,000 feet (305 m) thick (Figure 4).

Major Lithologies

Throughout the study area, the Devonian-Mississippian shale sequence consists of two dominant lithologies -- brownish-black, organic-rich shale and greenish-gray, organic-poor shale or mudstone (Figure 5). Two other lithologies, limestone with cone-in-cone structure and siltstone, also occur, but only in thin beds. Dolomitic

FIGURE 4.--Total isopach map for the Devonian shale sequence (Ohio, Olentangy, and Marcellus(?) Shales). Note rapid thickening in easternmost Kentucky and western West Virginia.



OHIO, OLENTANGY & MARCELLUS (?) SHALES

CONTOUR INTERVAL = 100'
(20' WEST OF 84° 15')

PREPARED BY LINDA J. PROVO
UNIVERSITY OF CINCINNATI
FOR
ERDA CONTRACT AT (05-1) - 1650
1976

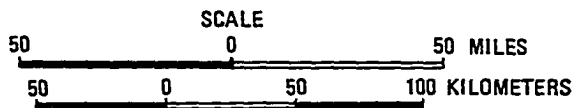
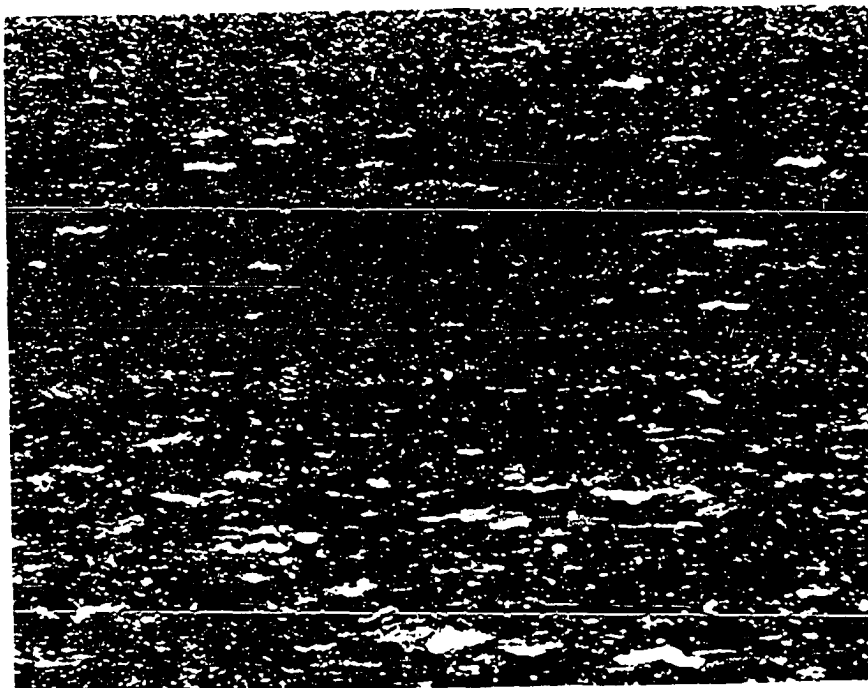


FIGURE 5.--Photomicrographs of thin-sections of shaly lithologies from the Upper Devonian shale sequence:

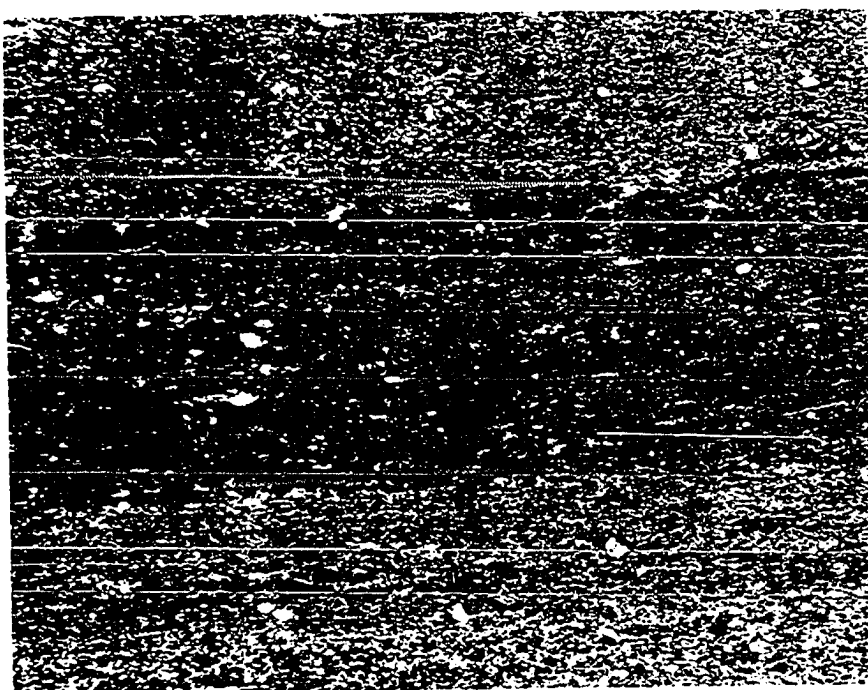
A. Dark, organic-rich shale. Sample no. 17381. Note shreds of organic matter (white) which define bedding, and variation in concentration of organic matter, shown by light and dark bands. 40x.

B. Light, organic-poor shale enclosing a band of dark, organic-rich shale. Sample no. 17384. 40x.

A.



B.



mudstone, shale, and sandstone are also present locally in the lower part of the shale section (Appendix A, sections 4, 5, and 6). Detailed hand-specimen descriptions of these lithologies as observed in ten outcrops are provided in Appendix A.

In fresh exposures, brownish-black, organic-rich shale (Figure 5.A.) is massive, dense, and fractures subconchoidally. Weathering of this shale produces fissile, brittle plates and chips which are bleached light-gray in color. Dark shale is well-laminated (Figure 5.A.), a characteristic emphasized by its fissility. Pyrite is abundant as scattered spherules, blebs, nodules, and aggregates which are locally concentrated along bedding planes. White and yellowish sulfate and reddish and brownish oxide resulting from the weathering of pyrite coat joint and bedding plane surfaces. Phosphate nodules, ovoid to amoebiform in shape, are common in the upper part of the Devonian-Mississippian shale sequence, forming a persistent horizon over most of the study area (Appendix A, sections 3 through 8).

In contrast, organic-poor shale and mudstone (Figure 5.B.) is greenish-gray to light olive-gray to medium light-gray and weathers to light-gray and yellowish-gray clay, forming recessive layers less resistant than black shale and readily covered by talus. Organic-poor shale is silty, pyritic, and locally concretionary. In general, it is poorly laminated with a hackly fracture and commonly occurs interbedded with darker, organic-rich shale in thin couplets usually a few tenths of a foot in thickness.

Plant and animal fossils were observed in both of these lithologies. Common plant fossils include round, spore-like Tasmanites (Wall, 1962), coalified fragments of Callixylon, and the fossil alga Foerstia, which occurs in a well-defined zone ranging from three to forty-three feet in thickness (Appendix A, sections 2, 3, 4, 5, and 9). Schopf and Schwietering (1970) describe this distinctive fossil and show its distribution in Devonian black shale within and nearby the study area of this report.

Conodonts, phosphatic remains of linguloid and orbiculoid brachiopods, and fish parts are locally common on bedding planes. Smooth-sided, gently curved burrows are present, most commonly at the contact between dark shale and overlying greenish-gray shale.

Minor Lithologies

Minor lithologies, such as limestone and siltstone, occur in beds whose thickness ranges from 0.1 foot to 2 feet. Limestone beds with cone-in-cone structure may be continuous or discontinuous and are present in the upper one-third of the shale sequence in outcrops along the western margin of the study area (Appendix A, sections 1 through 5). They are typically stained reddish-brown.

Siltstone is present as discrete, continuous beds only in outcrops in the eastern portion of the study area (Appendix A, sections 9 and 10). Siltstone beds contain fine specks of organic debris, are micaceous and argillaceous, and are stained with limonite. Planar and ripple-cross-lamination is present, and bedding may be disrupted by burrows. Trace fossils also occur on bedding surfaces. Flute casts and faint current

lineations are present on the soles of some beds, and T_{ab} and T_{abc} Bouma (1962) sequences occur in a few siltstone beds.

Petrographic examination of about 25 thin sections of samples selected from these two lithologic types provided the following additional information. Dark, organic-rich shale consists primarily of the clay mineral illite with minor amounts of chlorite (identified by X-ray analysis), clay-sized quartz, and organic matter. Organic matter is typically reddish-brown and occurs in three forms (Figure 5.A.): (1) shreds and flakes parallel to bedding; (2) flattened cases of the spore-like Tasmanites; and (3) amorphous masses which lend a deep-reddish-brown color to fine particles of clay and quartz, making it difficult to estimate the amounts of these constituents in thin section. Dark shales which are particularly rich in organic matter are estimated to contain up to 25 percent organic matter.

Minor constituents of organic-rich shale -- those which generally make up no more than ten or fifteen percent of this lithologic type -- are quartz, pyrite, and dolomite. Quartz occurs as single grains or in laminae only a few grains thick. Grains are medium- to coarse-silt-sized, angular to elongate, and monocrystalline. Pyrite is present as blebs, spherules, euhedral crystals, and framboidal masses, and dolomite as irregularly shaped grains and rhombs 0.005 to 0.06 mm in size. Individual grains of chert, muscovite, and plagioclase feldspar occur rarely.

Organic-poor shale and mudstone differ from dark, organic-rich shale in containing notably less organic matter (Figure 5.B.). The

amount of clay minerals and minor constituents such as quartz, pyrite, and especially dolomite correspondingly increases. Lighter color of this lithology can be attributed to virtual absence of fine, amorphous organic matter.

Bedding

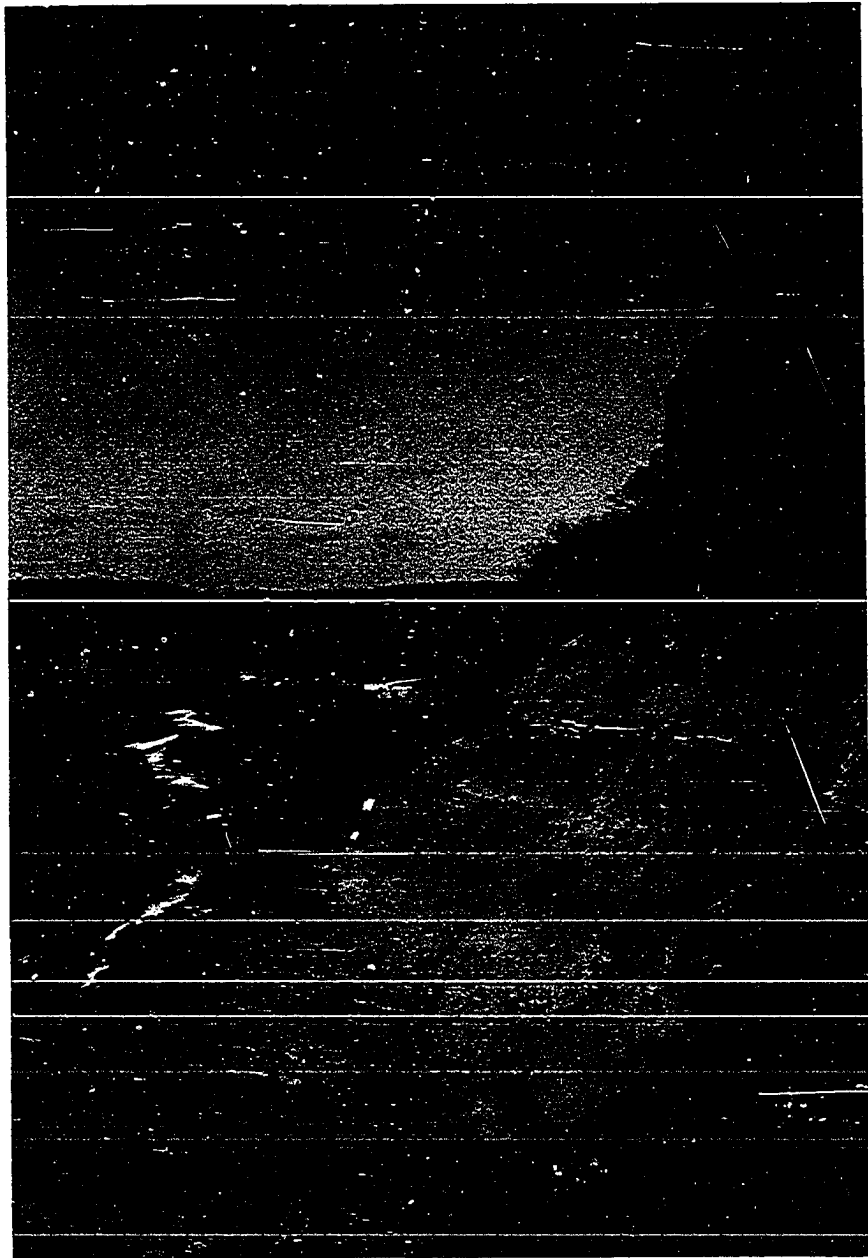
In both of these lithologies, bedding is emphasized in several ways. Shreds of organic matter and flattened spores lie parallel to bedding, as do elongate quartz grains. Variation in amounts of certain constituents also defines bedding. For example, concentration of organic matter is not uniform but increases and decreases from bedding plane to bedding plane, a feature generally recognizable by changes in color (Figure 5.B.).

Laminae of quartz silt also accentuate bedding, and pyrite blebs and spherules, when present, may be concentrated along bedding planes. Fine-grained (0.06 mm and less) dolomite may also occur in laminae one or two grains thick. In organic-poor shale and mudstone, these constituents rather than organic matter define bedding when it is present in this lithology. Such shales, however, are typically poorly laminated because of the lack of contrast in lithologic constituents and lack of platy, organic particles, both of which emphasize bedding.

Banding

In outcrops, cores, and thin section, the alternation of black, organic-rich shale and greenish-gray, organic-poor shale produces a banding (Figure 6) which must be related to depositional events,

FIGURE 6.--Megabanding in the Devonian shale sequence at Copperas Mountain near Bainbridge, Ohio (see Figure 2, location 1). Massive, dark-colored cliff in the upper right-hand portion of the photograph is the Cleveland Shale, which is underlain by alternating black and gray shales of the Three Lick Bed. Below the third gray shale bed of the Three Lick is the Upper Huron Shale.



possibly turbidity currents. Hesse (1975, Table 2), for example, suggested that lithologic characteristics such as color, bioturbation, grain size, and grading can be used to differentiate turbiditic mudstones from pelagic mudstones, thus defining their origin. The banding in Devonian-Mississippian shales (Figure 6) -- which is produced by differences in lithologic constituents -- may be of a similar origin. Organic-poor shales were probably deposited when there was an increase in clastic materials introduced into the basin, perhaps by turbidity currents some distance from where these shales were being deposited. Such an increase would dilute the relative amount of organic matter in these shales by cessation of either production or preservation of organic material. During the intervals between turbidity currents, organic-rich shales could be deposited, as clastic input would be minimal. If the origin of organic-poor shales is related to non-production of organic matter, seasonal or longer-term changes in organic supply and, therefore, in productivity, may explain the alternation of dark and light shales. But if organic matter was produced and not preserved in these shales, a change in paleocirculation, creating mildly oxidizing conditions, could account for the banding observed in the Ohio Shale. The markedly burrowed zone at the base of one megabanded unit (Three Lick Bed; Figure 6, and Appendix A, section 3) supports such an increase in oxygenation.

The occurrence of siltstone beds in outcrops of the Devonian-Mississippian shale sequence in eastern Kentucky and Tennessee with turbiditic characteristics such as partial Bouma (1962) sequences,

sole marks, and alternation of coarse- and fine-grained rocks, strongly suggests that turbidity currents are the cause of at least part of the microscopic and megascopic banding in these shales. Turbidites have also been reported from outcrops of Upper Devonian rocks in the northern part of the Appalachian Basin. In New York, tongues of black shale occur between turbiditic siltstones and shales (Walker and Sutton, 1967, p. 1021; Sutton and others, 1970, fig. 7).

The two lithologic types, therefore, which characterize the Ohio Shale in the central Appalachian Basin are easily distinguished in the field by color and sometimes weathering characteristics. These megascopic differences can be related to compositional differences, as shown by thin section study and X-ray analysis. The next question to consider is the vertical arrangement of these two lithologies. Is there an orderly, recognizable, and traceable sequence in which these rock types occur? If so, how may such a sequence, as defined from surface exposures, be traced into the subsurface?

INTERNAL STRATIGRAPHY

Introduction

Historically, Appalachian stratigraphers have been more interested in the lower and upper contacts of the Ohio Shale than in what lies between these contacts. In fact, all rock below the Lower Mississippian Berea Sandstone and above Middle Devonian and older carbonate rocks is usually called "Devonian shales", although it may not be Devonian or shale. Only a few attempts at subdivision of the Ohio Shale and its equivalents have been made, and certainly the relationships between local systems of subdivision throughout the Appalachian Basin are poorly understood. Subsurface thicknesses approaching 1,800 feet (540 m) in southeastern Kentucky and exceeding 2,500 feet (750 m) in West Virginia suggest that there ought to be an internal stratigraphy for the Ohio Shale. Ideally, such an internal stratigraphy should be recognizable also in outcrop, where thicknesses seldom exceed 300 feet (90 m).

What characteristics of the Ohio Shale and its equivalents have been used to subdivide these formations stratigraphically? Members of the Ohio Shale and equivalent formations have been delineated on the basis of: (1) color; (2) other lithologic features such as concretions; (3) fossil occurrences and ranges; (4) joints; and (5) weathering (Table 1).

Lithology, equated with color, is probably used most commonly. As described in the previous section, the Ohio Shale in the western portion of the Appalachian Basin consists of two lithologies -- a

TABLE 1.--Principal stratigraphic studies of the Ohio Shale and equivalents in the Appalachian and Illinois Basins. Criteria for subdivision of formations into members are shown in the right-hand portion of the table.

REFERENCE	FORMATION AND NUMBER OF MEMBERS	LOCATION	LITHOLOGY	LITHOLOGIC FEATURES	FOSSIL OCCURRENCES AND RANGES	JOINTS	WEATHERING
Campbell 1946	New Albany Shale, 4	Indiana Kentucky	black shale, gray shale, calcareous shale	phosphate nodules; cone-in-cone	brachiopods <u>Schizobolus</u> , <u>Lingula melie</u>	direction, horizontal spacing, vertical range	---
Hoover 1960	Ohio Shale, 3	Ohio	brown-black shale, gray- black shale, blue-gray clayey shale	cone-in-cone, calcareous concretions, pyrite	---	---	---
Conant and Swanson 1961	Chattanooga Shale, 2	Tennessee	black to dark gray shale, medium light gray to medium gray claystone; bentonite	basal lag sandstone; phosphate nodules	---	---	massive or friable
Lineback 1968 1970	New Albany Shale, 5	Indiana	brownish-black and greenish- gray shales and mudstones; minor dolomite and sandstone	phosphate nodules; pyrite; dolomite concretions	European conodont zonation	---	---

fissile, organic-rich black shale and a greenish-gray, organic-poor mudstone or shale which may be calcareous. Other lithologic features on which stratigraphic subdivisions are based include calcareous concretions, phosphate nodules, pyrite, limestone beds with cone-in-cone structure, and (in Tennessee only) bentonite beds.

Members of the Ohio Shale have also been defined by the presence of fossils, particularly the brachiopods Schizobolus and Lingula melie (Campbell, 1946) and algal remains such as Foerstia sp. (Schopf and Schwietering, 1970). Conodont studies by Hass (1947, 1958) for the Appalachian Basin, by Collinson and others (1962) for the upper Mississippi Valley, and by Klapper (1966) and Sandberg and others (1972) for the western United States have provided biostratigraphic zonation useful in regional correlation but not especially helpful in separating internal stratigraphic units.

In addition, patterns of joints within the black shale sequence (Campbell, 1946) and weathering characteristics (Conant and Swanson, 1961) have been used to distinguish several members.

Nearly all of the characteristics (Table 1) which have been used to differentiate the Ohio Shale's members can be observed or recognized only in outcrop. Because a much greater volume of the Ohio Shale occurs in the subsurface than in outcrop, the differentiating characteristics are useful for only a very small percentage of the total shale section. The key question, then, is how may these characteristics be discerned in available subsurface data such as wire-line logs and well cuttings?

Little progress has been made towards answering this question. Very few stratigraphic studies have been based on subsurface data. Schwietering (1970) discussed the stratigraphy of the Devonian shales in Ohio and used stratigraphic nomenclature applied to outcrops for both his subsurface and his outcrop sections. Walls (1975) described five facies within the black shale section in the subsurface of portions of Kentucky, Virginia, and West Virginia, but did not suggest any stratigraphic names for these facies or relate them to nearby outcrops.

Possibly the most successful integration of outcrop and subsurface stratigraphy was that of Lineback (1970), who subdivided surface exposures of the New Albany Shale into five members (Table 1). From subsurface data, however, he was able to recognize only his two lowermost lithostratigraphic units. As Lineback suggests, the problem is one of resolution. How may beds of greenish-gray shale only a few inches thick be distinguished on wire-line logs or recognized in well cuttings, where samples may be homogenized over intervals as great as thirty feet?

The approach used here to resolve discrepancies between outcrop and subsurface stratigraphy of the Ohio Shale section is to compare outcrop sections with nearby wells. A carefully measured and described exposure, with a set of scintillation counts, is compared with subsurface information such as a gamma ray-neutron log, well cuttings, or a core from a nearby well. It must be remembered that, on a regional scale, more units as well as greater variation within units should be expected in subsurface sections, whose thickness may

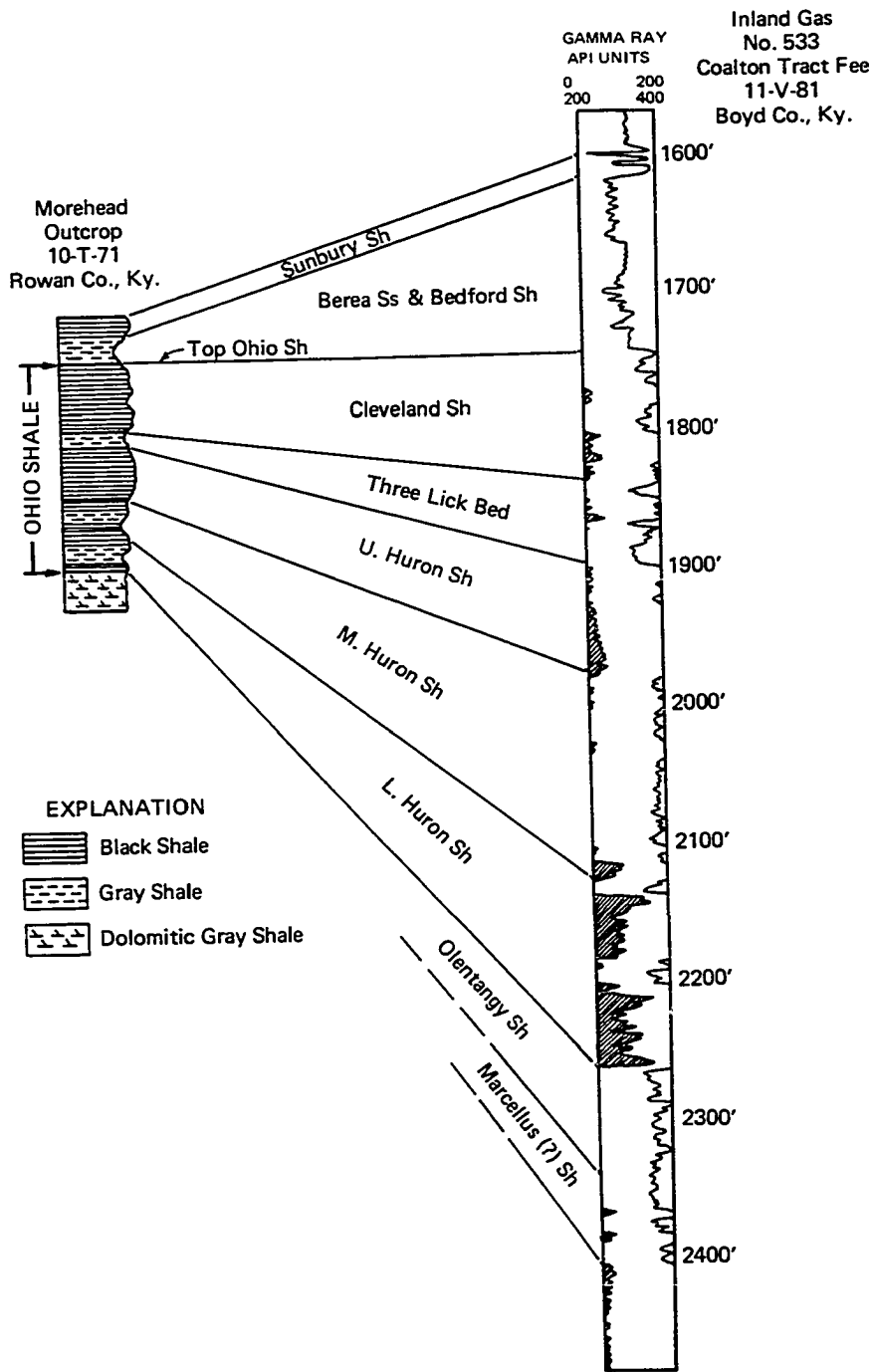
be more than ten times that of surface sections. In comparing neighboring outcrop and subsurface sections, on the other hand, it is usually necessary to combine several outcrop units into one which can be recognized on a wire-line log or in well cuttings.

Stratigraphic Subunits

Within the Devonian-Mississippian shale sequence, five to seven stratigraphic subunits can be recognized in outcrop and in the subsurface of eastern Kentucky and nearby (Figure 3) using this procedure. Generally, outcrops may be divided into five major subunits, while thicker subsurface sections consist of up to seven subunits. A complete outcrop of the Ohio Shale along Interstate 64 near Morehead, Rowan County, Kentucky (Figure 7; Appendix A, section 3), nicely displays these five units. For the equivalent subsurface section, Inland Gas Company No. 533 Coalton Tract Fee, 1,030 feet FNL x 1,310 feet FWL of section 11-V-81, Boyd County, Kentucky (Figure 7), is designated a reference well. This well, in which seven subunits can be discerned, is particularly suitable as a reference section because there are gamma ray and compensated formation density curves and a complete set of well samples available.

In Kentucky, the seven subunits of the Devonian-Mississippian shale sequence are equivalent to the Cleveland, Chagrin, and Huron shale members of the Ohio Shale, the Olentangy Shale, and possibly the Marcellus Shale as described from outcrops and the subsurface of Ohio (Hoover, 1960, p. 5-6; Lewis and Schwietering, 1971, fig. 2). Specific

FIGURE 7.--Seven stratigraphic subunits of the Upper Devonian shale sequence as observed in outcrop near Morehead, Rowan County, Kentucky (Figure 2 and Appendix A, section 3), and on gamma ray curve from reference well, Boyd County, Kentucky. Olentangy and Marcellus(?) Shales are not present in this outcrop, where the Ohio Shale rests unconformably on the Silurian Crab Orchard Formation. See Table 2 for further description of these units.



correlation of Devonian-Mississippian shales in eastern Kentucky with those of Ohio will be discussed in a following section.

In the reference subsurface section, the seven stratigraphic subunits which can be separated on the basis of their gamma ray characteristics are, from top to bottom: (1) Cleveland Shale; (2) Three Lick Bed; (3) Upper Huron Shale; (4) Middle Huron Shale; (5) Lower Huron Shale; (6) Olentangy Shale; and (7) Marcellus(?) Shale. Lithologic interpretation of each subunit is based on gamma ray curves, sample study, and comparison of measured outcrop sections (Table 2; Figure 7).

The Cleveland, Upper Huron, and Lower Huron Shales are black, organic-rich, radioactive shales, while the Three Lick Bed and Middle Huron and Marcellus(?) Shales are interbedded black and greenish-gray, organic-poor shales. In contrast, the Olentangy contains no dark shale but consists only of greenish-gray, organic-poor shale which may be calcareous and is not highly radioactive.

Certain lithologic features may be restricted to one or two of these stratigraphic subunits and thus are useful in identifying subunits in outcrop or when subsurface samples are available. Thin limestone beds with cone-in-cone structure occur in the Cleveland Shale, Three Lick Bed, and Upper Huron Shale (Table 2; Appendix A, sections 1 through 5), while phosphatic nodules occur only in the Cleveland Shale (Table 2; Appendix A, sections 2 through 8). Large calcareous concretions are present in the Lower Huron Shale as observed in outcrops in Adams County, southern Ohio and Lewis County, northern Kentucky.

TABLE 2.--Characterization of seven subunits of Upper
Devonian shale sequence in central Appalachian
Basin, based on 900 wells and ten outcrop
sections, and suggested stratigraphic equivalents.

		UNIT	RANGE IN THICKNESS (FT.)	GAMMA RAY CURVE CHARACTERISTICS	LITHOLOGIC INTERPRETATION
OHIO SHALE		CLEVELAND SHALE	5 - 200	Radioactivity close to or exceeding 200 API units.	Brownish-black, organic-rich shale with phosphatic nodules near top.
		THREE LICK BED	<1 - 70	Three or four closely spaced negative deviations (<i>less than 200 API units</i>) on gamma ray curve.	Interbedded brownish-black and greenish-gray shales or mudstones; limestone with cone-in-cone may be present.
	HURON SHALE	UPPER HURON SHALE	15 - 115	Moderately radioactive, between 100 and 200 API units.	Massive brownish-black shale.
		MIDDLE HURON SHALE	20 - 200	Slightly less radioactive than Upper Huron Shale.	Brownish-black and gray shales, interbedded in lower half; <u>Foerstia</u> found in outcrop and core.
		LOWER HURON SHALE (driller's Cinnamon or Brown Shale)	20 - 400	Highly radioactive, usually exceeding 200 API units, with 1 to 4 thin zones of lesser radioactivity.	Brownish-black, organic-rich shale with 1 to 4 thin zones of greenish-gray to gray shale.
	OLENTANCY SHALE (driller's White Slate)	10 - 300	Low radioactivity, typically 100 API units.	Greenish-gray to gray, organic-poor shale and mudstone; may be calcareous.	
	MARCELLUS (?) SHALE	20 - 250	Thin intervals of high radioactivity (<200 API units) within zones of moderate radioactivity (100-200 API units)	Greenish-gray shale interbedded with brownish-black, organic-rich shale; commonly pyritic.	

Recognition of these seven subunits in the subsurface depends on contrasts in radioactivity of each unit. Tops of the Cleveland Shale, Three Lick Bed, Upper and Lower Huron Shales, Olentangy Shale, and usually the Marcellus(?) Shale are easily picked (Figure 7) because overlying units differ significantly in lithology or in arrangement of lithologic constituents. The contact between the Upper and Middle Huron Shales, on the other hand, is not as sharply defined. Although lithologies of these two subunits differ (the Middle Huron containing more greenish-gray shale), their radioactivities as expressed by gamma ray curves are nearly equal.

Therefore, a small but widely identifiable decrease in radioactivity which is probably related to subtle lithologic changes represents the contact between the Upper and Middle Huron Shales. This contact is also difficult, if not impossible, to recognize in outcrop, where a massive, homogeneous unit of black shale underlies the distinctive Three Lick Bed (Appendix A, section 2, unit 17; section 3, unit 8) and overlies a sequence of thinly interbedded greenish-gray and black shales.

Although there is a strong lithologic contrast between the massive black shale and the thinly bedded shales observed in outcrop, the slight decrease in radioactivity shown on gamma ray curves for nearby subsurface sections is not in response to this particular lithologic break. The subsurface definition for the Upper and Middle Huron contact results in a Middle Huron Shale, which is much thicker than the apparently equivalent surface unit as defined by natural lithologic

break. Because the greater part of the Devonian-Mississippian shale sequence lies in the subsurface, it is best to define stratigraphic subunits there rather than from surface exposures.

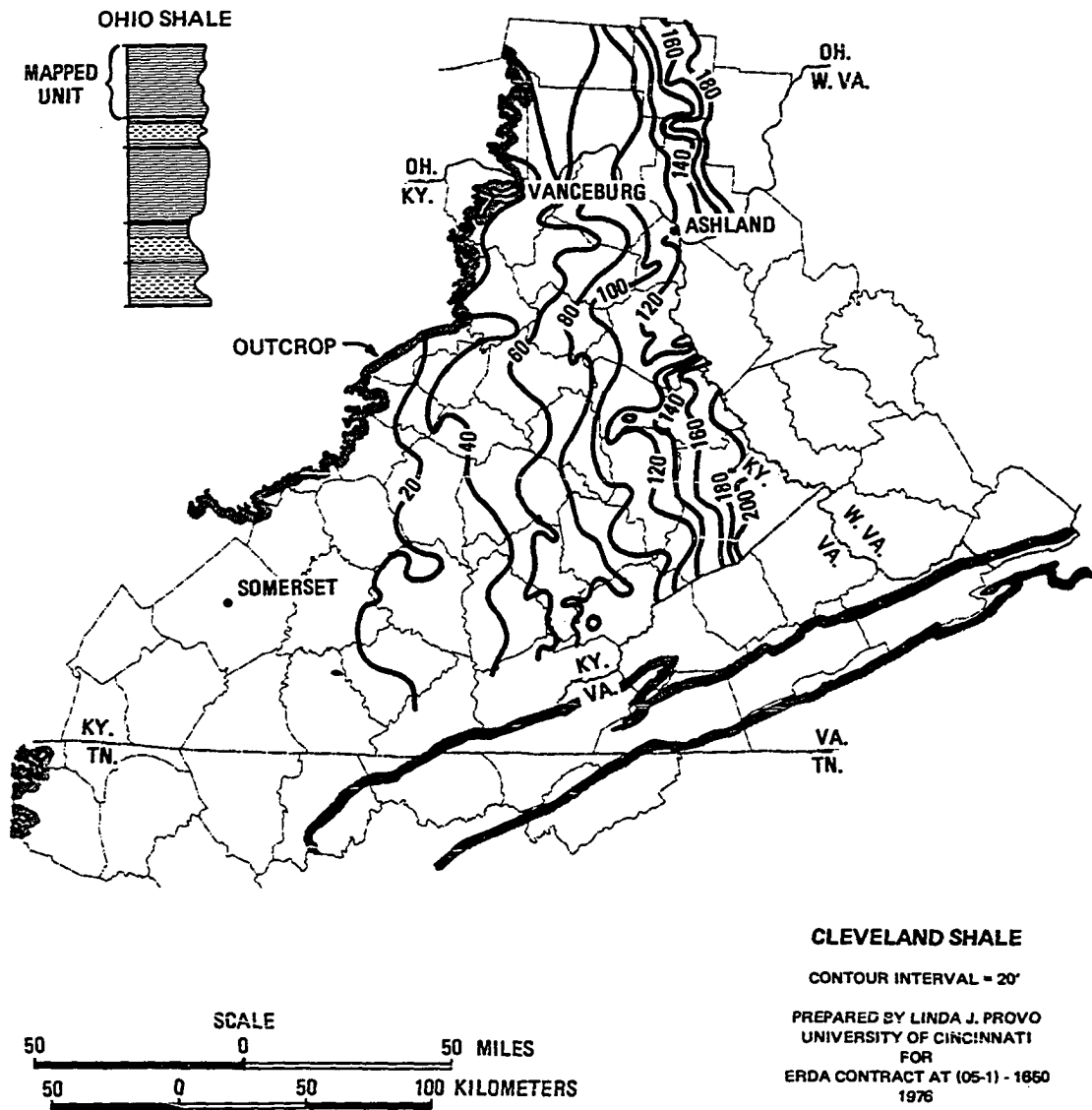
Thickness and Distribution

The seven stratigraphic subunits of the Devonian-Mississippian shale sequence were mapped in the subsurface of eastern Kentucky, southeastern Ohio, western West Virginia and northern Tennessee (Figure 1). Over much of this area, at least five, and commonly all seven, of these subunits can be recognized (Figure 3).

Cleveland Shale

The Cleveland Shale is traceable along the Ohio Shale's outcrop from southern Ohio southwestward to the vicinity of Somerset, Kentucky (Figure 8; Figure 2, locations 6 and 7), and is probably equivalent in north-central Tennessee (Figure 2, location 8) to the upper black shale of the Gassaway member, Chattanooga Shale (Conant and Swanson, 1961, fig. 5). In outcrops in the eastern portion of the study area, the black, fissile shale with phosphatic nodules, which characterizes the Cleveland Shale, is not present (Figure 2, locations 9 and 10; Appendix A). Instead, the section consists primarily of greenish-gray shale and siltstone with minor black shale. Likewise, in southwestern Virginia, the equivalent of the upper part of the Ohio Shale (the Big Stone Gap member of the Chattanooga Shale) contains gray siltstone interbedded with black shale (Roen and others, 1964, p. 47). Thus, as the Ohio Shale thickens eastward (Figure 4), facies change from dark shale to lighter-colored, organic-poor shale and siltstone.

FIGURE 8.--Isopach map of Cleveland Shale showing slight thickening related to structural features in east-central Kentucky.



In the subsurface, the Cleveland Shale can be distinguished on wire-line logs when the total thickness of the Ohio Shale is 50 feet or greater. In thin subsurface sections in south-central Kentucky and northern Tennessee (Figures 4 and 8), identification of the Cleveland Shale is impossible. The Cleveland Shale attains a maximum thickness of 200 feet (61 m) in eastern Kentucky, but generally is not recognizable in West Virginia or Virginia.

Two factors contribute to the inability to recognize the Cleveland Shale and other subunits in very thin and in very thick subsurface sections. The first of these is mechanical, because wire-line logs are necessary to identify subsurface stratigraphic units. On many wire-line logs which penetrate thin sections, the gamma ray curve commonly goes off-scale, eliminating any small responses. Certain key beds, such as the Three Lick, which underlies the Cleveland and marks the Cleveland's basal contact, are defined in the subsurface by slight decreases in radioactivity which, therefore, are not visible on such logs. Furthermore, where these key beds -- the gray and black shales of the Three Lick -- are less than two feet thick, they are too thin to produce a response on gamma ray curves (Provo and others, in press, fig. 8). In sections less than 50 feet (15 m) thick, usually only the upper and lower contacts of the Ohio (or Chattanooga) Shale can be picked with certainty.

The second reason for loss in resolution of the Cleveland Shale and other subunits is geological. As dark shale in the upper portion of the Ohio Shale is replaced by lighter-colored shale and siltstone,

gamma ray responses become increasingly less distinctive because these lithologies are not as highly radioactive as dark shale. In fact, the first unit which can be recognized easily on wire-line logs of thick sections is the Lower Huron Shale. Moreover, even dark shale from the eastern portion of the study area is less radioactive than lithologic equivalents from outcrops along the western margin of the basin, resulting also in gamma ray curves which are unlike those from wells located further west in the basin. For example, dark shale from the Mountain Branch section (Appendix A, section 9; Appendix B, sample 19913) contains 18 ppm uranium, while similar shale from east-central Kentucky (Appendix A, section 4; Appendix B, sample 17341) and southern Ohio (Appendix A, section 2; Appendix B, sample 19901) contains 35 to 48 ppm uranium. Thus, facies changes with corresponding dilution of radioactivity destroy the original basis for defining and recognizing stratigraphic subunits in the upper portion of the Ohio Shale.

The general pattern of basinward thickening of the Cleveland Shale (Figure 8) shows two lobate areas, one in eastern Kentucky and the other in southeastern Ohio. This pattern is similar to one described by Lewis and Schwietering (1971, fig. 3), who show four such thick accumulations in the Cleveland Shale of Ohio separated by east-west trending areas of thin Cleveland Shale. As these authors suggest (p. 3482), variations in thickness of the Cleveland Shale are likely related to variations in sediment supply to the northern and central Appalachian Basin from eastern source areas. Whether this same lobate pattern also characterizes the Cleveland Shale or its

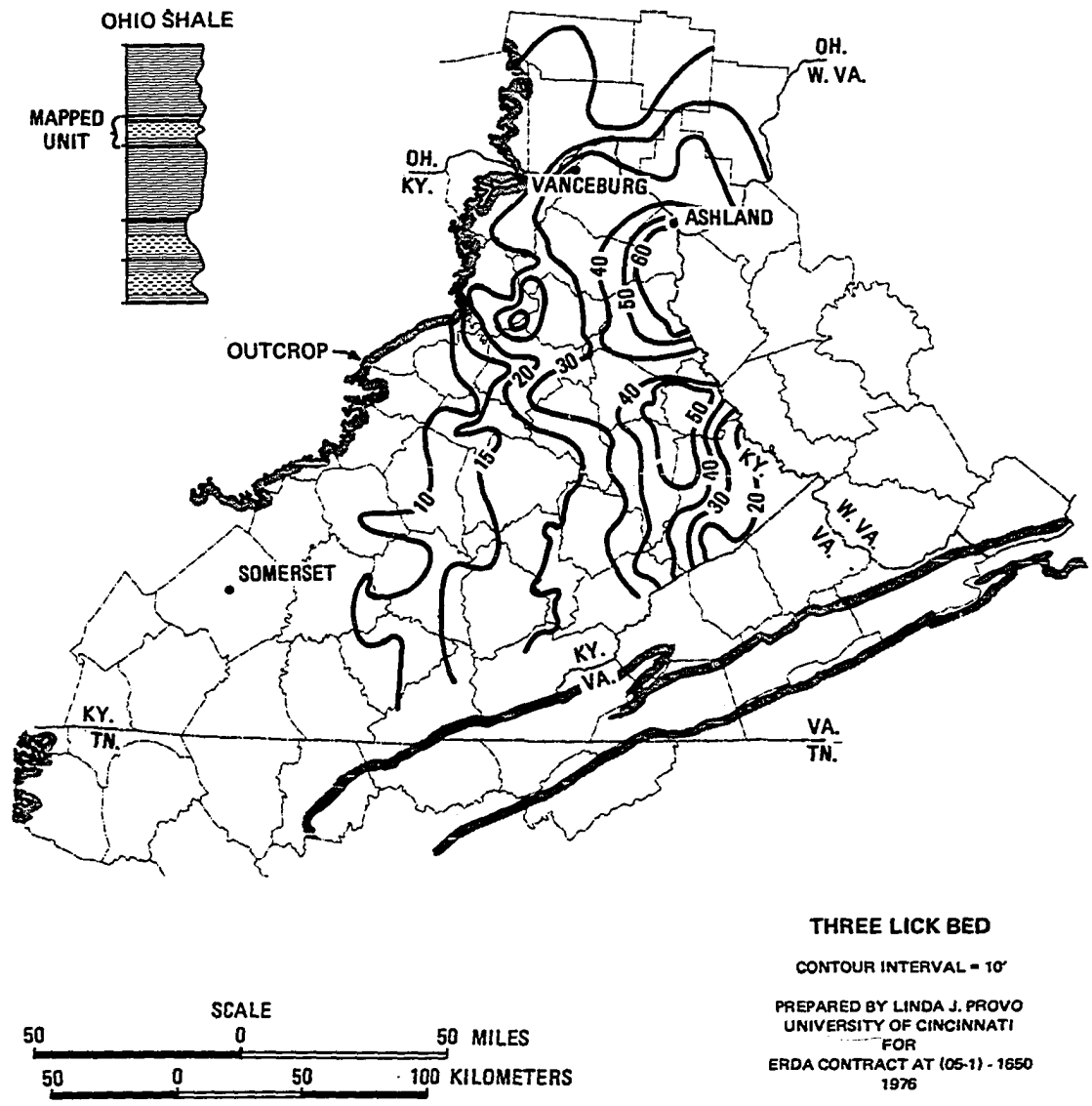
equivalent in the southern Appalachian Basin cannot be determined because of inability to separate the Cleveland from other subunits using wire-line logs from this region, where the Devonian-Mississippian shale sequence is relatively thin (Figure 8).

Three Lick Bed

The Three Lick Bed is a thin but persistent subunit of the Ohio Shale easily traceable in outcrop from southern Ohio to northern Tennessee (Provo and others, in press, fig. 8). The three thin beds of greenish-gray shale which characterize this subunit are enclosed by much thicker, homogeneous, fissile black shale (the Cleveland and Upper Huron), forming a sharp lithologic contrast which is commonly accentuated by weathering (Figures 6 and 9). In south-central Kentucky, the greenish-gray shale beds of the Three Lick are less than one-tenth foot thick (Appendix A, sections 6 and 7), but, nonetheless, easily recognized. In northern Tennessee three burrowed zones represent the gray shales of the Three Lick (Appendix A, section 8). Therefore, although the Three Lick Bed is not a thick unit, its lateral continuity is notable.

In the subsurface, the Three Lick Bed can be recognized on wire-line logs over southern Ohio and much of eastern Kentucky (Figure 9), where it has a maximum thickness of 75 feet (23 m) in Boyd County, northeastern Kentucky. Beyond this area the Three Lick Bed cannot be identified due to loss of its distinctive gamma ray signature by thinning and facies changes, the same problems encountered in tracing the Cleveland Shale.

FIGURE 9.--Isopach map of Three Lick Bed (partial equivalent of Chagrin Shale). Note two lobate areas of maximum thickness in eastern Kentucky.



As in the Cleveland Shale, two relatively thick lobate masses disrupt the pattern of eastward thickening in the Three Lick Bed (Figure 9). These lobate masses are located in eastern Kentucky, the more southerly of the two being in approximately the same position as a lobe of the Cleveland Shale (Figure 8). The thin ridge which separates the two Three Lick lobes in east-central Kentucky (near contours labelled "20" and "30" in Figure 9) is located along the Paint Creek fault system (Figure 10). This structural feature likely controlled, in part, the distribution of the Three Lick Bed, along with variation in sediment supply as suggested for the Cleveland Shale.

Upper Huron Shale

The Upper Huron Shale is identifiable over much of the same area as the two subunits which overlie it (Figure 11). Where the Three Lick Bed cannot be distinguished, neither can the Upper Huron. The same problems of thinning, facies changes, and recognition of slight responses on gamma ray curves also prevent tracing of the Upper Huron Shale into south-central Kentucky and western West Virginia.

The rate of thickening of the Upper Huron Shale from outcrop eastward into the Appalachian Basin increases rapidly in extreme eastern Kentucky, forming a small but pronounced lobe (Figure 11). The position of this lobe -- slightly south of a similar lobe in the Three Lick Bed (Figure 9) -- suggests that, during the time of Upper Huron deposition, the dominant source of sediment was located further south than that of the Three Lick Bed.

FIGURE 10.--Structural contours drawn on top of the Ohio Shale. Longitudinal east-west fault in east-central Kentucky is the Paint Creek.

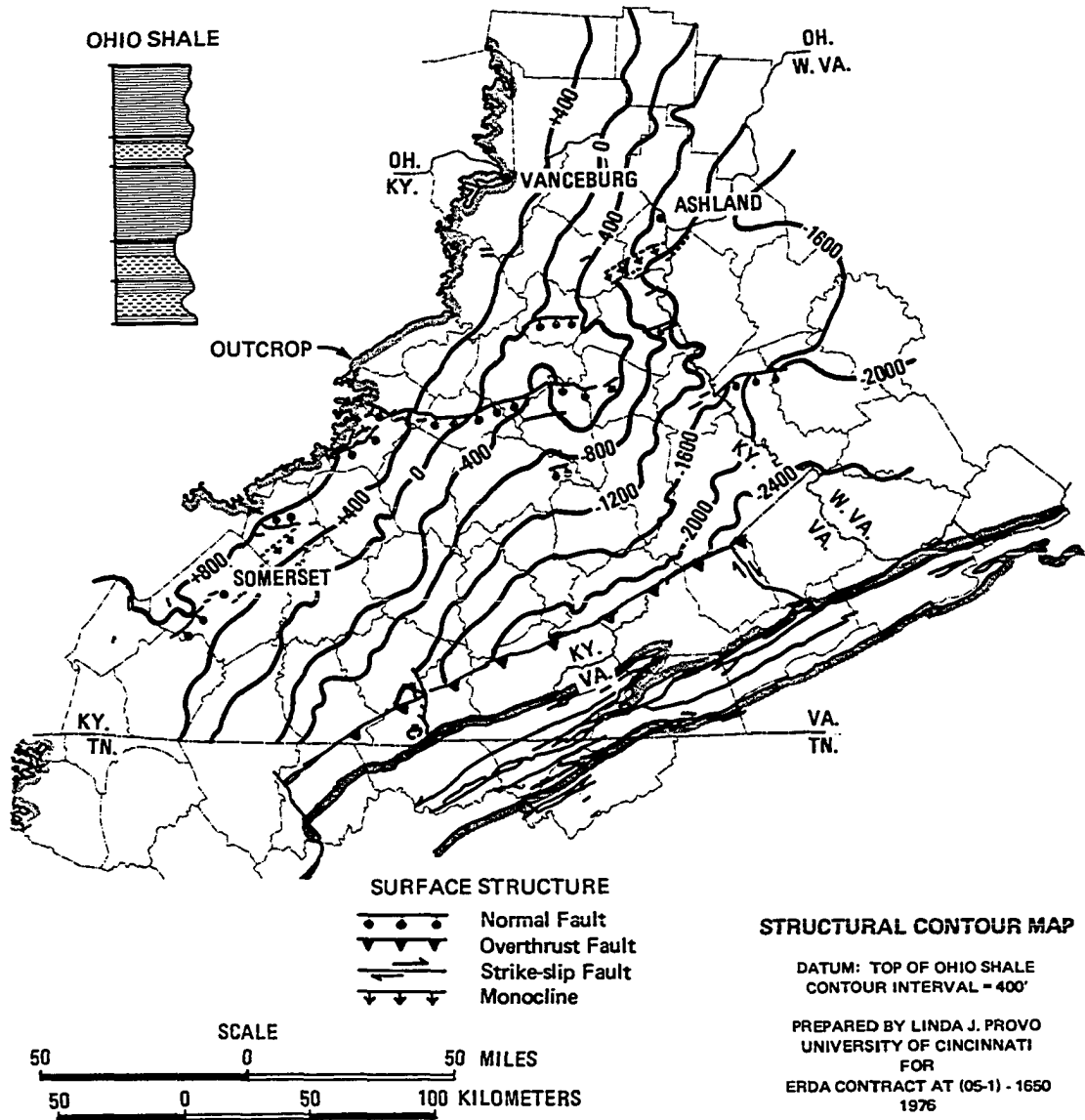
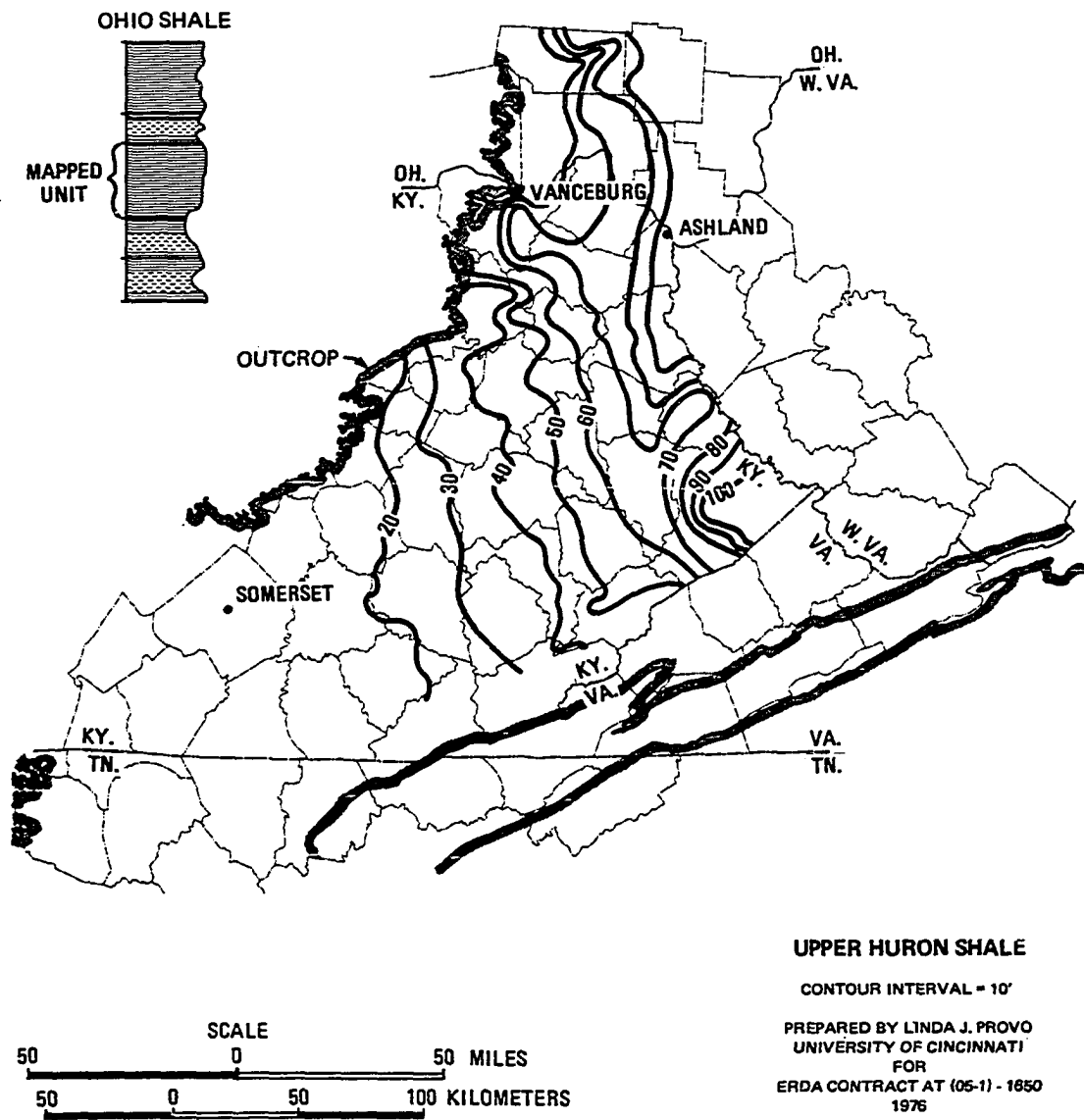


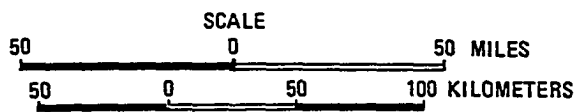
FIGURE 11.--Isopach map of the Upper Huron Shale. Part of the Chagrin Shale of Ohio may be included in this unit.



UPPER HURON SHALE

CONTOUR INTERVAL = 10'

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The presence of another lobe is suggested in Ohio, near the northern boundary of the study area (Figure 11). Here a narrow ridge of thin Upper Huron Shale appears to separate two thicker lobes. Further study of the Upper Huron Shale in central Ohio may show that this feature is indeed a distinct lobe within this subunit.

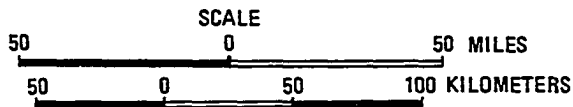
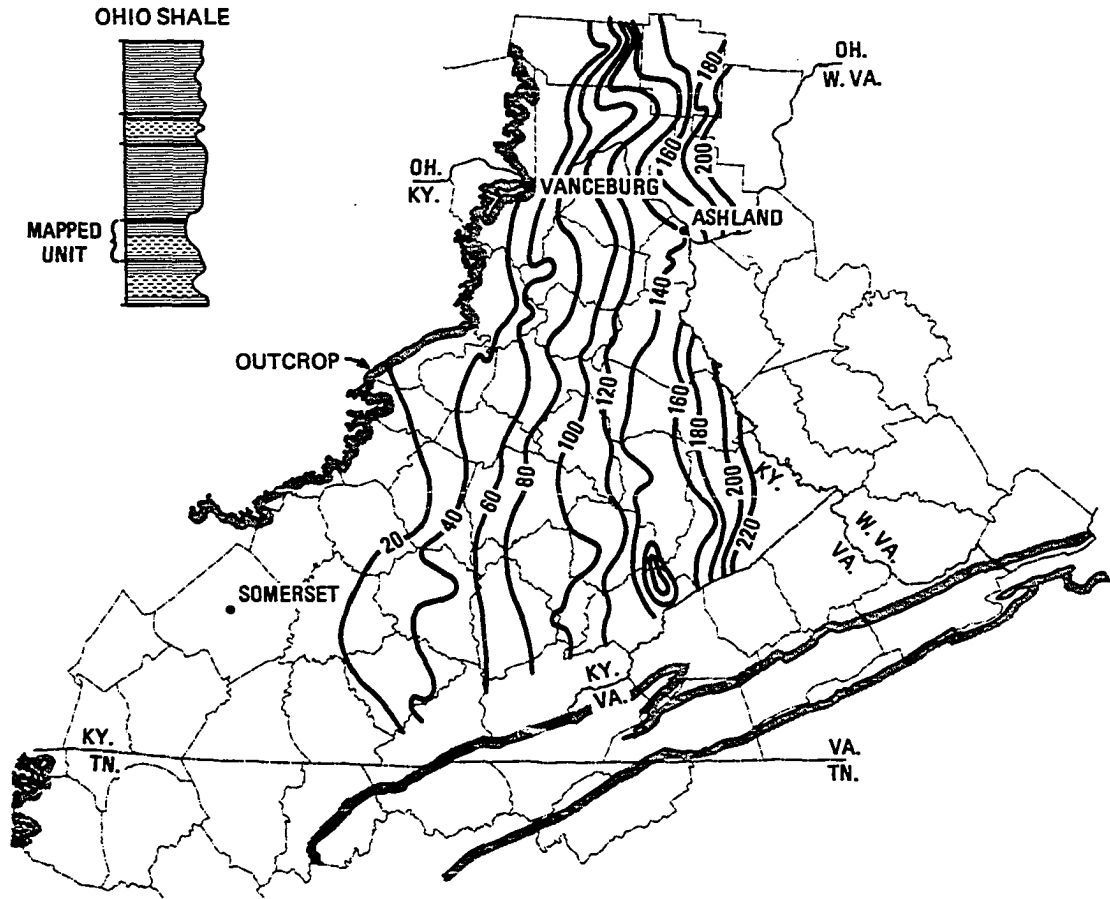
Middle Huron Shale

In outcrop, the Middle Huron Shale is present in southern Ohio, extending as far south as Berea, Kentucky (Figure 2, location 5). This subunit contains the fossil alga Foerstia (Appendix A, sections 2 through 5,9), which aids in tracing it in outcrops along the western Appalachian Basin and on the basin's east side, provided that the assumption that Foerstia is restricted to a single horizon is true. Schopf and Schwietering (1970, fig. 2, p. 6-7) discuss the significance of the narrow stratigraphic zone occupied by Foerstia, suggesting it required a particular littoral environment for reproduction and that it may mark a consistent time zone.

Like the overlying subunits, the Middle Huron has a wide distribution in the subsurface of southern Ohio and eastern Kentucky (Figure 12). Attempts to follow it into south-central Kentucky and western West Virginia, however, were unsuccessful for the same reasons which prevent the tracing of overlying subunits into these areas.

Two lobe-shaped masses of Middle Huron Shale are apparent. One, in southeastern Ohio (Figure 12, above "Ashland"), trends nearly east-west and is separated from a narrower, more elongate lobe slightly to the north by an area of thin Middle Huron. Orientation of this lobe is northeast-southwest.

FIGURE 12.--Isopach map of Middle Huron Shale showing locally thick areas in southeastern Kentucky.



MIDDLE HURON SHALE

CONTOUR INTERVAL = 20'

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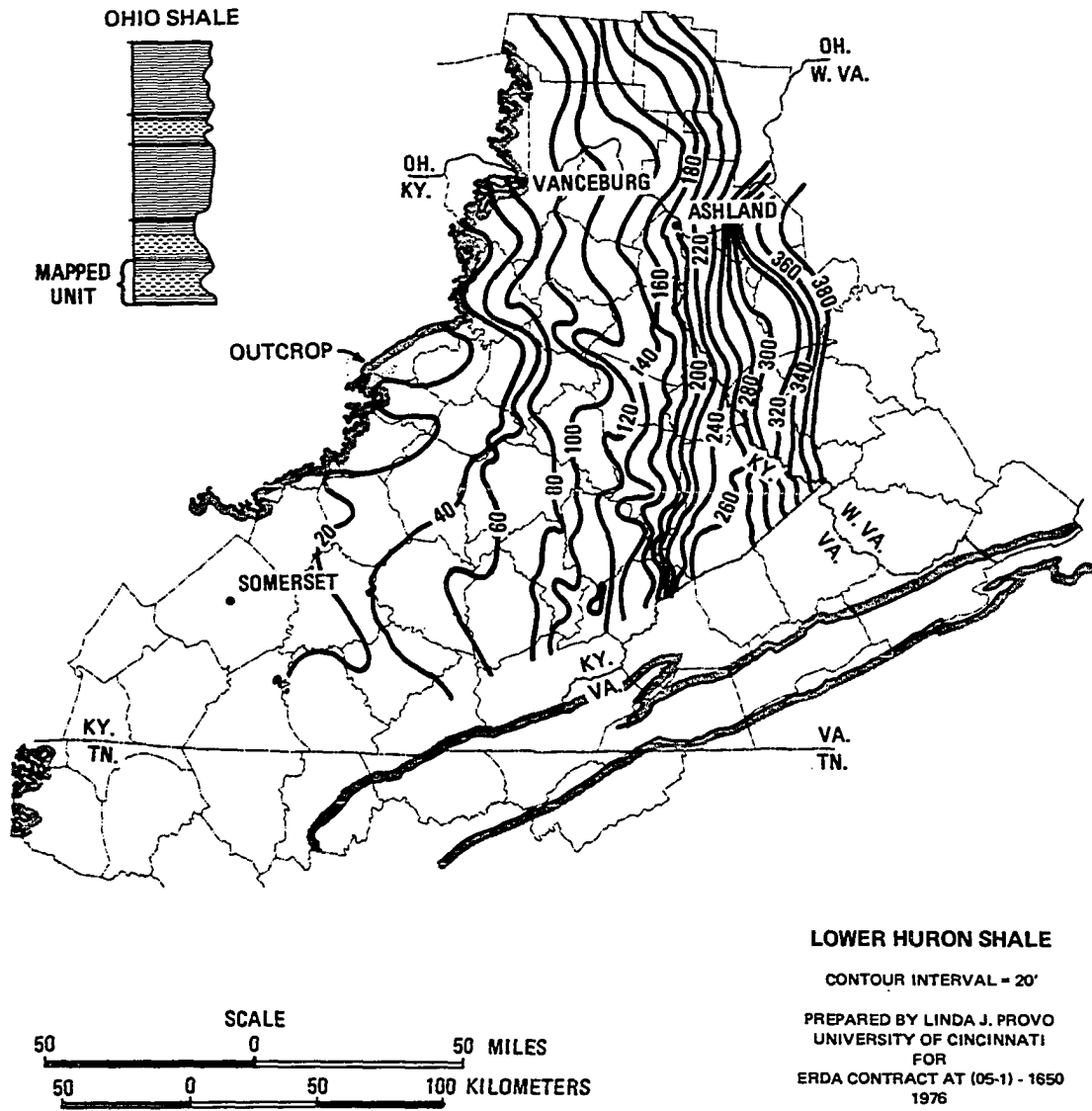
The second lobe is rather poorly defined and located in extreme eastern Kentucky (Figure 12). A locally thick body of Middle Huron Shale occurs to the west of this feature. In contrast to the Middle Huron, all three subunits which overlie it were characterized by distinct lobate masses in easternmost Kentucky or very nearby. Consequently, the Upper Huron Shale and younger subunits likely represent a change in direction of maximum sediment supply.

Lower Huron Shale

In considering the extent and thickness of the Lower Huron Shale (Figure 13), three features are strikingly obvious: (1) it is traceable much farther east than overlying subunits; (2) it attains a maximum thickness of 380 feet (116 m), much greater than thicknesses of younger subunits; and (3) its rate of thickening is, in places, far greater than that of other subunits.

The ability to recognize the Lower Huron Shale over such a wide area is controlled by two factors. Its high radioactivity causes a sharp, off-scale deflection on gamma ray curves, and its lithologic character is not greatly altered by facies change, as determined from sample study. Moreover, because the Lower Huron Shale is so distinctive, it can sometimes be identified with certainty on driller's logs, which refer to it as the "Lower Cinnamon" (Table 2). In mapping this subunit, all thicknesses obtained from driller's logs were compared with thicknesses from nearby wells with wire-line logs as a check on reliability of such data.

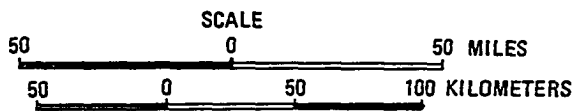
FIGURE 13.--Isopach map of Lower Huron Shale, which is easily traceable into West Virginia. Structural features dating from Precambrian time influenced deposition of this unit in east-central Kentucky.



LOWER HURON SHALE

CONTOUR INTERVAL - 20'

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In outcrop, however, the Lower Huron extends only as far south as Berea, Kentucky (Figure 2, location 5). It is likely present in northeastern Tennessee (Figure 2, location 9; Appendix A, section 9, below unit 10), where Foerstia -- the fossil alga usually found in the Middle Huron Shale -- was observed in outcrop. If Foerstia is limited to the same particular horizon in this portion of the Appalachian Basin as in the western portion (see Schopf and Schwietering, 1970), then the Lower Huron Shale occurs somewhere below the Foerstia zone of section 9. The lithology of the presumed Lower Huron interval could not be determined precisely here because the section was covered.

Although the Lower Huron Shale thickens rapidly east of the 140-foot contour (Figure 13), it thins west of this line at a rate comparable to that for the four overlying subunits. This suggests that subsidence and subsequent basin-filling were greater in the eastern portion of the study area, while sedimentation in the extreme western portion of the central Appalachian Basin was influenced to a lesser degree by such processes.

The lobate pattern which characterized maps of the Cleveland, Three Lick, and Upper and Middle Huron (Figures 9, 11, and 12) is not as marked in the Lower Huron interval. One rather small lobe is present just east of Ashland, Kentucky (Figure 13), but none can be distinguished in extreme eastern Kentucky where such features commonly occur in overlying subunits.

Small irregularities in the Lower Huron Shale are noticeable in the western part of the map area. The pronounced westward curvature

of the 100- and 120-foot contours in east-central Kentucky (Figure 13) are probably related to a small fault in Elliott County, Kentucky (Figure 10). The more extensive Paint Creek fault system, located to the south of the small fault just described, also seems to have had some influence on sedimentation along its length, where slight thickening occurs on its downdropped side (Figures 10 and 13).

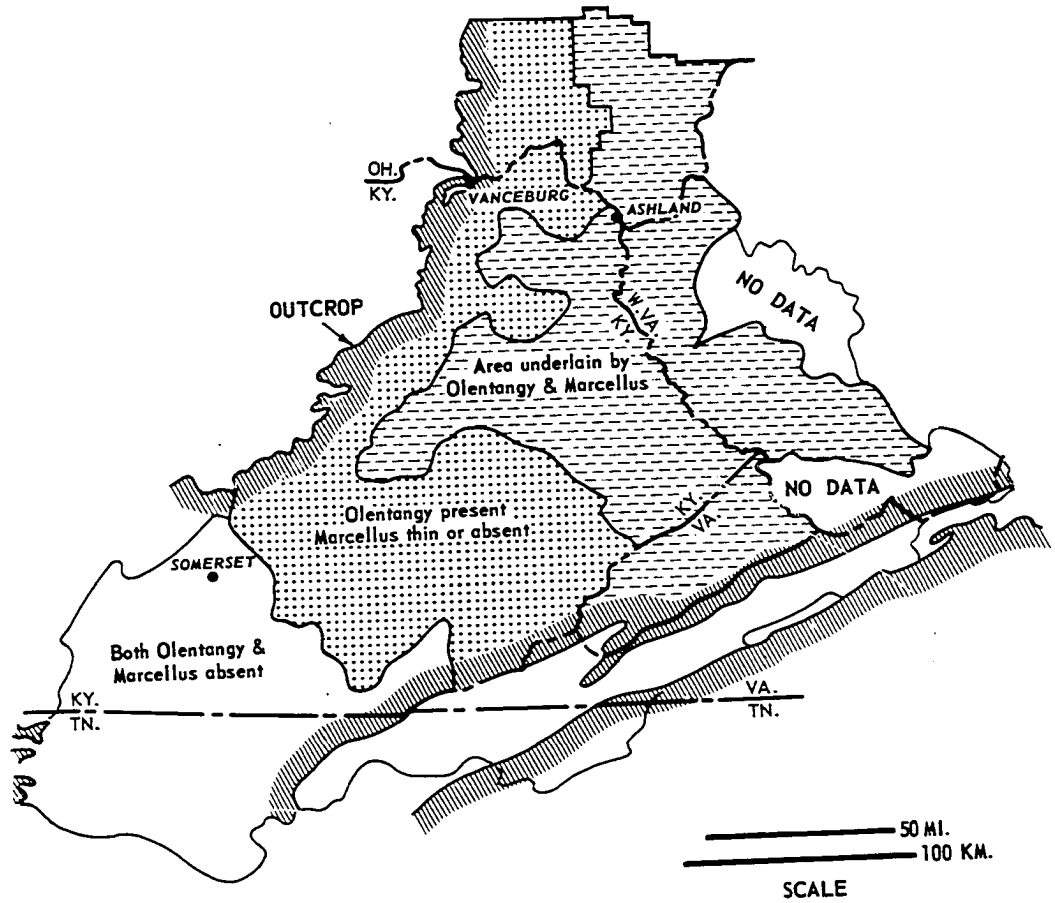
Olentangy Shale and Marcellus (?) Shale

Although the Olentangy and Marcellus(?) Shales are not subunits of the Ohio Shale, lithologic similarities between these two formations and the Ohio Shale result in their being regarded as part of the Devonian-Mississippian shale sequence. The fact that carbonate rocks and sometimes a major disconformity underlie the Olentangy and Marcellus(?) Shales also contributes to the placement of these formations in the Devonian-Mississippian shale sequence.

The Olentangy Shale was observed in only one of the ten measured sections (Appendix A, section 2) and in outcrop near Vanceburg, Kentucky (Figure 14), south of which it cannot be traced at the surface. In none of the measured sections were the dark shales of the Marcellus(?) seen.

These two subunits of the Devonian-Mississippian shale sequence are more widely distributed in the subsurface where they occur in 47 counties in Ohio, Kentucky, Virginia, and West Virginia (Figure 14). They are not recognizable in the subsurface of northern Tennessee or south-central Kentucky, partly because of problems in identifying them in sections which are thin, and partly because of their absence over much of this area.

FIGURE 14.--Distribution of Olentangy and Marcellus(?)
Shales. Note restriction of these two units
to deeper, central portion of the Appalachian
Basin.



Traced eastward from Kentucky into West Virginia, the Olentangy and Marcellus(?) Shales thicken from less than 20 feet and 10 feet, respectively, just east of the outcrop along the western margin of the Appalachian Basin to 340 feet (104 m) and 280 feet (85 m) in western West Virginia. In southeastern Ohio, the Olentangy is slightly over 100 feet (30 m) thick and the Marcellus(?), about 60 feet (18 m) thick. These two formations are easily recognized on wire-line logs because their lithology is markedly different from that of the overlying Lower Huron Shale (Table 2), producing a conspicuous response on gamma ray curves (Figure 7) as well as compensated formation density curves. Longitudinal and perpendicular sections (Figures 15 and 2, and Table 3) show the internal stratigraphy and the persistence of the above stratigraphic subunits of the Upper Devonian shale sequence in Kentucky and nearby.

Regional Correlation

An important question arises out of the identification of seven stratigraphic subunits in the Devonian shale sequence in eastern Kentucky and their occurrence over much of the central Appalachian Basin. How do these seven subunits correlate with equivalent stratigraphic intervals outside the study area? The widespread distribution of Upper Devonian rocks in North America was mapped by Conant and Swanson (1961, pl. 14), and lithologic similarities between Upper Devonian sequences from widely scattered locations has been noted (Provo, 1976). Stratigraphic nomenclature for Kentucky, Ohio, and Tennessee and proposed correlations are shown in Table 4.

FIGURE 15.--Schematic cross sections showing internal stratigraphy of the Upper Devonian shale sequence in eastern Kentucky and nearby. Datum is top of Ohio Shale; undivided Bedford Shale and Berea Sandstone overlie datum. (See Figure 2 for lines of section. Numbers refer to well locations in Table 3.)

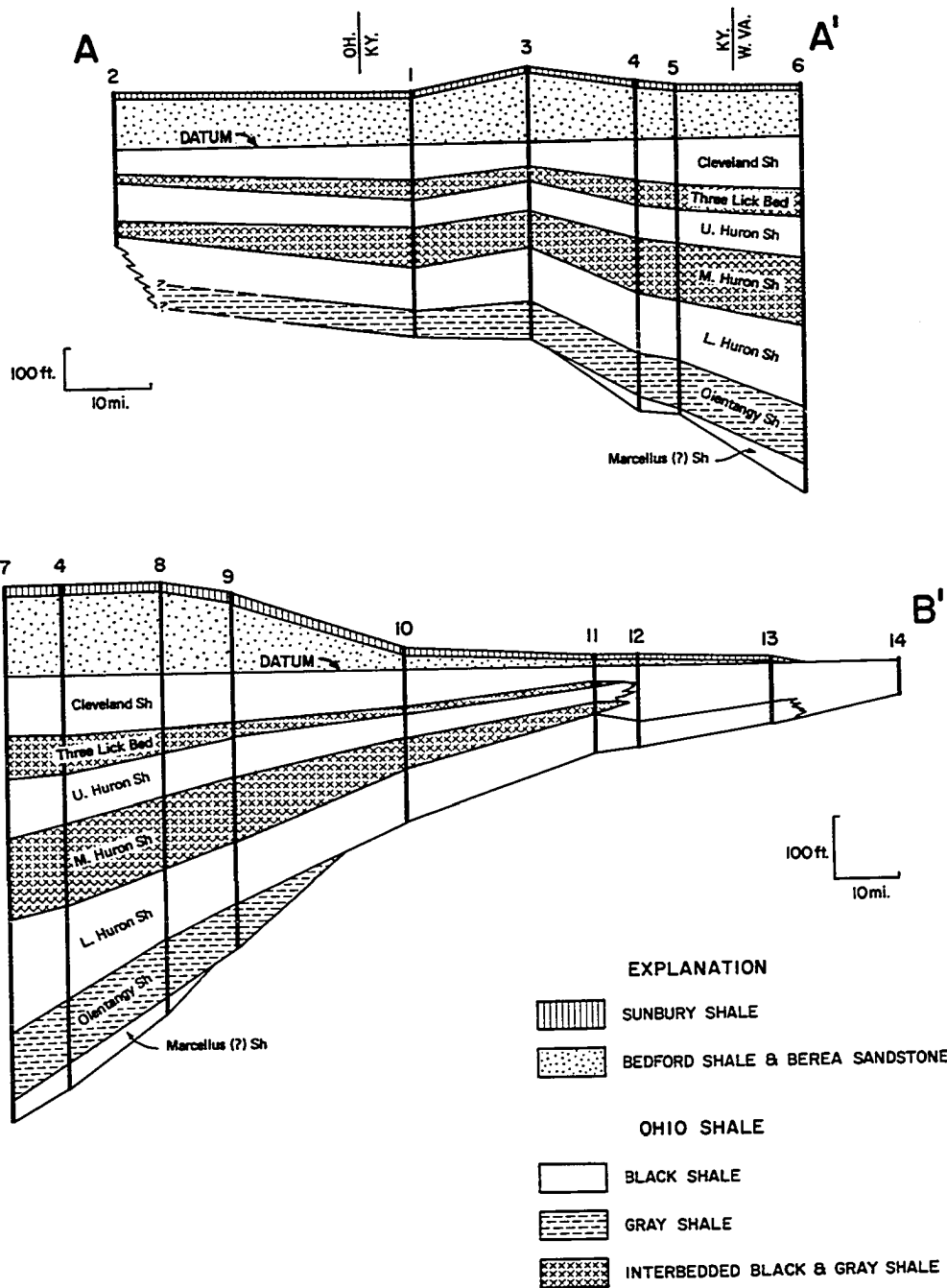


TABLE 3.--Outcrop section and wells used in construction
of cross sections, Figure 15.

Outcrop 2. Tener Mountain, Adams County, Ohio
(see also Appendix A)

Wells with wire-line logs

- (1)..... Ashland Oil No. 1 Gilliam
16-Z-78
Greenup County, Kentucky
- (3)..... United Carbon No. 1 Felty, et al.
3-W-79
Greenup County, Kentucky
- (4)..... Inland Gas No. 533 Coalton Tract Fee
11-V-81
Boyd County, Kentucky
- (5)..... Inland Gas No. 542 Young
6-U-82
Lawrence County, Kentucky
- (6)..... United Fuel Gas No. 9509-T United Fuel Gas Fee
Deed 9342 Permit No. 1549
23-T-84
Wayne County, West Virginia
- (7)..... Inland Gas No. 559 Daniels
5-W-83
Boyd County, Kentucky
- (8)..... Monitor Petroleum No. 2-G Ison-Stephens Unit
13-T-79
Elliott County, Kentucky
- (9)..... Monitor Petroleum No. 1 Ison
3-R-78
Morgan County, Kentucky
- (10)..... Holly Creek Production No. 2 White
20-O-73
Wolfe County, Kentucky
- (11)..... L. O. Hale No. 1 Bowman
22-L-69
Owsley County, Kentucky
- (12)..... Planet Petroleum No. 1 Cavins
1-J-68
Jackson County, Kentucky
- (13)..... H. D. Atha No. 1 Stewart
13-H-65
Laurel County, Kentucky
- (14)..... D. Proctor No. 1 Slavins
24-H-61
Pulaski County, Kentucky

TABLE 4.--Comparison of stratigraphic nomenclature and lithology of Chattanooga Shale (Tennessee), Ohio Shale (Kentucky), and Ohio Shale (Ohio).

	<u>TENNESSEE</u>		<u>KENTUCKY</u>		<u>OHIO</u>
CHATTANOOGA SHALE	Upper Gassaway (black shale)	OHIO SHALE	Cleveland Shale (black shale)	OHIO SHALE	Cleveland Shale (black shale)
	Middle Gassaway (gray + black shale)		Three Lick Bed (gray + black shale)		Chagrin Shale (mudstone + siltstone)
	Lower Gassaway (black shale)		Upper Huron Shale (black shale)		Huron Shale (black + gray shale)
	Upper Dowelltown (gray + black shale)		Middle Huron Shale (gray + black shale)		
	Lower Dowelltown (black shale)		Lower Huron Shale (black shale)		
	OLENTANGY SHALE		OLENTANGY SHALE		Upper (gray shale)
	MARCELLUS (?) SHALE		OLENTANGY SHALE		Lower (black shale)

As stated earlier, the five stratigraphic subunits of eastern Kentucky's Ohio Shale correlate well with those of the Ohio Shale in Ohio (Table 4) and, therefore, Ohio stratigraphic nomenclature should be used for equivalent units in Kentucky, where detailed stratigraphic nomenclature is presently lacking. The Cleveland Shale member of the Ohio Shale is recognizable over much of central Ohio (Lewis and Schwietering, 1971, fig. 4). The distinct lithology of the Cleveland (Table 2) facilitates its identification in surface exposures and in the subsurface of Kentucky, where it is recognized as far south as Knox County, Kentucky, and also in outcrop near Somerset, Kentucky (Figure 8).

In Tennessee, correlation of the underlying Three Lick Bed with the middle unit of the Gassaway member of the Chattanooga Shale (Provo and others, in press) suggests that the Gassaway's upper unit, consisting of massive black shale (Table 4), is equivalent to the Cleveland Shale. Conant and Swanson (1961, fig. 11) trace the upper unit of the Gassaway as far north as Pulaski County, south-central Kentucky, and show that it thickens from six to thirteen feet, with increased thickness being especially noticeable in phosphatic beds near the top of the Gassaway. This thickness compares well with 14 feet of black shale (the Cleveland) immediately overlying the Three Lick Bed, measured at another nearby outcrop in Pulaski County (Figure 2; Appendix A, section 6). Thus, the Cleveland Shale and the upper unit of the Gassaway member are equivalent and extend from northern Ohio to southern Tennessee.

The Three Lick Bed, a thin but remarkably continuous and distinctive bed, is traceable over much the same area as the Cleveland Shale (Figure 9) and, in Ohio, is equivalent to the Chagrin Shale member of the Ohio Shale (Table 4). The Chagrin Shale, consisting of siltstone and grayish shale, was named and described from a type locality in northern Ohio (Hoover, 1960, p. 5-6), and its lithologic character in the study area is not the same as that observed at its type locality.

The interbedded greenish-gray and black shales of the Three Lick Bed, as interpreted on wire-line logs, occur in the upper portion of the Chagrin Shale (compare Figure 7 with Lewis and Schwietering, 1971, fig. 2.B.) and likely represent a western tongue of the Chagrin. As the Chagrin thickens eastward in Ohio, the Three Lick Bed cannot be recognized on gamma-ray curves (see Lewis and Schwietering, 1971, fig. 2.A) due to facies changes like those which occur in this unit when traced from Kentucky eastward into West Virginia.

In northern Tennessee, the best correlation is with the middle unit of the Gassaway member of the Chattanooga, which was traced into Kentucky as far north as Wolf Creek Reservoir (Conant and Swanson, 1961, p. 40 and loc. 4 in their Table 13), near measured section 6 of this study (Figure 2). Thicknesses of the Three Lick Bed at these two locations compare well, being slightly over two feet. Along the western edge of the Appalachian Basin, therefore, the Three Lick Bed and its equivalent, the middle unit of the Gassaway, are traceable for nearly 450 miles (725 km), a conclusion based in part on data in Conant and Swanson (1961, p. 40) and Lewis and Schwietering (1971, fig. 2).

Outside the Appalachian Basin, the Three Lick Bed correlates with the lower part of the Camp Run member of the New Albany Shale (Lineback, 1970, p. 25) as described in western Kentucky and southern Indiana. Here, three beds of greenish-gray shale, each about one foot thick, are separated by brownish-black shale beds of similar thickness. This description of the lower Camp Run corresponds well with the Three Lick Bed as described from outcrops in eastern Kentucky and nearby.

The remaining three subunits of the Ohio Shale are correlatable with the Huron Shale member in Ohio (Table 4). The Huron was never further subdivided formally by Ohio stratigraphers, but Lamborn (1934, p. 357-358) noted that the thick bed of black shale near the base of the Ohio (that is, the Huron) was divided into two parts by a relatively thin bed of gray shale. There are strong similarities between gamma ray curves through the lower portion of the Ohio Shale in Ohio and those through the Huron Shale interval in Kentucky (compare Figure 7 with fig. 2.B. of Lewis and Schwietering, 1971), which indicates the equivalence of these two units. Extension of the threefold division of the Huron Shale northward into Ohio could be done easily and would facilitate identification, mapping, and evaluation of reservoir units.

To the south, correlation of the Huron Shale is less certain. Lithologically, the lower unit of the Gassaway member and the entire Dowelltown member (Table 4) are similar to the Upper, Middle, and Lower Huron Shales of Kentucky (Table 2; Conant and Swanson, 1961, fig. 5). Both of these intervals consist of interbedded gray and black shales between two massive black shales.

Certain features of these intervals, however, which would be useful in correlating them from Kentucky into Tennessee, are absent. The fossil alga Foerstia, for example, occurs in the Middle Huron in Kentucky, equivalent to the upper unit of the Dowelltown in Tennessee, when correlated by lithologic similarity and stratigraphic position. Conant and Swanson (1961) do not report the presence of Foerstia, but they do note a bentonite bed, the Center Hill (fig. 5), in the upper Dowelltown. Although the Center Hill bentonite bed is present over much of central Tennessee (Conant and Swanson, 1961, fig. 7), it is not known north of Jackson County, Tennessee, about 20 miles (32 km) southwest of measured section 8 (Figure 2), and is useless in correlating beyond that point. Therefore, based primarily on lithologic similarity and sequence, the best correlation of the Huron Shale is with the lower unit of the Gassaway and the entire Dowelltown member of the Chattanooga Shale of Tennessee (Table 4).

Correlating the Ohio Shale's five stratigraphic subunits from Kentucky, where they are well-defined, eastward into West Virginia is not a simple problem, because there the subsurface character of the Devonian shale sequence begins to change facies from a predominantly dark-colored, shaly interval to one containing siltstone and lighter-colored shale. Stratigraphically, the entire interval between the base of the Berea Sandstone and the top of the Onondaga Limestone is split into only two units, the Conewango and the Devonian Shale (Patchen and Larese, 1976, p. 4). Furthermore, Devonian strata in West Virginia were described and named from exposures in the extreme

eastern portion of the state, as summarized in Woodward's (1943, p. 11) work on West Virginia Devonian stratigraphy. Consequently, Devonian stratigraphic names in West Virginia, such as "Chemung" and Brallier Formations, apply to rocks which are much coarser-grained than equivalent Upper Devonian strata in Kentucky (Oliver and others, 1971, Sheet 1, section D-D'). The lithologic differences between western subsurface and eastern outcrops in West Virginia are diagrammed in Figure 16.

Recently, subdivision of the Devonian shale sequence in West Virginia has been attempted by explorationists whose interest lies in locating potential gas reserves. Such subdivisions have not been assigned formal stratigraphic names; each investigator uses his own system of identification, such as "Zone I" (Martin and Nuckols, 1976, p. 21) or "Middle Brown Horizon" (Bagnall and Ryan, 1976, fig. 8). These units are generally defined by gamma-ray characteristics.

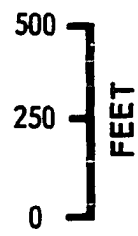
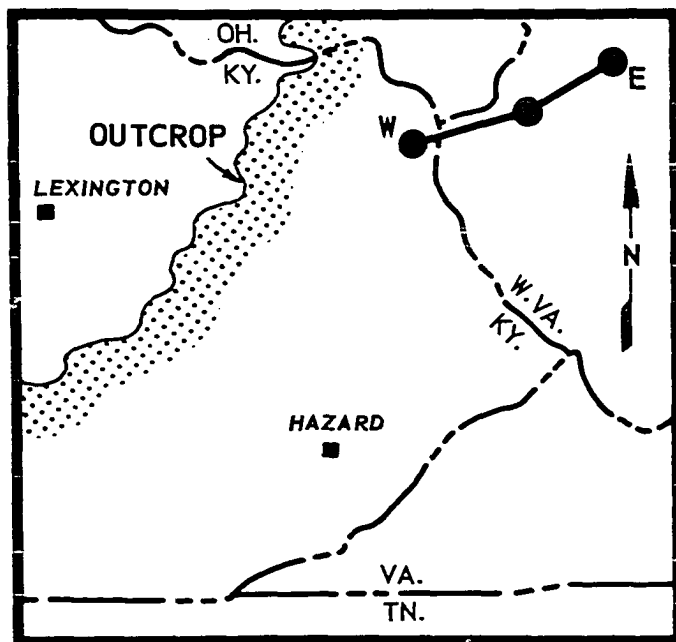
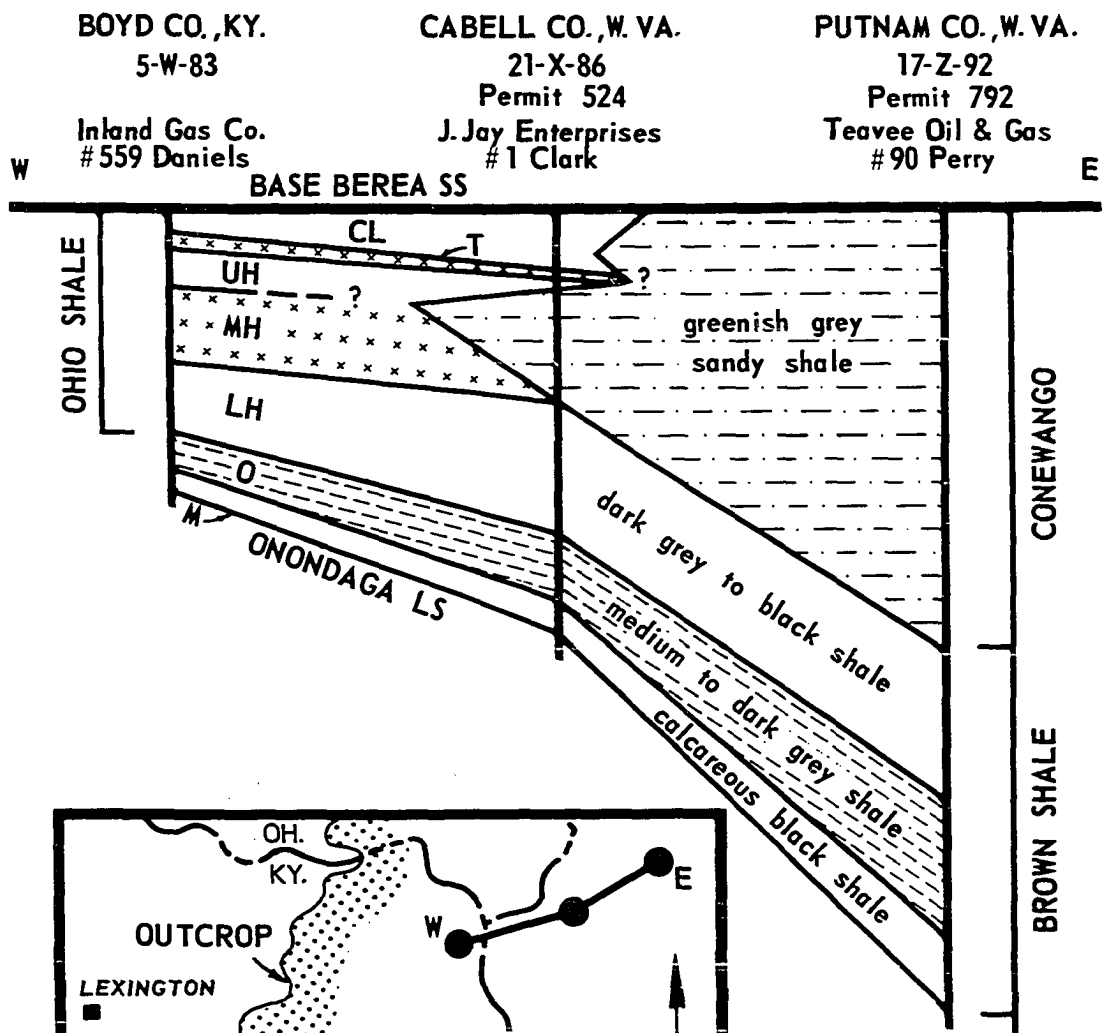
Patchen and Larese (1976, fig. 4), however, subdivide the Devonian shale sequence on the basis of lithology, recognizing in descending order: (1) greenish-gray, sandy shale; (2) dark gray to black shale; (3) medium to dark gray shale; and (4) calcareous black shale. These four lithologic zones are defined from Putnam County, West Virginia, which lies outside the study area (Figure 3, just east of the word "Ashland"). The zone of greenish-gray, sandy shale identified in Putnam County corresponds to the Cleveland Shale, the Three Lick Bed, and the Upper and Middle Huron Shales; the dark gray or black shale, to the Lower Huron; the medium or dark gray shale, to the Olentangy;

FIGURE 16.--Lithologic differences in Upper Devonian strata caused by facies changes, West Virginia. Note the predominance of shaly lithologies in the western portion of the state and the equivalent sandy and silty facies in the east (Patchen and Larese, 1976, fig. 1).

and the calcareous black shale, to the Marcellus(?) (Figure 17). In Cabell County, West Virginia -- the northernmost West Virginia County studied (Figure 3) -- the Three Lick Bed and Cleveland Shale can be recognized on a gamma-ray curve, and near the Kentucky-West Virginia border in Boyd County, Kentucky, all seven stratigraphic subunits of the Devonian shale sequence are present (Figures 3 and 7). Thus, over a total distance of approximately 75 miles (120 km), facies in the upper portion of the Devonian shale sequence change from predominantly fine-grained shales to silty and sandy shales characterized by low radioactivity and containing little organic matter. Siltstone, which likely occurs as thin beds or bands, also is present in this portion of the Devonian shale sequence and was observed in well samples from Lincoln County, West Virginia, about 20 miles (32 km) southeast of the line of section of Figure 17.

Careful study of all available well samples and, particularly, cores of the Devonian shale sequence in western West Virginia is needed to subdivide the interval above the Lower Huron Shale into recognizable, mappable stratigraphic units and assign formal stratigraphic names to them. For the Devonian shale sequence, stratigraphic names should change as facies change to convey some idea of the lithologic character of the interval which they represent. Thus, it is suggested that new names are needed for the upper part of the Devonian shale sequence in West Virginia, names which indicate what lies between black, organic-rich shales of Kentucky on the west and sandstones and siltstones of eastern West Virginia outcrops (Dennison, 1971, fig. 6; Dennison and Head, 1975, fig. 13).

FIGURE 17.--Schematic cross section showing effect of facies changes on identification of stratigraphic subunits of Devonian shale sequence. Note lateral continuity of Lower Huron, Olentangy, and Marcellus(?) Shales into West Virginia.
CL Cleveland; T Three Lick; UH Upper Huron;
MH Middle Huron; LH Lower Huron; O Olentangy;
M Marcellus(?).



SEDIMENTOLOGY OF DEVONIAN-MISSISSIPPIAN BLACK SHALES

Defining stratigraphic subunits of the Ohio Shale and determining their lithologic character reveals very little about the sedimentological processes which controlled the deposition of black, organic-rich muds in the central Appalachian Basin during Late Devonian time. The key question which logically follows characterization of the Ohio Shale is: How are lithology and stratigraphy related to the depositional environment of Devonian shales?

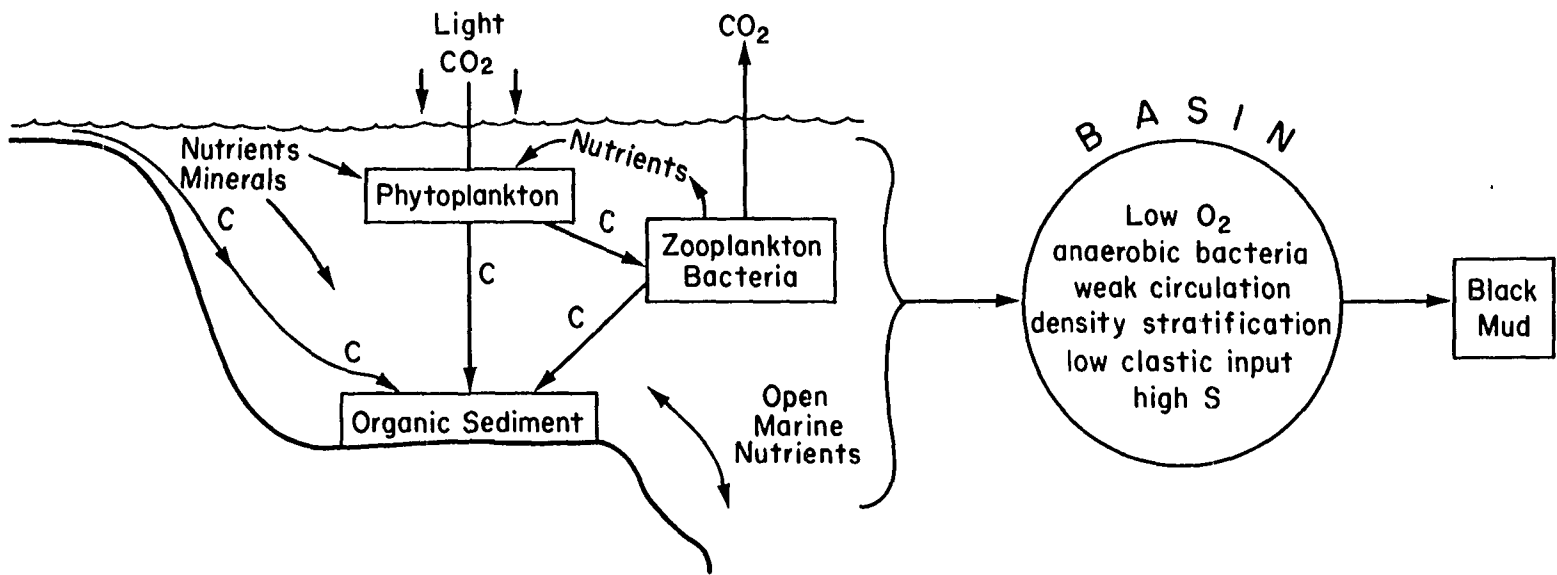
In answering this question, one must also look for modern analogs for the Ohio Shale and for other examples of black shale, be they of Devonian or other ages. This approach to interpreting depositional environment for the Ohio Shale is necessary largely because of lack of features such as sedimentary structures and vertical sequences which usually help to identify depositional setting.

Environments of Black Mud Deposition

Modern

Deposition of black, fine-grained sediments rich in organic matter is presently occurring in a variety of geographic locations (Figure 18), some of which were discussed by Twenhofel (1939) and Strom (1939). These authors cite many examples of black mud deposition, including specific locations such as Chesapeake Bay, the Black Sea, and the Gulf of Aqaba. Twenhofel (1939, p. 1197) lists eight general environments where black muds may accumulate; among them are lakes, mudflats, barred basins, and abyssal areas of oceans. Based on these studies, one can

FIGURE 18.--Schematic representation of factors controlling deposition of black, organic-rich mud. Organic matter (represented as carbon, "C") enters a basin through streams and is produced within the basin by death of marine plants and animals. Once organic matter accumulates in sediment, conditions which favor its preservation include density stratification, low clastic input, and weak circulation.



conclude that black mud deposition may occur independently of water depth and salinity and can be areally extensive or areally restricted (Figure 18). Thus, there is a wide range of modern environments which may represent the type of sedimentation which occurred in the central Appalachian Basin during Late Devonian time.

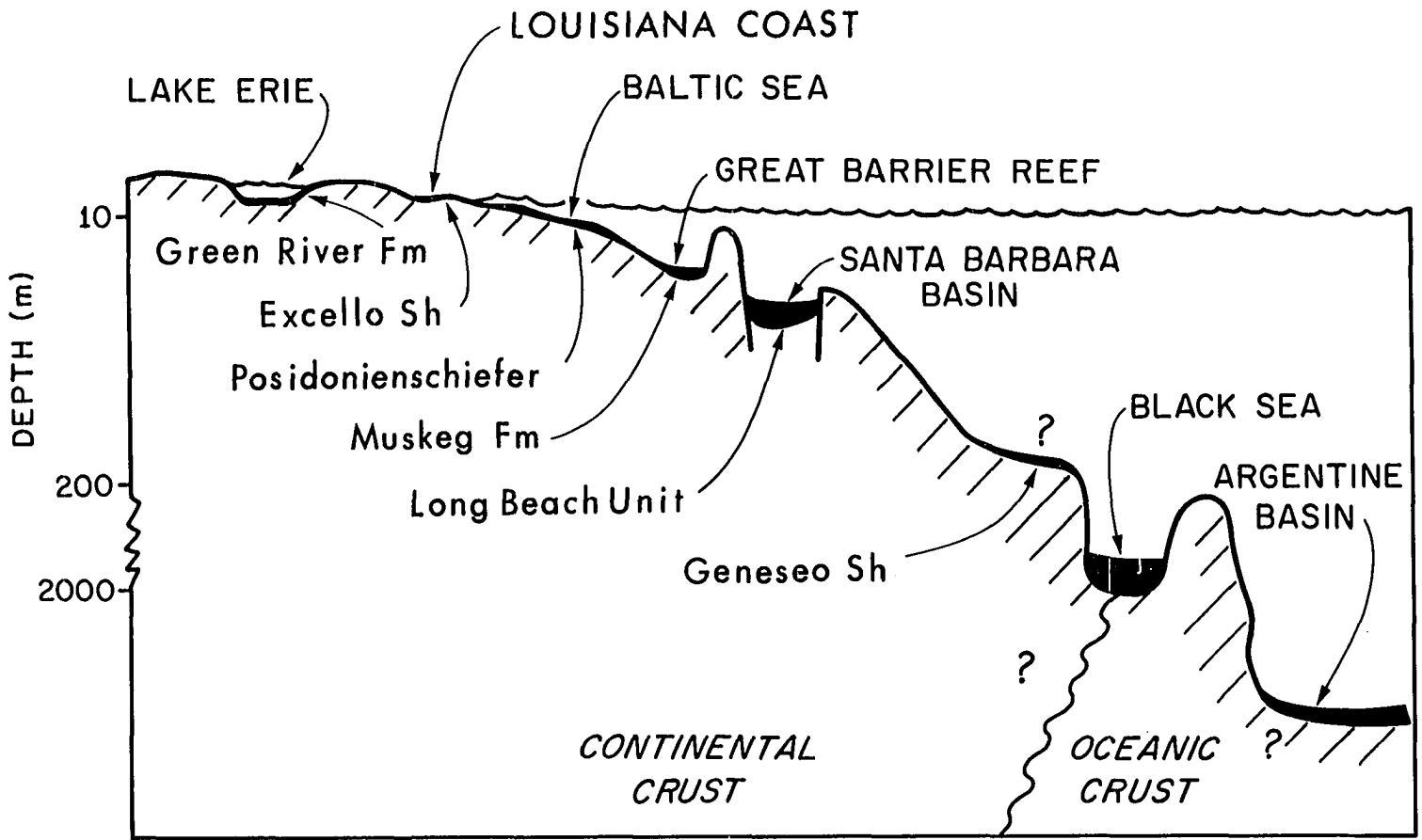
Ancient

Besides the Ohio Shale and its equivalents, there are numerous ancient examples of black, organic-rich shales, some of which are shown in Figure 19. Some black shales are as old as Precambrian (Nonesuch Shale, Michigan; White and Wright, 1954, fig. 2); others are Cambrian (Alum Shales, Sweden; Swanson, 1960b, p. 21); and a few are Tertiary or younger (Long Beach Unit, California; Truex, 1972, fig. 3). Much data on ancient bituminous shales has been collected by Bitterli (1963), who recognized ten different basin types which characterize bituminous sequences (including oil shales, marls, organic-rich limestones, in addition to black shales) of western Europe. Although the geologic record contains many black shales, perhaps none of them had so widespread a distribution as the Upper Devonian Ohio Shale and related rocks of similar age and lithology in North America, estimated to occupy over 500,000 square miles (1.28×10^6 sq. km).

Characterization

What conditions characterized Upper Devonian depositional environments and allowed the widespread accumulation of black, organic-rich muds? One of the necessary conditions for deposition of such sediment is presence of organic matter, which must not only be abundantly

FIGURE 19.--Modern (capital letters) and ancient environments of black mud deposition. Note that black muds can accumulate at any depth and in many different depositional settings.



produced, but also preserved. Organic matter, represented simply as carbon, may be carried into a depositional basin by streams. Added to this terrestrial supply is organic matter produced by death of marine plants and animals and by bacteria (productivity) within a basin (Figure 18).

Deposition of organic-rich sediments, however, also depends upon preservation of organic matter, generally by certain chemical and physical characteristics of the water mass which prevent or inhibit destruction of organic matter. First, the water mass must be stratified with respect to density. Such a stratification inhibits turnover or vertical mixing of the water mass, thus favoring a low oxygen content and creating a reducing environment. These conditions, in turn, inhibit oxidation of organic matter and create in the water column conditions unfavorable or even toxic to marine life. With a bottom-dwelling population that is limited or absent, destruction of organic matter is minimal.

Another means of restricting circulation has been suggested by Lineback (1968, 1970) in his analysis of the New Albany Shale in Indiana. He proposed (p. 1301) that a dense, floating mat of algae covered the New Albany sea and acted simultaneously as a source of organic matter and as a means for restricting circulation. Periodically, break-up of the algal mat by storms, disease, or unfavorable water conditions resulted in deposition of lighter-colored, organic-poor shale.

Keulegan and Krumbein (1949, p. 859) proposed a third means of restricting circulation, suggesting that gentle bottom slopes could cause waves to break gradually and slowly. With most of the wave energy dissipated, they propose, circulation would be minimal. However, the presence of bipolar cross-bedding in many skeletal carbonates on cratons suggests that at least tidal currents -- if not wave-induced currents -- can operate far onto cratons even on their gentle slopes.

To prevent dilution of organic matter by other sediment such as mud, silt, or sand, the amount of clastic sediments entering a basin must be relatively low. Water depth (a favorite source of controversy among those who study Devonian black shale) is not, therefore, a critical factor in accumulation of black, organic-rich muds. Provided favorable conditions for production and preservation of organic matter exist, deposition of black mud conceivably could occur independently of water depth.

Depositional Models for Appalachian Black Shales

Shallow Cratonic Sea

In south-central Kentucky, where the Devonian shale sequence is relatively thin (Figure 4), deposition likely occurred in a shallow, cratonic sea of depths less than 100 feet (30 m), which spread to the south into Tennessee and northern Alabama. Conant and Swanson (1961, p. 60) list seven important stratigraphic, paleogeographic, and paleontologic features which support a shallow-water origin for the Chattanooga Shale in Tennessee. Their evidence, including presence of a basal, shallow-water sandstone, shallow-water sedimentary features,

occurrence of Lingula, and a dominance of consistently shallow seas in this area throughout Early Paleozoic time, is very compelling and applicable also to the Devonian shale sequence in south-central Kentucky. These same authors (p. 52) describe the Late Devonian sea in Tennessee as "...a fingering and interconnecting shallow sea spread among broad flat lowlands". Such a sea advanced over lowlands of negligible relief and "the erosive power of wave, current, and tidal action was at a minimum, by reason of extreme shallowness of the sea in the irregularly shaped and sized pans" (Conant and Swanson, 1961, p. 52).

Arguing similarly, Breger and Brown (1963, p. 744-745) suggest that the Chattanooga Shale was deposited in many small lake-sized bodies separated by ridges; these "lakes" gradually increased and coalesced. The ridges served as a barrier to circulation and aided in creating a reducing environment suitable for preservation of organic matter. Such a depositional environment, these authors state, was comparable to that of coastal salt marshes of Louisiana (Figure 19).

Evidence of the system of ridges and embayments of Breger and Brown (1963, p. 744) is also seen in southern Kentucky just west of Burkesville (very near the southernmost sample point in Kentucky on Figure 1, about 90 miles northeast of Nashville). Here, the Chattanooga Shale is only a few inches thick (Cattermole, 1963). Its thinness suggests that this area was relatively high, like a ridge, and received sediments for only a brief period of time. It is probable that the shale near Burkesville represents one of the farthest westward advances of the Chattanooga sea in the southern Appalachian Basin.

Evidence for existence of shallow, epicontinental seas in the southwestern portion of the Appalachian Basin during Chattanooga time is reasonably sound and certain. But does this sort of depositional environment also apply to the Devonian shale sequence to the north and east in Kentucky and Ohio, where outcrop thicknesses are from three to ten times greater than in southern Kentucky and subsurface sections are as much as 80 times thicker?

Many of the same characteristics which were used by Conant and Swanson (1961) to establish the depositional environment for the Chattanooga Shale persist to the north in Kentucky. For example, the Ohio Shale rests directly and unconformably on older rocks, generally carbonates (Appendix A, sections 2 through 5). Thin laminae or lenses of siltstone, more indicative of shallow than deep water (Conant and Swanson, 1961, p. 61), are common in the Ohio Shale, as are linguloid brachiopods. Throughout Early Paleozoic time, shallow-water sedimentation was also widespread in this part of the Appalachian Basin as it was over most of the eastern interior of the United States. Furthermore, Devonian shales from Kentucky and Ohio are lithologically similar to their equivalents in Tennessee.

Cratonic Basin

Very little specific information has been published regarding depositional environment of the Devonian shale sequence in Kentucky and Ohio. Rich (1951) supported a deep-water origin for many of the Devonian black shales in the Appalachian Basin, including the Ohio and Chattanooga, and cited evidence (p. 2022-2035) he believed was proof

they were "fondo" deposits. According to Rich, deposition occurred in deep, unaerated portions of an extensive basin characterized by low clastic input. Earlier, Kindle (1912, p. 204), who studied the Cleveland, Chagrin, and Huron Shales in Ohio, suggested that the Chagrin represented a nearshore, shallow-water deposit and the Cleveland and Huron were deep-water facies of the Chagrin and also offered the Black Sea as a modern analog for Ohio Shale deposition. His conclusions were based primarily on lithologic and paleontologic differences between the Chagrin and Cleveland-Huron. More recently, Foreman (1959, p. 80) used the presence of radiolaria with delicate tests found in calcareous concretions in the Huron Shale, southern Ohio, as evidence supporting deposition in relatively shallow water. Finally, Lewis and Schwietering (1971, p. 3482) regarded the Cleveland Shale in Ohio as a deep-water, western facies of the Catskill delta sediments, but offered no information on the older units of the Ohio Shale. Thus, the word controversial well describes the ideas about the origin of the Ohio Shale and its equivalents in the central Appalachian Basin north of Tennessee.

The next logical question is, "What insights regarding the origin of the Ohio Shale may be gained from a broader perspective by considering the other Upper Devonian rocks in the Appalachian Basin?"

From western New York State, black shale tongues extend eastward, where they are contained within prodeltaic (slope and basin) siltstone and mudstone (Sutton, 1963, fig. 2, p. 96-97; Rickard, 1964; Sutton and others, 1970, fig. 7). Some of these siltstones and shales lying

between black shale are turbidites, as documented by Walker and Sutton (1967, p. 1021), who believe that increasing water depth was responsible for deposition of black shale.

In Pennsylvania, West Virginia, and Virginia, Upper Devonian rocks of the Senecan and Chautauquan Series (Table 5) consist of sandstone, siltstone, and some shale and represent a wide variety of depositional environments, including deep-water, prodeltaic turbidites, shallow-water deltaic deposits, barrier deposits, estuarine beds, and subaerial delta plain deposits (Dennison, 1971, fig. 1, p. 1184-1186). Collectively, eastern equivalents of the Ohio Shale form the Catskill Delta complex, the dominant element controlling Middle and Late Devonian sedimentation in the Appalachian Basin (Dennison, 1971, fig. 1).

Further south, in Tennessee, one of the best exposures of Upper Devonian strata includes over 2,000 feet (610 m) of Chattanooga Shale (Dennison and Boucot, 1974, fig. 3). This section, located near outcrop section 9 of this report (Figure 2 and Appendix A), consists of grayish-black shale and lighter-colored shales and thin siltstones. No interpretation of the origin of the Chattanooga in eastern Tennessee -- markedly different in thickness and lithology from equivalent exposures in central Tennessee studied by Conant and Swanson (1961) -- was offered, but equivalent strata in the subsurface of southwestern Virginia are believed to represent delta front, prodelta, and offshore marine facies (Walls, 1975, p. 361-362). Black shales which occur in this area were deposited during transgressive cycles, while siltstones resulted from periods of marine regression associated with a prograding delta located in Virginia (Walls, 1975, fig. 8).

TABLE 5.--Devonian and Lower Mississippian time-stratigraphic terminology. Appalachian black shales are Frasnian through Early Tournaisian in age.

Millions Of Years Ago		European Series	Appalachian	
			Series	Stage
340	MISS.	TOURNAISIAN	OSAGEAN	
			KINDERHOOKIAN	
350		FAMENNIAN	CHAUTAUQUAN	BRADFORD
				CASSADAGA
		FRASNIAN	SENECAN	COHOCTON
				FINGER LAKES
360		GIVETIAN	ERIAN	TAGHANIC
				TIOUGHNIOGA
				CAZENOVIA
370		EIFELIAN		ONESQUETHAW
		EMSIAN		
380		SIEGENIAN	ULSTERIAN	DEERPARK
				HELDERBERG
390		GEDINNIAN		

In summary, Late Devonian sedimentation throughout the length of the Appalachian Basin was dominated by a series of deltas (Dennison and Head, 1975, fig. 12) along the basin's eastern margin. Westward across the basin, facies associated with this system of deltas were controlled by variations in sea level and clastic supply. It is likely, therefore, that deposition of the Ohio Shale was related to the development of this eastern deltaic complex.

Black Shale and Turbidites

The association of black shale with turbiditic siltstones and mudstones in the Upper Devonian sequence of New York suggests that black shale represents distal facies of turbidites deposited beyond prodelta slopes. The source area of such sediments was located to the east, as inferred from reconstruction of Devonian depositional systems by Sutton and others (1970, fig. 7). With strong influxes of clastic material (probably a result of deltaic progradation), turbidites had their maximum westward extent and black shale was confined to the extreme western portion of New York. During subsequent periods of transgression, black shale tongues penetrated eastward over 200 miles (320 km) into central New York (based on data from Rickard, 1964). Thus, in the northern Appalachian Basin, occurrence of black shale depends on oscillations in sea level, which are also reflected in variations in the rate of delta progradation.

The effect of delta progradation on black shale deposition during Late Devonian time in New York was twofold: (1) it restricted deposition of black shale to the extreme western portion of the Appalachian

Basin; and (2) it diluted organic-rich muds with large volumes of clastic sediment. It is also possible that improved circulation or seasonal variations in organic productivity resulted in destruction or decreased amounts of organic matter and deposition of organic-poor shales instead of black, organic-rich shales.

An important conclusion regarding water depth can be drawn from the sequence of Devonian strata in New York. During transgressive phases, there was a wider range of water depths in which black shale deposition occurred -- from as little as 100 feet (30 m) in western New York to several hundred feet in central New York (700 feet or 215 m, as estimated by Hand and others, 1973, p. 174). Water depths were probably shallowest along the western margin of the Appalachian Basin, away from the centrally located axis of maximum thickness of Devonian strata (Conant and Swanson, 1961, fig. 13). In contrast, during periods of regression, deposition of black shale occurred only in the western, shallow portion of the Appalachian Basin.

Deposition of black shale in the western Appalachian Basin likely persisted through much of the Late Devonian because of several conditions: (1) shallow, gently sloping shelf; (2) abundance of marine plants; and (3) lack of and distance from major source areas of clastic sediments. The first two of these conditions were instrumental in restricting circulation. Once poor circulation was established, the water mass attained a density stratification which further inhibited circulation and favored preservation of organic matter. Finally, low clastic input prevented the dilution of organic matter

by sands, silts, and clays. With increased clastic input, widespread gray shale beds, like the Three Lick, were deposited. The origin of thinner, less persistent gray shales, such as those which occur in the Middle Huron Shale, can be attributed to local, short-lived phenomena which temporarily improved circulation -- possibly break-up of an algal flotant by disease or storms. It is possible that these thin gray shale interbeds may also be related to pulses of sedimentation in the eastern portion of the Appalachian Basin, but recognition of such small variations on sea level curves such as that of Dennison and Head (1975, fig. 2) would be extremely difficult.

One additional fact regarding the depositional history of the Upper Devonian shale sequence must be explained. Deposition of black shale began in early Late Devonian time in New York, with most of the New York black shales lying below the Dunkirk Shale of Late Cohocton age (Table 5). The base of the Dunkirk is generally regarded as equivalent to the base of the Huron Shale of Ohio and Kentucky (Schwietering, 1970, p. 20). Thus, the black Devonian shales in the central Appalachian Basin were deposited after the main episodes of black shale deposition in the northern Appalachian Basin.

The reasons for this difference are likely related to the sequence of basin filling and development. The oldest subunits of the Devonian shale sequence, the Olentangy and Marcellus(?), are restricted mainly to the central portion of the basin, with the Olentangy having a greater areal extent than the Marcellus(?) (Figure 14). The Olentangy Shale is also absent on the Cincinnati Arch (Schwietering, 1970, p. 37), probably a topographically high feature during Olentangy time.

As the basin filled, deposition and depositional environments prograded westward across it, and deposition began to occur in places formerly emergent, especially in the southwestern Appalachian Basin. Thus, the Huron Shale extends much farther west and south than the Olentangy (Figures 13 and 14). As the Late Devonian sea extended itself over the interior of the United States, black shale was deposited because favorable conditions developed in the necessarily shallow sea along the basin's western margin. Most importantly, these conditions include gentle bottom slope and poor circulation. While the Huron and younger black shales were being deposited in Ohio and Kentucky, deposition of sandy and silty facies occurred in New York (Rickard, 1964), which implies that basin filling was well advanced in the northern Appalachian Basin and that organic-rich muds could not accumulate because of the abundance of clastic sediments and their gradual extension into westernmost New York State.

URANIUM IN DEVONIAN-MISSISSIPPIAN SHALES

One of the distinguishing features of Devonian-Mississippian black shales is their high uranium content. The amount of uranium in the black, organic-rich shales of the Upper Devonian shale sequence of the Appalachian Basin is greater than that contained in an average shale by as much as ten times (Turekian and Wedepohl, 1961, Table 2).

Uranium Content of Ohio Shale

How does the uranium potential of the Ohio Shale in Kentucky compare with that of the Ohio's equivalent in Tennessee, the Chattanooga, as reported by Conant and Swanson (1961)? To answer this question, 101 samples of Ohio Shale and its equivalents from Kentucky, Ohio, Tennessee, and Alabama were analyzed for uranium (Figure 1). Fourteen of these were core samples; the remainder were from outcrops of Devonian Shale (Appendix B).

The amount of uranium was determined by fluorimetric analysis, in which each sample was dissolved in a mixture of nitric, perchloric and hydrofluoric acids and then mixed with aluminum nitrate. To this mixture, ethyl acetate was added, which extracts uranium. Evaporation of the ethyl acetate layer and addition of flux followed by heating produced a pellet of sample whose fluorescence was measured with a fluorimeter. From fluorescence measurements, the amount of U_3O_8 (ppm) was calculated for each sample.

The amount of uranium ranges from 1 to 106 ppm (Figure 20 and Appendix B) and varies geographically (Figure 21). Such variation is

FIGURE 20.--Cumulative curve and histogram of uranium content of 103 samples of Devonian-Mississippian shale from Ohio, Kentucky, Tennessee, and Alabama. Note two dominant subpopulations which are related to lithology and organic content.

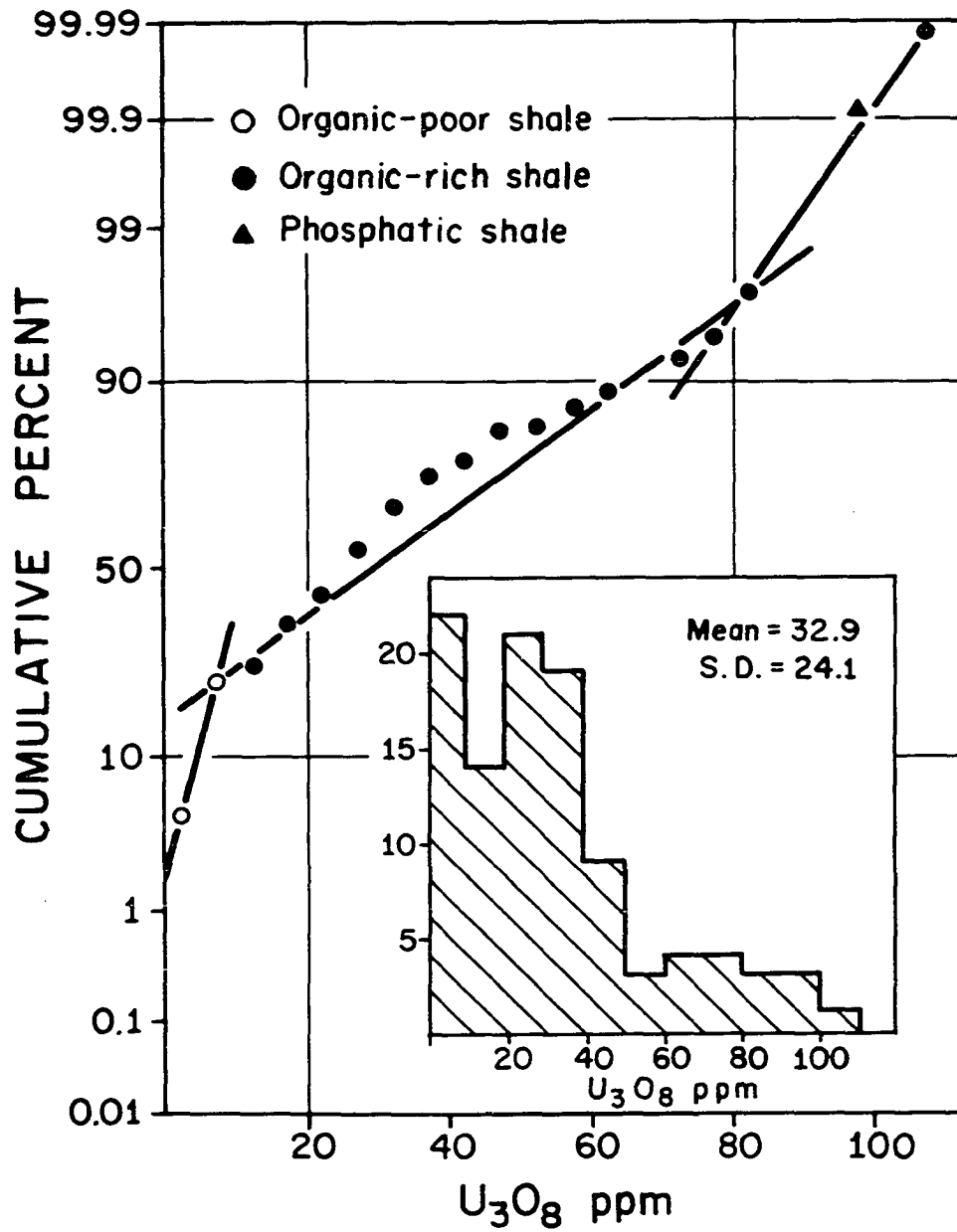
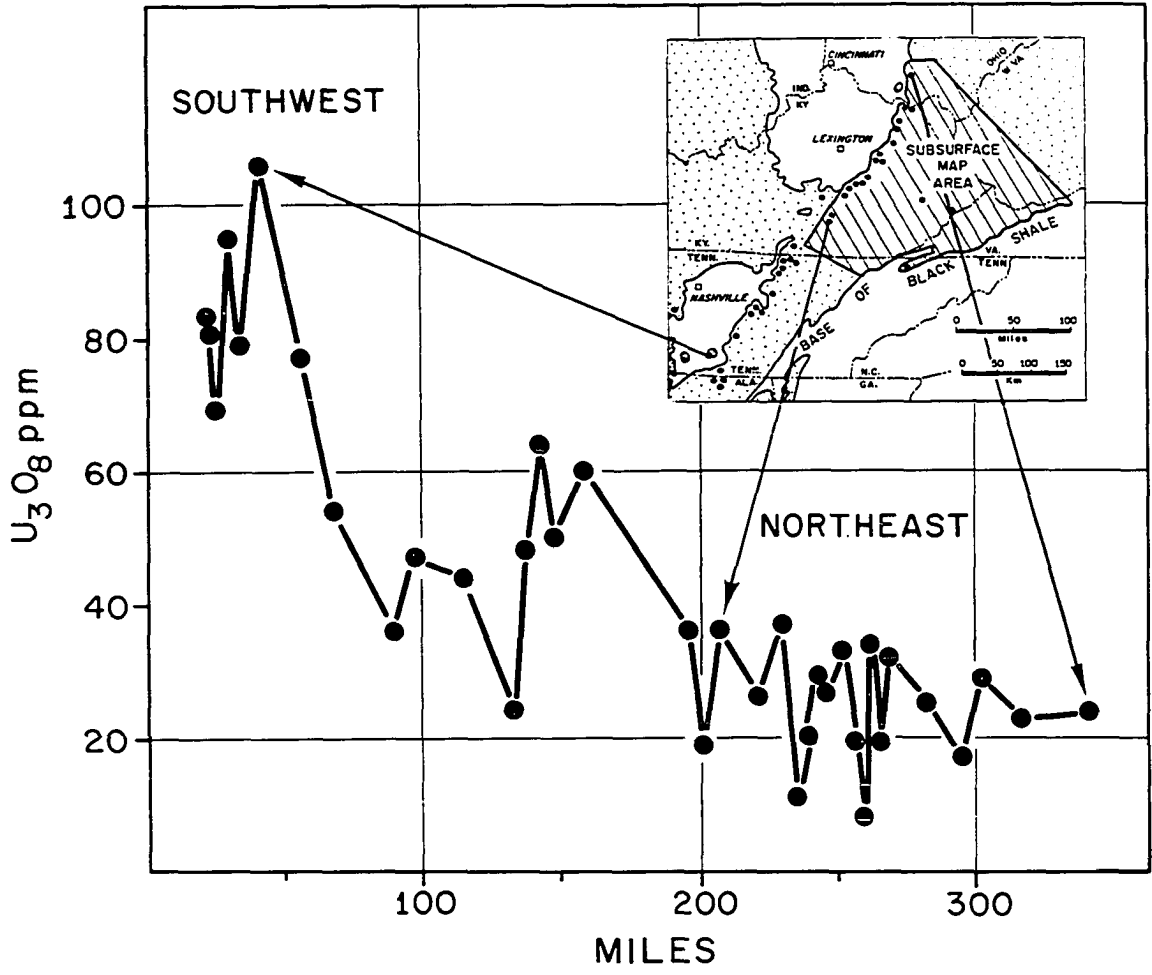


FIGURE 21.--Variation of uranium content of Devonian-Mississippian shales with position in basin. Samples from the southwestern portion of the Appalachian Basin contain more uranium than those from the central portion of the basin, a phenomenon probably related to the total amount of and the type of organic matter in these shales. Organic geochemical analyses to determine the precise relationship between uranium and organic matter are currently in progress.



in agreement with results of Conant and Swanson (1961) and Breger and Brown (1963), who both show a decrease in uranium content northward from Tennessee.

Two important questions are suggested by Figures 20 and 21. First, what sort of variation in uranium content is there vertically throughout the seven units of the Ohio Shale in Kentucky? And, what are the reasons for regional and stratigraphic variations in uranium content?

For the Cleveland Shale, Three Lick Bed, and the total Huron Shale of the Ohio Shale in Kentucky, the average amount of uranium per unit is about 30 ppm (Table 6), with the exception of the Three Lick Bed, which contains only 15 ppm. Average uranium content for all samples from the Cleveland, Three Lick, and Huron is 27.7 ppm. The Olentangy and Marcellus(?) Shales are excluded from Table 6 because of the low (typically less than 10 ppm) uranium content of the Olentangy and lack of samples from both units -- they rarely occur at the surface. The greatest range in values from a single unit, 67 ppm, occurs in the Lower Huron Shale (Table 6). In general, uranium content varies little from one stratigraphic unit to the next, provided lithologies of each unit are similar.

An illustration of the effect of lithology on uranium content is seen in the Three Lick Bed. The low average uranium content of this unit can be attributed to the relative abundance of greenish-gray, organic-poor shale in it (Figure 7 and Table 2), but black, organic-rich shale from this unit contains about the same amount of uranium as those units containing abundant black shale (Appendix B, samples 19899 and 19903).

TABLE 6.--Average uranium content and total amount of uranium per unit for the Ohio Shale in eastern Kentucky.

UNIT	Arithmetic Average Uranium Content (ppm)	Sample Size	Range in Uranium Content (ppm) with Standard Deviation	Volume of Shale (cu.mi.)	Total Uranium per Unit (tons x 10 ¹²)
CLEVELAND SHALES	28.9 ±6.4	10	19 - 48 S.D. = 11.1	115	1.23
THREE LICK BED	15.2 ±8.0	6	6 - 28 S.D. = 9.7	61.4	0.65
UPPER HURON SHALES	31.0 ±6.1	4	26 - 36 S.D. = 5.2	84.7	0.90
MIDDLE HURON SHALES	30.5 ±12.2	6	6 - 47 S.D. = 14.8	146.2	1.56
LOWER HURON SHALES	31.1 ±10.1	10	7 - 74 S.D. = 17.5	182.5	1.95
Total Uranium in Ohio Shale					6.28
¹ Tons of uranium were calculated using a density of 2.3 for the shale. Confidence limits for average uranium content are 90 percent.					

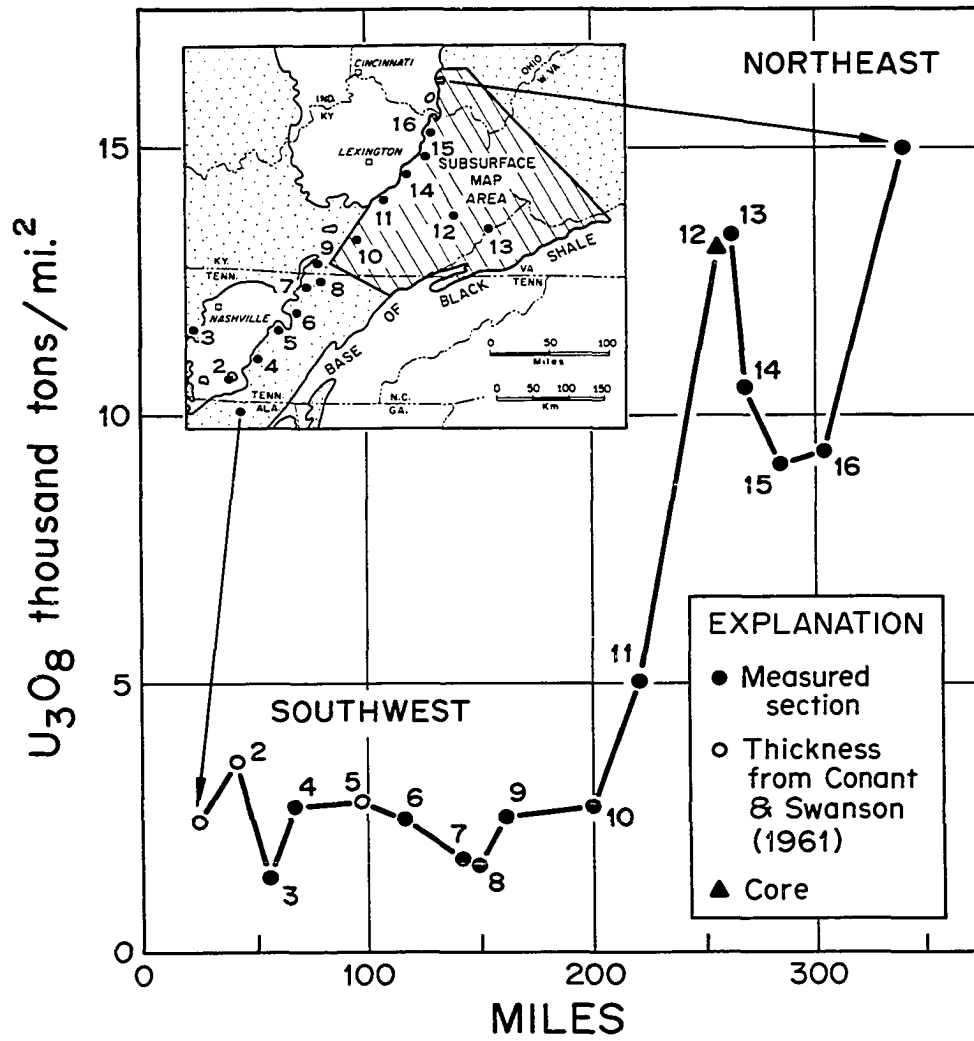
The total tonnage of uranium per unit for the Cleveland Shale, Three Lick Bed, and total Huron Shale of the Ohio Shale was calculated, using the values of uranium in Table 6. For Kentucky east of longitude $84^{\circ}20'$ west, the volume of rock in each unit was obtained from isopach maps of these units (Figures 8, 9, 11, 12 and 13) by finding the area between each contour line with a planimeter and multiplying that area by the average thickness of the contour interval.

Because the concentration of uranium in each unit is nearly equal, the thicker units (Cleveland, Middle and Lower Huron) obviously constitute the greatest source of uranium. The total amount of uranium contained in the uppermost five units of the Devonian shale sequence in eastern Kentucky is estimated to be 6.28×10^{12} tons (Table 6). In comparison, the Gassaway member of the Chattanooga Shale in eastern Tennessee, whose average thickness is only 15 feet (4.5 m), contains about 4.5×10^6 tons of uranium (Conant and Swanson, 1961, p. 76).

As a further illustration of the effect of stratigraphic thickness on uranium reserves, the tonnage of U_3O_8 per square mile was computed for shale sampled from outcrops and core ranging from less than 20 feet to over 300 feet (6 m to 91 m) in thickness (Figure 22). Tonnage of uranium was calculated for the entire Ohio (Chattanooga) Shale, but not for individual stratigraphic subunits. For samples from different but nearby outcrops having the same thickness, uranium concentration was averaged to obtain a single, representative value.

Although the Chattanooga Shale in southern Tennessee and northern Alabama contains from 70 to 100 ppm U_3O_8 (Figure 21), its thinness

FIGURE 22.--Variation of uranium tonnage per unit area in Devonian-Mississippian shales with position in basin. Although shale from the southwestern portion of the study area contains up to 106 ppm U_3O_8 (see Figure 21), its thinness results in a low tonnage of U_3O_8 per square mile. Where outcrop thickness exceeds 100 feet (30 m), the amount of U_3O_8 per unit area increases greatly, reaching a maximum of slightly more than 15,000 tons per square mile in southern Ohio, where average U_3O_8 content of individual samples is only 25 ppm.



contributes to its relatively low tonnage of uranium per unit area, generally less than 3,000 tons per square mile (Figure 22). In northern Kentucky and southern Ohio, however, the amount of uranium per square mile increases to a maximum of about 15,000 tons per square mile (Figure 22), more than five times as much uranium as contained in thin exposures to the south. The unusually thick exposure of Ohio Shale at Mountain Branch in eastern Kentucky (Appendix A, section 10) is estimated to contain over 13,000 tons of uranium per square mile even though no samples from that outcrop contain more than 20 ppm U_3O_8 . Thus, both thickness and uranium concentration must be considered to make a proper evaluation of uranium reserves for the Devonian-Mississippian shales in the central Appalachian Basin. And clearly, per square mile of surface area either strip-mined or mined by some method of underground leaching, eastern Kentucky is superior to Tennessee.

What stratigraphic and regional trends are suggested by the data in Table 6 and Figures 21 and 22? First, for the Ohio Shale in Kentucky, there is little variation in average uranium content between each stratigraphic subunit. The highest amounts of uranium are found in the Lower Huron Shale, low in the section. It is also this interval on gamma-ray curves which is most radioactive. Conant and Swanson (1961), however, found that the upper half of the Chattanooga Shale in Tennessee was more uraniferous than the lower.

Secondly, although the Ohio Shale in Kentucky is much thicker than its partial equivalent in Tennessee (the Gassaway Member), it is

less rich in uranium, the average content being 30 ppm. A typical sample from the Gassaway member contains 60 ppm (Conant and Swanson, 1961, p. 71). This decrease in uranium content northward along the outcrop from Tennessee is illustrated in Figure 21. As outcrop thickness increases in the same direction, however, the amount of uranium per square mile also increases from less than 1,500 tons per square mile to over 15,000 tons per square mile (Figure 22).

Factors Controlling Uranium Concentration

Thus, the two most important factors controlling uranium concentration in Devonian-Mississippian shales are lithology and position within the basin. And the basic difference between shales with high concentrations of uranium and those with low is organic content. Shales rich in organic matter are also typically rich in uranium.

The association of uranium and organic matter in shales has been noted in many studies (Brown, 1956, p. 461; Swanson, 1956, p. 454; 1960a, p. 78, 86; 1960b, fig. 2; Kepferle, 1959, p. 602; Conant and Swanson, 1961, p. 73; Breger and Brown, 1963, p. 753). In fact, organic matter is generally believed to complex and retain uranium -- carried to depositional sites by streams or existing as a normal constituent of seawater -- from seawater (Conant, 1956, p. 466; Breger and Brown, 1963, p. 752, 754).

Variations in uranium content vertically throughout the Ohio Shale section (Table 6), as discussed earlier, are related to lithology, especially the proportion of organic matter to detrital matter in these shales. Where organic matter was abundant or undiluted by large

amounts of clastic sediments containing little organic matter, shales have high concentrations of uranium. However, there must be another factor influencing the amount of uranium in Devonian-Mississippian shales, because even organic-rich shales from eastern Kentucky contain less uranium than similar shales to the west and south.

The relationship between the amount of organic matter and geography and uranium content of Devonian-Mississippian black shales may be explained in three ways. Perhaps the rate of sedimentation varied throughout the Appalachian Basin, thus allowing more time for extraction of uranium from seawater by organic matter in areas of slow sedimentation. Second, it is possible that more uranium entered the depositional basin in Tennessee than in Ohio and Kentucky because of streams carrying high amounts of uranium. Finally, the type of organic matter as well as its absolute amount could have influenced the concentration of uranium in Devonian-Mississippian black shales.

To determine which of these three situations correctly explains the relationship between amount of organic matter and geography and uranium content, three types of organic geochemical analyses need to be done on samples of Devonian-Mississippian shales: (1) amount of organic carbon; (2) amount of extractable organic matter; and (3) stable isotope ratios (C^{12}/C^{13}). These additional analyses will provide a better understanding of sedimentological processes which control uranium concentration.

First, determining the amount of organic carbon and extractable organics should show how these two variables correlate with uranium

concentration. In addition, these two variables will provide a better geochemical characterization of black shale; in this report, this was estimated by lithology (color) and stratigraphy. Second, stable isotope ratios (C^{12}/C^{13}) indicate whether the organic matter in the shale was of marine or terrestrial origin (Degens, 1969) and, thus, should allow evaluation of the influence of the type of organic matter as well as its absolute amount. These ratios likely vary throughout the basin with depositional setting and, therefore, determination of these ratios should aid in improving prediction of uranium trends. Finally, these organic geochemical analyses will make it possible to compare this study with others of uranium geochemistry. It is suggested that these analyses be done on outcrop and, most importantly, core samples to provide an adequate geochemical characterization of Devonian-Mississippian shales and to determine more precisely the role of organic matter in the concentration of uranium.

DEVONIAN-MISSISSIPPIAN BLACK SHALE WORLDWIDE

Many characteristics of Devonian-Mississippian black shales set them apart from other shales -- color, fissility, high concentrations of both uranium and organic matter, as well as limited fauna. Another noteworthy characteristic is their widespread occurrence in not only the Appalachian Basin, but also other basins in the United States (Conant and Swanson, 1961, pl. 14). This widespread distribution prompted an important question: where else do Devonian-Mississippian black shales occur? By searching the geologic literature on Devonian shales and by correspondence with many geologists familiar with Devonian sections worldwide, it was discovered that Devonian-Mississippian black shales extend northward from the United States into Canada and are present on three other continents as well.

Present Distribution and Thickness

North America

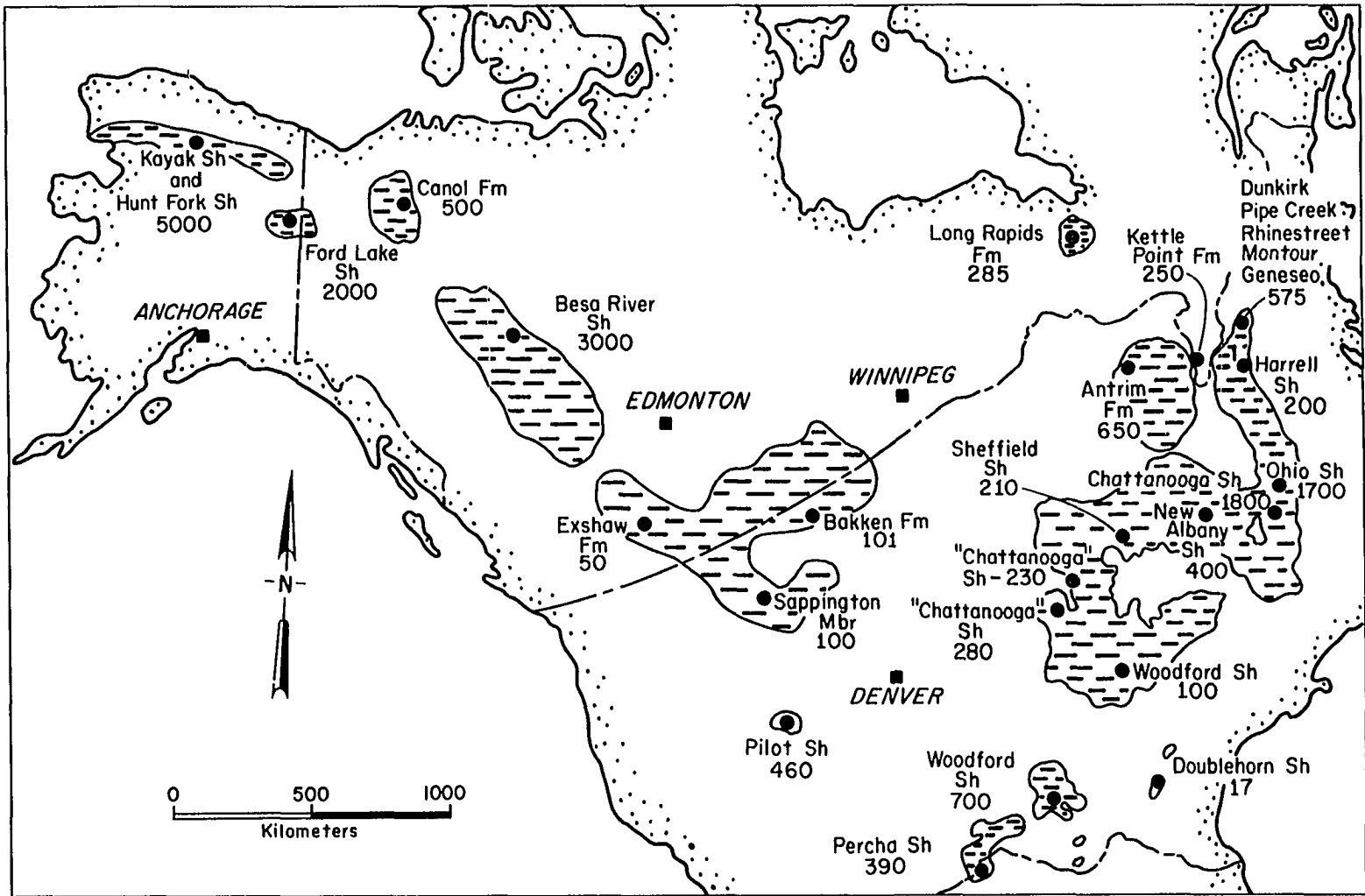
In North America, Devonian-Mississippian black shales have a widespread distribution both in outcrop and in the subsurface. Twelve basins in the United States and four in Canada contain black shales of Late Devonian or Early Mississippian age. In addition, black shale has a limited distribution in northern Mexico, near the United States-Mexican boundary. Approximately 500,000 square miles (1.3×10^6 sq. km) of the North American continent are presently still underlain by these shales, but deposition of these black shales originally could have

occurred over as much as 900,000 square miles (2.3×10^6 sq. km) of North America.

Devonian-Mississippian black shales were first recognized and are perhaps best developed in the Appalachian Basin of the eastern United States, where they extend from New York State to Alabama and are present in nine states (Figure 23). These shales, known by 13 different stratigraphic names in the Appalachian Basin, are thickest, over 2,000 feet (610 m) in portions of eastern Kentucky and Ohio and of western West Virginia. Thinnest sections occur along the western and southern margins of the Appalachian Basin, near the axis of the Cincinnati Arch. Here, thickness of entire exposed sections may be only 20 feet (6 m) or less, and the thinnest section known is in south-central Kentucky and is only 4 feet (1.2 m) thick (Cattermole, 1963). Age of Appalachian black shales ranges from Middle Devonian (Marcellus Shale, present in the central part of the Appalachian Basin where basin fill is thick) to Early Mississippian (Sunbury Shale).

The stratigraphic equivalents of these black, organic-rich, fissile shales occur in 25 other states and six Canadian provinces (Figure 23). They are found as far west as Texas and New Mexico. Transitional Devonian-Mississippian black shale is also found in Utah and in western Wyoming and Montana, two states distinguished by black shale whose thickness is as little as one-tenth foot and traceable over many square miles (Benson, 1966, fig. 16). Estimated maximum thicknesses of midwestern black shales, such as the Woodford (Figure 23), range from about 100 feet to 300 feet (30 m to 91 m).

FIGURE 23.--Distribution and maximum thickness (in feet) of Devonian-Mississippian black shales (open shale pattern) in North America, with formation names. Thickness of Dunkirk and related shales in New York State is an aggregate thickness. See Table 7 for annotated references to these shales.



North of the Appalachian Basin, Devonian-Mississippian black shales are found in Michigan and Ontario as far north as southernmost Hudson Bay (Figure 23). Black shale is also known from the western Canada sedimentary basin, several small basins in the Canadian Arctic, and the Alaskan North Slope Basin (Figure 23). Although black shale of the northern Great Plains of the United States and Canada is transitional across the Devonian-Mississippian boundary (Macqueen and Sandberg, 1970, p. 47), it appears to be predominantly Early Mississippian in age.

Thicknesses of northern black shales are comparable to those of the midwestern black shales, ranging from 50 to 500 feet (15 to 150 m). Unusually thick sections in British Columbia and Alaska consist of sandstone, conglomerate, siltstone, and other shales in addition to black shale and, in this respect, are similar to Appalachian black shales, which are associated with thick clastic basin fill of the Catskill Delta. The proportion of black shales to these other lithologies, however, is not yet well-known for western Canadian and Alaskan sections. Throughout North America, 30 different stratigraphic names have been assigned to Devonian-Mississippian black shales (Figure 23 and Table 7).

Other Continents

Because of the widespread occurrence of Devonian-Mississippian black shales over such a large region of North America, it seems only natural to ask, "Do black shales of this age occur on other continents besides North America?" And the answer is, "Yes, black shales of

TABLE 7.--Annotated references to Devonian black shales worldwide, with formation names and basins in which they occur.

PART A: NORTH AMERICA

FORMATION	BASIN	REFERENCE	
OHIO SHALE	Appalachian	Hoover, 1960	Defines internal stratigraphy of outcropping Devonian shales in Ohio and recognizes three members: the Cleveland, the Chagrin, and the Huron.
DUNKIRK, PIPECREEK, RHINESTREET, MONTOUR, and GENESEO SHALES	Appalachian	Rickard, 1964	A correlation chart of Devonian rocks in New York, which nicely show the relationship of these thin black shale tongues to grey shales and siltstones of the Catskill delta.
HARRELL SHALE	Appalachian	Dennison & Head 1975	A long review of evidence supporting sealevel fluctuations in the Appalachian Basin during Silurian and Devonian. Much information on stratigraphy, sedimentation, and tectonics. A good place to start when a regional synthesis is needed.
CHATTANOOGA SHALE	Appalachian	Conant & Swanson 1961	An exhaustive study of the "type" black shale in Tennessee, including sections on stratigraphy, age, mineralogy, paleontology, structure, tectonics, economic geology and paleogeography. The authors recognize five members and two lithologies in the standard section, and map the distribution of stratigraphic equivalents of the Chattanooga in the U. S.
NEW ALBANY SHALE	Illinois	Lineback, 1968	An article of regional interest, which accomplishes two things: (1) revision of New Albany Shale stratigraphy; (2) interpretation of depositional environment. Suggests a floating algal mat ("flotant") produced organic matter and restricted circulation.
ANTRIM SHALE	Michigan	Cohee & Others 1951	An older but excellent set of maps, cross sections, and gas production data.

PART A: NORTH AMERICA -- Continued

FORMATION	BASIN	REFERENCE	
LONG RAPIDS FORMATION	Moose River	Sanford & Norris 1973	Part of a series of articles on future petroleum provinces in Canada. Here, black shale yields oil.
SHEFFIELD SHALE	Forest City	Collinson, 1967	A regional study of Devonian rocks from Indiana to Nebraska by a conodont expert, with detailed correlation chart and several cross sections.
CHATTANOOGA SHALE	Salina	Lee, 1956	Stratigraphic and structural history of this basin by a long-time student of Kansas geology.
WOODFORD SHALE	Ouachita-Arkoma	Amsden & Others, 1967 Amsden & Klapper, 1972	These two papers, by a midcontinent stratigrapher and a conodont biostratigrapher, give much stratigraphic data for the Oklahoma area. Interesting discussion of a producing, basal sandstone to the black shale.
DOUBLEHORN SHALE	(Texas)	Cloud & Others, 1957	A short account of Devonian-Mississippian transitional rocks in Texas described from thin (15'), scattered surface exposures near the Llano Uplift.
PERCHA SHALE	Tobosa	Kottlowski, 1963	Comprehensive review of Paleozoic and Mesozoic rocks in southern New Mexico. Describes a facies change within this black shale.
BAKKEN FORMATION	Williston	Kents, 1959	Saskatchewan stratigraphy. Shale sequence enclosed between two carbonate sequences. Many subsurface maps. Suggests new exploration objectives based on structural features.
PILOT SHALE	Great	Sandberg & Poole, 1975	Part of an investigation of source rocks in the Great Basin, Utah-Nevada. Here, carbonaceous shale intertongues with turbidites and debris-flow deposits. Some data on organic carbon content, soluble hydrocarbon content, and maturation.

PART A: NORTH AMERICA -- Continued

FORMATION	BASIN	REFERENCE	
SAPPINGTON MEMBER	Williston	Gutschick & Rodriguez 1975	Although this paper's first purpose is to summarize brachiopod faunas of the Sappington, it also contains a useful stratigraphic column and correlation chart. Regional surface and subsurface correlation substantiated by fossil data demonstrates that dark shale in Sappington is equivalent to Exshaw of Alberta. Thirty references on northern Rockies stratigraphy and biostratigraphy.
EXSHAW SHALE	Williston	MacQueen & Sandberg 1970	Lithology, mineralogy, stratigraphic relations, and biostratigraphy of a thin Devonian-Mississippian black shale of western Canada. Based on 20 measured sections. Suggest that deposition occurred in shallow marine, euxinic lagoons.
BESA RIVER SHALE	Northeast British Columbia	Pelzer, 1966	Predominantly a geochemical study of this British Columbian black shale with some stratigraphy and biostratigraphy. One of the thickest North American black shales (3,000 feet).
CANOL FORMATION	Peel-Anderson	Bassett, 1961	One of many papers in a volume of Arctic geology. Suggests the stratigraphic relations of this unit may be similar to those of the Exshaw.
FORD LAKE SHALE	Eagle-Kandik	Brabb, 1969	Brief mention of a thick transitional Devonian-Mississippian black shale in Alaska.
KAYAK & HUNT FORK SHALES	North Slope	Bowsher & Dutro 1957	Two papers containing most of what is known about Paleozoic stratigraphy in Alaska's Brooks Range. Dark shale and argillite up to 1,000 feet thick.
PART B: OTHER CONTINENTS			
<u>SOUTH AMERICA</u> Rincón Formation Tononó Formation	Salteño	Mingramm & Russo 1972	Lower and Middle Devonian black shales - Upper Devonian rocks are missing here. Correlation chart for Argentina, Paraguay, and Bolivia.

PART B: OTHER CONTINENTS -- Continued

SOUTH AMERICA -- Continued

FORMATION	BASIN	REFERENCE	
LONGÁ SHALE	Maranhão	Mesner & Wooldridge 1964	Good summary of Brazilian Paleozoic and Mesozoic paleogeography with detailed lithologic column for this basin. Authors correlate this basin with three others in Brazil. Figure 21 shows that most of South America (except for this basin) was emergent during Late Devonian.
PONTA GROSSA FORMATION	Parana	Lange & Petri 1967	The Ponta Grossa, Middle to Late Devonian in age, has 20 m of black shale at top. Thickens greatly to the northwest, attaining a thickness of 5,000 m in the Bolivian Andes.
BARREIRINHA SHALE	Amazon	Morales, 1959 Ludwig, Schmitz, & Mayer 1968	Two papers - one in English, the other in Portuguese - which nicely describe the Paleozoic history of this basin. The more recent paper is a detailed facies analysis of this formation and contains much analytical data on this important source bed. Suggest deposition was in a deep marine basin.
<u>AFRICA</u> BOKKEVELD & WITTEBERG SERIES	Cape	DeVilliers, 1967	A brief, general paper from the 1967 Symposium on the Devonian held in Calgary. Not much is known about these groups, sequences of clastic rocks which contain black shale.
DRA FACIES	Tindouf	Hollard, 1967	Only one or two paragraphs briefly mentioning this black shale found in northwestern Africa. About 150 m thick.
UNNAMED BLACK SHALE	Oued Mya & Oued Rhir	Ortynski, Perrodon & deLapparent, 1959	Review of paleogeography and structural history of Paleozoic and Mesozoic basins in northern Sahara, where black shale, black limestone, and sandstone characterize Frasnian and Famennian rocks.

PART B: OTHER CONTINENTS -- Continued

FORMATION	BASIN	REFERENCE
<u>EUROPE</u> Hunsrück Büdesheim Nehden Wissenbach Flinz Kellwasserkalk	Variscan	Krebs, 1969a, b Many of these German black shales are associated with carbonate reefs and have limited distribution, while others are thin and areally extensive and may represent initial deposits of transgressing seas.
DOMANIK FACIES	Russian Platform	Nalivkin, Rzhonsnitskaya, - & Markovskii, 1973 895 pages on Devonian stratigraphy and paleontology of the Soviet Union. Two volumes, in Russian. This sequence of Frasnian bituminous shale and limestone from the area near Moscow ranges from 100-300 feet in thickness.

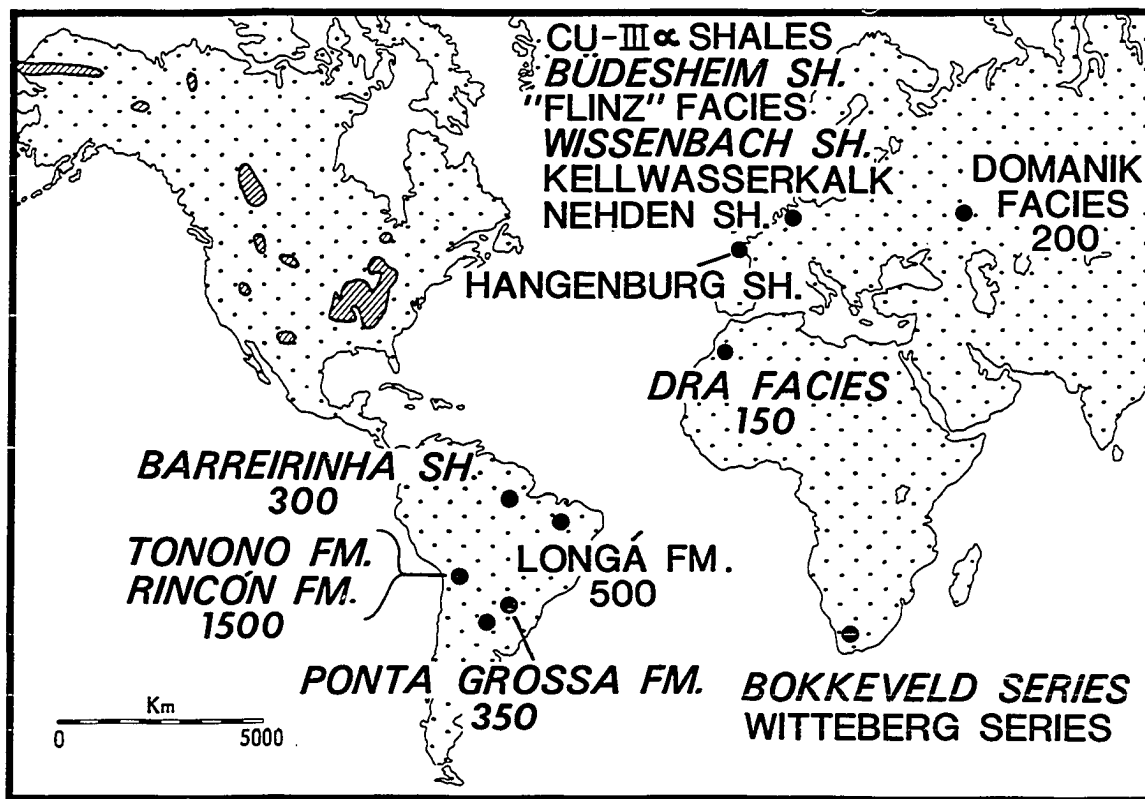
Devonian and Mississippian age are present in South America, Africa, and Europe" (Figure 24).

South American black shales occur in four or five separate basins (Figure 24), and their thickness ranges from 990 to 4,950 feet (300 to 1,500 m). Unlike black shales of North America, these shales generally are strictly Devonian in age and may be as old as Early Devonian (e.g., Rincón and Tonono Formations, Figure 24). Commonly, the Upper Devonian section is not preserved in South American basins which contain black shale. This may mean that conditions for deposition of black shale began here earlier than in North America and that such conditions may have ended here sooner than in North America.

Devonian black shales are probably present in South Africa, contained within thick sandstone sequences of the Bokkeveld and Witteberg Series (Figure 24). The age of these two series, however, is still disputed. Youngest estimated age is Early Carboniferous, based on plant remains and fish fossils, but other fossil evidence gives a maximum age of Early Devonian for the lower portion of the Bokkeveld Series (DeVilliers, 1967, p. 304). In northwestern Africa, according to Ortyński and others (1959) and Hollard (1967), there are about 660 feet (200 m) of black shale whose age ranges from Eifelian through Frasnian (Table 5) in the Tindouf Basin of Morocco (Figure 24).

In Europe, Devonian-Mississippian black shales are present in Germany and the Soviet Union west of the Urals (Figure 24). Two types of black shale are recognized from the Devonian and Lower Carboniferous of Germany: (1) black shales of basinal areas, and (2) transgressive

FIGURE 24.--Worldwide distribution and maximum thickness (in meters) of Devonian and Mississippian black shales. Early and Middle Devonian shales are shown by slant lettering. Area underlain by Devonian-Mississippian shales in North America is indicated. See Table 7 for annotated references to these shales.



shales, as thin intercalations of black shale within other sedimentary rocks (Table 8). The Nehden, Hunsrück, Büdesheim and Wissenbach Shales are all examples of basinal black shales, and they range in age from Givetian to Famennian (Table 5). The second type of black shale, which sometimes is represented by black limestone and marl, occurs in Belgium as well as Germany (Figure 24), is from 16 to 165 feet (5 to 50 m) thick, and is assigned to the Frasnian and to the Early Carboniferous on the basis of conodont and goniatite faunal successions.

Similarly, bituminous shales and limestones known collectively as the Domanik Facies (Figure 24) are reported from the Russian platform in the western Soviet Union (Nalivkin, 1973; Nalivkin and others, 1973). Thickness of these rocks ranges from 100 to 295 feet (30 to 90 m). They are Frasnian in age.

Worldwide Geology of Black Shale

Depositional and Tectonic Settings -- North America

During Late Devonian and Early Mississippian time, North America was characterized by deposition of black, organic-rich shale over a vast area, covering perhaps one-eighth of the continent (Figure 23). Other sedimentary rocks are associated with this black shale and include conglomerate, sandstone, siltstone, shale and some carbonate rocks. Sedimentation during the Late Devonian and Early Mississippian was confined to the central portion of North America. The Canadian Shield, Transcontinental Arch, and the Ozark Dome probably were positive areas supplying, however, only minor volumes of sediments to various basins. Fringing the North American continent on the east, west,

TABLE 8.--Types of Devonian-Mississippian black shales in central Europe. All examples are from Germany, except the Hangenburg Shale, which occurs also in Belgium (see Figure 24).

TYPE	OCCURRENCE	LITHOLOGY AND PALEONTOLOGY	EXAMPLE AND REFERENCE
<p style="text-align: center;">BASINAL</p>	<p>Associated with shelf-derived turbidites</p>	<p>Dark, bituminous shales. Fauna pelagic, with conodonts, crinoid stems, and graptolites.</p> <p>Chondrites - type trace fossils</p>	<p style="text-align: center;">WISSENBACH SHALE (MIDDLE DEVONIAN)</p> <p style="text-align: center;">KREBS, 1969a</p>
	<p>In inter-reef basins; may occur with carbonate turbidites</p>		<p style="text-align: center;">NEHDEN SHALE (UPPER DEVONIAN)</p> <p style="text-align: center;">KREBS, 1971</p>
	<p>Precursor of flysch sediments</p>		<p style="text-align: center;">CU-III ALPHA BLACK SHALES (LOWER CARBONIFEROUS)</p> <p style="text-align: center;">FRANKE, 1973</p>
<p style="text-align: center;">TRANSGRESSIVE</p>	<p>Transgressive facies associated with development of Variscan geosyncline</p>	<p>Black, bituminous limestone and marl; some shale in basinal areas</p>	<p style="text-align: center;">KELLWASSERKALK (LOWER UPPER DEVONIAN)</p> <p style="text-align: center;">BUGGISCH, 1972</p>
	<p>Shallow to basinal facies</p>	<p>Black shale with conodonts, graptolites and some brachiopods</p>	<p style="text-align: center;">LIEGENDE ALAUNSCHIEFER (LOWER CARBONIFEROUS)</p> <p style="text-align: center;">KREBS, 1969b</p>
	<p>Slow, suspension settling on basinal rises</p>	<p>Black limestone and shale with graptolites, spores</p>	<p style="text-align: center;">HANGENBURG SHALE (UPPER DEVONIAN)</p> <p style="text-align: center;">PAPROTH AND STREEL, 1970</p>

and north were geosynclines or miogeosynclines being filled with sediments derived from orogenic uplift marginal to the Devonian landmass. Parts of northern Europe, Scandinavia, Greenland, the Canadian Arctic, the east coast of North America and possibly North Africa formed this extensive landmass where sedimentation took place in intermontane basins and on alluvial plains (Woodrow and others, 1973, fig. 1). In latest Devonian time and subsequently, thrusting towards the continent ended episodes of sedimentation in some of these areas.

The marginal geosynclines were the key elements of Devonian paleogeography of North America and likely had a pronounced effect on the deposition of black shale. What influence did these tectonic features have on sedimentation during Late Devonian time? In the northern Appalachian Basin, for example, thin tongues of black shale are distal equivalents of prodeltaic silty and muddy turbidites (Sutton, 1963, p. 96-97; Sutton and others, 1970, fig. 7) and lie seaward of delta front, delta platform, distributary channel, and marsh deposits of the Catskill Delta of southeastern New York and Pennsylvania (Sutton and others, 1970, fig. 5). Regressive periods resulted in advancement of deltaic environments westward across the Appalachian Basin, while transgressive intervals allowed the eastward expansion of black shale environments. Thus, this occurrence of black shale clearly is related to the presence of a geosyncline and upland belt marginal to the North American craton.

Similar relationships between cratonic sedimentation and continental margin tectonism have been investigated by Sloss and Speed (1974)

for the Phanerozoic of North America. These authors recognized that three cratonic modes (emergent, oscillatory, and submergent; pp. 99-106) adequately describe the "behavior" of cratons and suggested that such modes were globally controlled by specific types of continental margin tectonism and occurred simultaneously on several cratons. Thus, in a general way, cratonic deposits such as the Ohio Shale can be related to plate tectonics.

Deposition of the Ohio Shale occurred during a submergent episode, the Kaskaskia (Sloss and Speed, 1974, Table 1 and fig. 4), in which a clastic wedge (Catskill delta) encroached upon the North American craton and the overall effect was marine transgression, although short-lived regressive phases also occurred. Along the periphery of the craton were mountain belts. Sloss and Speed (1974, p. 111 and fig. 7) argued that such mountain belts represented a response to plate convergence and concomitant subduction. From this, one can conclude that, during Ohio Shale time, collision of the North American plate with another continental plate occurred and that the Devonian Atlantic Ocean was either nonexistent or much smaller than the present-day one (see Dietz and Holden, 1974, fig. 7).

The origin of the Ohio Shale and related rocks can now be understood partly as a result of tectonism peripheral to the North American craton, which likely supplied large quantities of muddy sediment to interior cratonic areas. Locally, conditions such as density stratification, high rate of organic productivity, and a possible floating algal mat to restrict circulation gave rise to deposition of black, organic-rich shales.

In contrast to black shale as distal facies of turbidites is black shale which is present on much of the craton in the midwestern United States and the western United States and Canada (Figure 23). Included among these shales are the New Albany of Indiana (Lineback, 1968, p. 1301) and the Chattanooga of Tennessee (Conant and Swanson, 1961, p. 57), which represent deposition in shallow epicontinental seas with poor circulation, resulting from a combination of density stratification, abundant organic matter, and possible presence of a floating algal mat. In terms of cratonic sequences, these seas represented interior cratonic areas which were being encroached upon by clastic wedges along the continental margins.

Western black shales generally rest unconformably on Upper Devonian limestones such as the Palliser Formation, which underlies the black Exshaw Shale of Alberta, or on pale green to gray shales like the Three Forks Shale of Saskatchewan (Gutschick and Moreman, 1967, fig. 1). Their thickness is relatively uniform over wide areas and their time-stratigraphic equivalents are commonly shelf limestones or dolomites, unlike black shale of the Appalachian Basin. Lithologically, the Exshaw and related shales are like their Appalachian counterparts in that they consist of fissile, pyritic, carbonaceous shale with basal phosphatic sandstone (Macqueen and Sandberg, 1970, p. 37-38). Interbeds of greenish-gray shale are lacking in the Exshaw, however. The Exshaw is generally believed to be a shallow marine to brackish lagoonal deposit, which accumulated along the shores of a transgressive sea (Macqueen and Sandberg, 1970, p. 43), perhaps much like that in which the Chattanooga was deposited.

A different occurrence of Upper Devonian black shale is found in the eastern Great Basin of Nevada and Utah, where the Pilot Shale (Figure 23) was deposited between orogenic highlands on the west and a cratonic platform on the east (Poole, 1974, fig. 25). The upper part of the Lower Pilot Shale consists of dark, carbonaceous mudstone interbedded with thin, micritic limestone of deep-water origin (Sandberg and Poole, 1975, p. 6). This unit interfingers with thick, carbonate turbidite or debris-flow deposits probably derived from shelf limestones and is nearly 300 feet (93 m) thick (Sandberg and Poole, 1975, p. 7), about six times as thick as the Exshaw (Figure 23).

What was the Late Devonian tectonic framework of the western United States which resulted in these two vastly different settings of black shale? Devonian-Mississippian sedimentation adjacent to the western margin of the North American craton, from west to east, was controlled by an orogenic belt (the Antler), an elongate, foreland basin, and the stable craton (Poole, 1974, figs. 1 and 26). Gutschick and Moreman (1967, fig. 5) suggest that this tectonic framework resembles that of the Appalachian region.

In view of their position between sandy carbonate turbidites, the dark, carbonaceous muds of the Lower Pilot Shale probably are of hemipelagic origin and accumulated in bathyal waters (Poole, 1974, p. 70), perhaps as deep as those of the modern Black Sea (Figure 19). Circulation at such depths was likely poor, allowing accumulation of organic matter derived from shallower areas to the west and east. Subsidence and upwarp related to Antler orogenic activity could maintain the great depths of the Pilot Basin.

As the Antler flysch trough filled and eastward overthrusting occurred (Poole, 1974, fig. 25), loci of deposition shifted eastward and gradually encroached upon stable cratonic areas. Black shales like the Exshaw, which are slightly younger than the Pilot, represent initial, shallow-water transgressive deposits. The Exshaw and other shales, therefore, result from the same tectonic activity which was responsible for deposition of the Pilot Shale but are not in any other way genetically related to the Pilot, which represents an early phase of flysch sedimentation.

Finally, the association of the Pilot Shale with turbidites is similar to that of the Geneseo and other shales of the northern Appalachian Basin, but different in that the Pilot cannot be traced from bathyal areas onto cratonic areas. This suggests that deposition of the Pilot Shale, although related to the presence of a marginal geosyncline, was controlled primarily by local structural features and events.

Depositional and Tectonic Settings -- Other Continents

Do the distal geosynclinal and platform settings which characterize North American black shales adequately describe Devonian-Mississippian black shales from South America, Africa, and Europe? South American and African black shales may have much in common with the Ohio Shale and its equivalents in that they occur with sandstones, siltstones, and other shales. The Lower Curuá Formation of the Amazon Basin, for instance, consists of radioactive, laminated black shales which are succeeded by green and gray shales and siltstones, probably turbidites

(Ludwig and others, 1968). Black shale of marine origin is known from the Pimenteiras (Lower to Middle Devonian) and the Longá (Upper Devonian to Lower Mississippian) Formations of Brazil's Maranhão Basin, according to Mesner and Wooldridge (1964, fig. 7, p. 19-21), who suggest that the Devonian history of South American basins was one of regression. The occurrence of black shale between fluvio-deltaic sandstones and siltstones may be analogous to the thin black shales of the Upper Devonian of New York, which were associated with the accumulation of the Catskill Delta.

The association of black shale with turbidites is known also from Devonian and Lower Carboniferous sequences of northwestern and central Europe where sedimentation was controlled by the Variscan geosyncline and its basin and rise, "becken und schwellen", facies (Meischner and Scheider, 1970, fig. 1; Buggisch, 1972, p. 46-47). In Germany, these black shales are restricted to closed basinal areas seaward of shelves or to depressions upon shelves, where they may be intercalated with turbidites (Table 8). Black shales of the Nehden Stage may represent distal facies of turbidites (Einsele, 1963). The Wissenbach and Hunsrück Shales (Figure 24) are also classified as basinal black shales (Table 8) and may have an extensive areal distribution.

There is also a second type of European black shale which occurs as thin intercalations within other sedimentary facies and is very widespread (Table 8). Biostratigraphic evidence indicates that this type is isochronous.

The depositional pattern of shelf and basin was dominant in central Europe until Famennian time (Table 5), when it was replaced by a flysch basin, which received sediments from uplifted areas in south-central Europe (Dineley, 1975, fig. 11.A). The principal depositional and tectonic provinces of Europe during the Devonian and Early Carboniferous consist of the Caledonian mountain range and intermontane basins in the northern British Isles bordered by a marginal cratonic sea covering southern England, northern Germany, and the Low Countries (Dineley, 1975, fig. 8). Beyond the cratonic margin lay the basin of the Variscan (or Rhenish) geosyncline, extending eastward from France into Germany.

Within this framework, two general types of depositional settings of black shale are recognized (Krebs, 1969a, fig. 2) and may be called "basinal" and "transgressive" (Table 8). Basinal black shales are restricted in the sense that their origin is dependent on the presence of topographic features such as submarine rises or reefs which create barred basins. Such shales also accumulate in the deepest parts of larger basins, well away from shelf areas. Basinal black shales of central Europe differ from North American black shales in that they are sometimes associated with reefs (Table 8, Nehden Shale). This occurrence is not typical of North American black shale sequences, with the exception of black shales which occur in the Middle Devonian reef complexes of western Canada (Krebs and Mountjoy, 1972).

Transgressive black shales, on the other hand, have a much more widespread distribution and result from marine transgression over

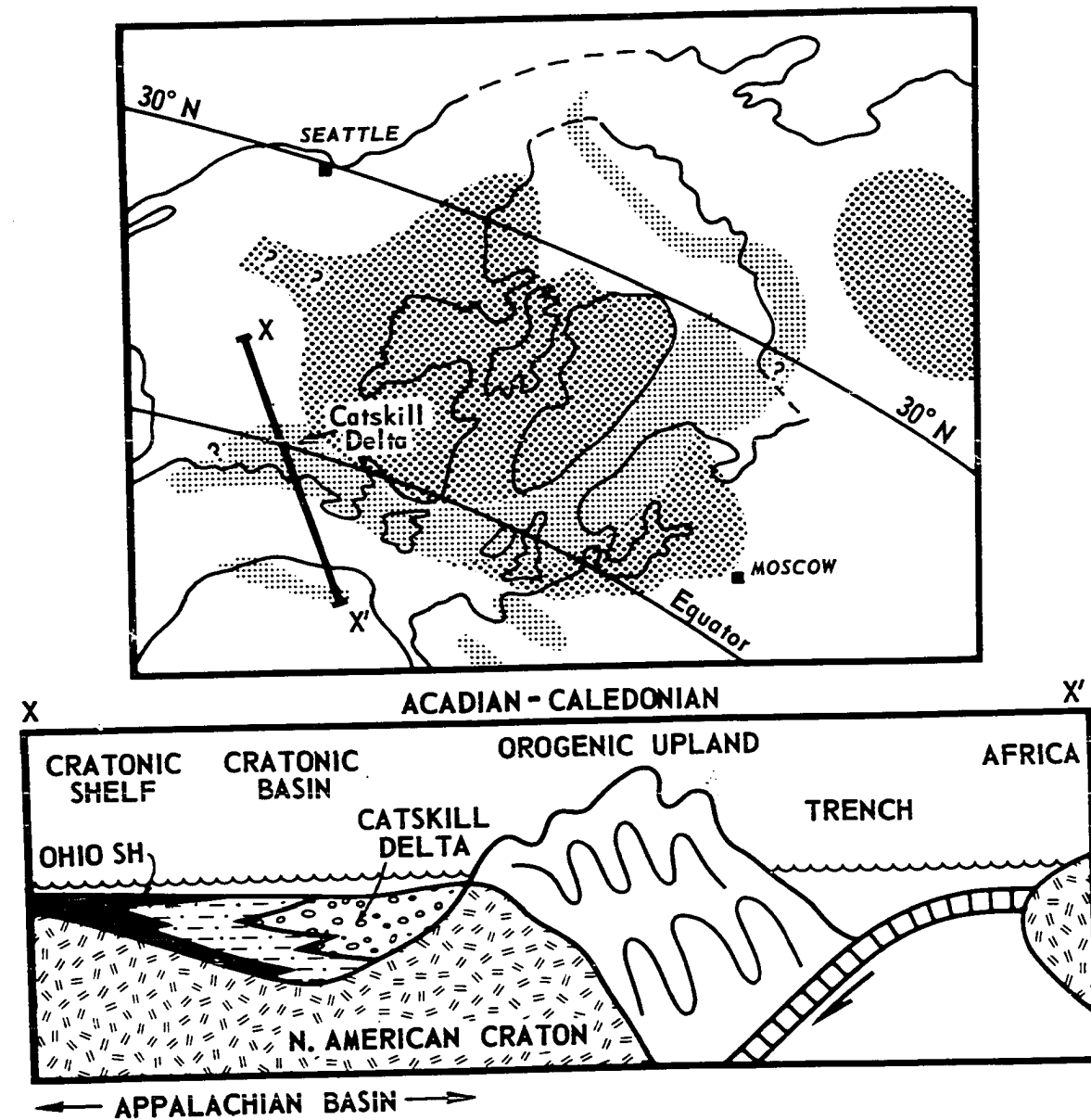
shallow shelf areas, but may also be present on submarine highs (Table 8, Hangenburg Shale). These shales also occur in shallow, limnic to fluviatile environments. The wide geographical distribution of this type of black shale is illustrated by the Kellwasserkalk, which is known from Belgium to Morocco (Buggisch, 1972, p. 46). Rapid transgressions which accompanied gradual shifting of the shelf margin of the Variscan geosyncline towards the craton were probably responsible for deposition of these areally extensive black shales or bituminous limestones (Buggisch, 1972, p. 48).

With respect to wide geographical distribution, transgressive black shales are similar to the Devonian-Mississippian black shales found over so great an area of North America. It is possible that North American and European black shales share a common origin, one which may be related to the development of the Appalachian and Variscan geosynclines.

Devonian Paleogeography and Black Shale

After examining the occurrences of Devonian-Mississippian black shales in North America and Europe, it is apparent that four basic paleogeographic features influenced the deposition of black, organic-rich shales: (1) miogeosyncline or cratonic basin; (2) shallow cratonic shelf; (3) orogenic belt with basins and ranges; and (4) stable land masses. In central Europe and the western United States, the arrangement of these elements, from sea to land, was geosyncline, shelf, and stable land mass (Figure 25), and resulted in the deposition of black shales like the Exshaw in North America and the Liegende

FIGURE 25.--Paleogeographic setting of Devonian-Mississippian shales in northern hemisphere (after Dineley, 1975, figs. 4 and 11). Stable land areas are heavily stippled; orogenic uplands, lightly stippled. Shelf seas and geosynclines surround the North Atlantic landmass. Ohio Shale accumulated in the western Appalachian Basin in response to deltaic progradation and marine transgression during an episode of submergence on the North American craton. Tectonism in bordering orogenic upland related to continental plate movement probably controlled pulses of deltaic sedimentation. Idealized cross section shows arrangement of paleogeographic and tectonic elements perpendicular to strike of Appalachian Basin.



Alaunschiefer in Germany. Beyond the land mass, an orogenic upland may have been present, as in Europe (Figure 25). Filling of geosynclinal basins and subsequent, cratonward shifting of shorelines were the regional factors controlling the origin of such black shales. Locally, the presence of a shallow, gently sloping shelf and perhaps a floating algal mat restricted circulation and created favorable conditions for the preservation of organic matter. In addition, input of coarse clastic sediments from the stable land mass and/or bordering upland had to have been minimal to allow accumulation of black, organic-rich muds.

One other type of black shale also occurred in this paleogeographic framework -- the basinal black shale such as the Pilot of Nevada and the cu-III alpha shales of Germany. These shales, as precursors of flysch sedimentation, were restricted to basinal areas in the geosyncline and, thus, are directly related to its evolution. Depth and basin morphology likely aided in restricting circulation. The origin of other European basinal black shales (e.g., Nehden) can be attributed to local features such as reefs, which restricted circulation and, hence, have little bearing on Devonian paleogeography.

The paleogeographic setting of Appalachian Devonian-Mississippian black shales was not exactly like that of European and western black shales (Figure 25). In eastern North America, the arrangement of paleogeographic features from sea to land was: (1) widespread, shallow cratonic sea; (2) cratonic basin; (3) narrow, "stable" land mass (subaerial Catskill Delta); and (4) orogenic upland. The occurrence of Appalachian black shales depended regionally on marine transgression,

which alternated with periods of deltaic progradation, caused by variations in the amount of sediment supplied from orogenic uplands. Such variations were probably related to tectonism peripheral to the North American craton (Figure 25), which, therefore, indirectly controlled the distribution of Appalachian black shale. Local conditions which favored black shale deposition included a stratified water mass, high rate of organic productivity, and, possibly, an algal flotant. The location of black shale environments away from upland source areas also favored deposition of black shale because coarse clastic input was minimal at such distances from uplands.

Climatically, deposition of Devonian black shales in North America probably occurred under equatorial conditions with warm to hot temperatures and locally variable rainfall patterns (Woodrow and others, 1973, pp. 3055-3058). The North Atlantic landmass (Figure 25) was situated between 20° N and S latitude of the equator (Woodrow and others, 1973, fig. 1; Dineley, 1975, fig. 3). Although paleoclimatic interpretation was based, in part, on geologic evidence from non-marine, coarse, Devonian clastics, the data can be applied reasonably to the lithologic equivalent of those rocks -- the Ohio Shale. Thus, a warm climate with variable, seasonal rainfall was dominant during Ohio Shale time.

One final question is suggested by Devonian paleogeography. Might there have been black shales deposited on what is now the eastern side of the Acadian-Caledonian upland (Figure 25) and in Greenland? In Greenland, the arrangement of paleogeographic features was similar to that of Germany and the Appalachian United States (Figure 25), with a

cratonic basin adjacent to an orogenic upland. Dineley (1975, p. 785) predicted that such a basin, if it existed, would contain either poorly sorted, coarse clastics derived from rapid erosion of highlands or coastal plain swamp sediments with coals, perhaps with black shales like those observed in Carboniferous coal measures.

On the other side of the Acadian orogenic upland (Figure 25), however, tectonism resulting from plate collision probably prevented the deposition of black shale during the Devonian. Furthermore, the unknown character of this continental margin and difficulty in documenting any ideas, due to post-Devonian movement of continental plates and possible destruction of the Devonian record off the present Atlantic coast, make such predictions highly speculative.

CONCLUSIONS

Measured sections and subsurface mapping of the Ohio Shale and its equivalents in the central Appalachian Basin have provided the following stratigraphic conclusions.

1. In northeastern Kentucky and adjacent areas, the Ohio Shale consists of five to seven easily recognized, mappable units in both subsurface and outcrop.
2. In south-central Kentucky, where the shale sequence is thin, these units cannot be separated.
3. From top to bottom, these seven units are the Cleveland Shale, Three Lick Bed, Upper, Middle and Lower Huron Shales, Olentangy Shale, and Marcellus(?) Shale.
4. Regional correlation of the uppermost five units is possible from northern Ohio, where they are equivalent to the Cleveland, Chagrin, and Huron members of the Ohio Shale, to Tennessee, where the Dowelltown and Gassaway members of the Chattanooga Shale are their equivalents.

Chemical and petrographic study of samples from these stratigraphic subunits indicate that:

1. The Ohio Shale consists of two dominant lithologic types: dark, organic-rich shale and greenish-gray, organic-poor shale or mudstone.

2. Minor lithologies include limestone with cone-in-cone structure, siltstone, discontinuous beds of pyrite, and phosphatic nodules. Of these, limestone and phosphatic nodules are found consistently in the upper one-third of the Ohio Shale, suggesting that they are stratigraphically significant.
3. Banding in these shales, caused by differences in lithologic constituents, is related to depositional events, one possibility being turbidity currents, within the Appalachian Basin. Seasonal or longer-term variations in organic productivity may also account for alternation of dark and light shales.
4. The percent of uranium in Upper Devonian shales is greatest in Tennessee and Alabama and is controlled by the amount of organic matter and by position within the depositional basin, the latter reflecting specific depositional conditions which led to uranium enrichment.

Economic conclusions include:

1. The amount of uranium in all samples of the Ohio Shale and equivalents ranges from 1 to 106 ppm. The average amount of uranium per unit in the Ohio Shale in Kentucky is 27.7 ± 3.2 ppm at 90 percent confidence limits.

2. For the Cleveland Shale, Three Lick Bed, and total Huron Shale in Kentucky, the arithmetic average amount of uranium per unit with 90 percent confidence limits is as follows:

Cleveland Shale:	28.9 ± 6.4 ppm
Three Lick Bed:	15.2 ± 8.0 ppm
Upper Huron Shale:	31.0 ± 6.1 ppm
Middle Huron Shale:	30.5 ± 12.2 ppm
Lower Huron Shale:	31.1 ± 10.1 ppm

3. In Kentucky, the five most uraniferous units of the Ohio Shale are estimated to contain 6.28×10^{12} tons of uranium and, thus, must be considered a very low-grade, but major, source of uranium.
4. The Cleveland and Lower Huron Shales, because they are thickest and easily recognized, would be most suitable for future economic exploration.
5. Per unit area, black shale in central and northern Kentucky and southern Ohio contains more tons of uranium than equivalent shale in Tennessee and northern Alabama, primarily because the stratigraphic interval is thicker.

Basin analysis of the Ohio Shale and its equivalents in the central and eastern Appalachian Basin indicates that:

1. Deposition of Ohio Shale occurred on very shallow, cratonic shelf seas in the western portion of the Appalachian Basin, but in deeper seas eastward toward the distal fringes of the Catskill delta.

2. Deposition of black, organic-rich mud occurs when there is both a high rate of production of organic matter and a stratified water mass, which encourages its preservation.
3. Conditions in the western Appalachian Basin which favored the deposition of black mud include a stratified water mass, high rate of organic productivity, and a possible floating algal mat. Distance from major, eastern source areas kept coarse clastic input at a minimum.
4. Episodes of deltaic progradation and of marine transgression associated with the Catskill Delta controlled the distribution of black shale facies in the western Appalachian Basin.

Finally, literature study of other Devonian black shales in North America and other continents reveals that:

1. Black shale of Devonian age is found in 26 states of the United States, six provinces and territories of Canada, and on three other continents.
2. There are two basic types of black shale, basinal and transgressive: basinal black shales may be distal facies of turbidites or may be associated with growing carbonate reefs, whereas transgressive black shales are areally extensive deposits resulting from marine transgression over shallow shelf areas.

3. Four elements of Devonian paleogeography characterize the occurrence of black shale: cratonic shelf, geosyncline (cratonic basin), orogenic upland, and stable landmass. These elements are present in the Appalachian United States, the western United States, and north-central Europe. Deposition of black shale occurred on cratonic shelves and in cratonic basins which were being supplied sediments from orogenic uplands marginal to the North American and European cratons.
4. In North America, Devonian-Mississippian black shale was deposited during a period of cratonic submergence related to tectonism peripheral to the craton's margins, caused, in turn, by movement of continental plates. Such periods of submergence were characterized by an overall marine transgression of the craton with minor regressive intervals. In Europe, irregular topography of basin and shelf resulted in deposition of some black shales by creating locally restricted basins, while others were controlled by the development of a geosyncline marginal to the European craton.

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APPENDIX A--DESCRIPTIONS OF THE TEN MEASURED SECTIONS
OF THE OHIO AND CHATTANOOGA SHALES OF THIS
REPORT

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APPENDIX A—DESCRIPTIONS OF THE TEN MEASURED SECTIONS
OF THE OHIO AND CHATTANOOGA SHALES OF THIS
REPORT

SECTION 1

Copperas Mountain Section

Nearly complete section of Ohio Shale in a spectacular exposure, where Paint Creek impinges at base of and undercuts Copperas Mountain in Ross County, Ohio, approximately 3.9 airline miles east of Bainbridge by way of U.S. Highway 50, Jones Levee Road and Storm Station Road, on the Morgantown 7.5' Quadrangle (1,802,300 feet east, 450,000 feet north, Ohio coordinate system, south zone). Because of the steep slopes and cliffs, we could only obtain detailed lithologic observations at considerable hazard; and, consequently, the section was described in reconnaissance only except for some details of the Three Lick Bed. However, the section is notable for the outstanding exposure of the Three Lick Bed, which can be seen from afar when driving east on U.S. Highway 50 from Bainbridge, and for its unique system of buttresses. Described with Jacob's staff, Abney level, and tape by Roy C. Kepferle, J. Barry Maynard, Paul Edwin Potter, Wayne A. Pryor, and Rene Ulmschneider on August 31 and September 8, 1976. Scintillometer survey was made on August 31.

	Thickness (feet)
Mississippian:	
Berea Sandstone (incomplete):	
6. Sandstone, weathers yellowish gray and iron-stained and fine in dense, hard resistant beds 0.2 to 0.4 foot thick; sole marks include grooves and trace fossils. Slightly slumped; caps ridge.	2.0+
Bedford Shale:	
5. Shale, mainly covered except for lower part, which is partially exposed in a slump scar near the top of the cliff about 100 feet north of the trail. Sandstone in float in slump scar is thin-bedded and rippled and has numerous sole marks as is typical of the Bedford; mud- stone is greenish gray with iron-stained siltstone concretions near base. Sharp basal contact is well exposed at base of scar but is partially covered at the highest point of the cliff 285 feet above low- water Paint Creek.	<u>83.0</u>
Total Mississippian (incomplete)	<u>85+</u>

Devonian:	Thickness (feet)
Ohio Shale (incomplete):	
4. Shale, brownish-black and blocky, forming a near vertical, jagged cliff easily seen from river level. Sharp basal contact.	65
Three Lick Bed:	
3. Mudstone and shale. Mudstone is greenish gray, weathers soft and contains minor pyrite. Shale is brownish black and forms thin fissle ledges. The mudstone forms three prominent beds; the upper is 5.0 feet, the middle is 1.7 feet, and the basal bed is 4.8 feet thick; the upper intervening black shale is 4.2 feet thick and split by a thin cone-in-cone limestone bed near its middle; the lower intervening black shale is 4.8 feet thick and contains several thin greenish-gray mudstone beds	<u>20.5</u>
Total Three Lick Bed	<u>20.5</u>
2. Shale, brownish-black, weathers to very steep flumes, many of which have thin, near vertical spectacular buttress-like divides. (We have not seen erosional patterns like this although they are reportedly common in parts of New York in the Upper Devonian shale sequence.) These buttresses extend nearly vertically from the base of the exposure to about 140 feet above Paint Creek, and then rise at about an angle of 30° up to the Three Lick Bed. Above this break in slope there is a distinct, regular banding characterized by couplets of resistant and nonresistant shale; the latter is recessive and accumulates a fine talus of light-gray weathered shale chips. Two thin, easily seen cone-in-cone limestone beds occur at 11 and 41 feet below the base of the Three Lick Bed; 35 feet below the Three Lick Bed is another less continuous thin cone-in-cone bed of limestone. About 65 feet above Paint Creek are three small concretions, 1 to 3 feet in size. Near the road, 15 to 25 feet above Paint Creek, is a zone of very large dolomitic concretions, some of which are hollow and all of which exhibit marked differential compaction in the shale; these concretions range in size from 1 to 6 feet. A thin, greenish-gray mudstone occurs beneath this zone. Some <i>Foerstia</i> were observed in the float near the base of the section	190

	Thickness (feet)
Devonian (continued):	
Ohio Shale (continued):	
1. Covered to low water Paint Creek.	<u>10</u>
Total Ohio Shale is approximately	<u>275+</u>
Total section is approximately 360 feet thick	

SECTION 2

Tener Mountain Section

Nearly complete section of Ohio Shale, Bedford Shale, Berea Sandstone, and Sunbury Shale exposed for 5.1 miles in roadcuts along both sides of Ohio Highway 32 near Peebles, Franklin Township, Adams County, Ohio. Base of section is on northwest side of Ohio Highway 32 at its junction with Ohio Highway 73 (Jaybird quadrangle), where lowermost 26.5 feet were measured and described. Upper 215.9 feet of section ending at top of Ohio Shale were measured along east side of Ohio Highway 32, (Byington quadrangle). Incomplete exposures of Bedford Shale, Berea Sandstone and Sunbury Shale on west side of Ohio Highway 32 at its intersection with Union Hill Road, 1.15 miles northeast (Byington quadrangle). Section measured, described, and sampled using Jacob's staff, Abney level, aneroid barometer, and tape, and its radioactivity profile measured using scintillometer by R. C. Kepferle, P. E. Potter, Linda J. Provo, and Tom Yu, June 25 and 29, 1976

	Thickness (feet)
Mississippian (incomplete):	
Cuyahoga Formation (incomplete):	
38. Siltstone (single bed), weathers yellowish-gray (5Y 8/i); <u>Zoophycos</u> -like burrows on top; limonite stain along joint. Two sets of sole marks at 205° and 280°, with blunter ends toward these directions. Massive bedding, probably Ta interval of Bouma (1962).	1.3
37. Shale, greenish-gray (5G 6/1), locally blackish-red (5R 2/2) to grayish-red (5R 4/2) higher in unit. Rare, poorly defined siltstone beds, olive-gray (5Y 4/1) to light-brownish-gray (5YR 6/1) with limonitic stain	<u>26.0</u>
Total Cuyahoga Formation (incomplete).	<u>27.3+</u>

Mississippian (continued):	Thickness (feet)
Sunbury Shale:	
36. Shale, black (N1) to grayish-black (N2), weathers medium light gray (N6) to yellowish gray (5Y 8/1) where stained with jarosite, grayish-brown (5Y 3/2) to dark yellowish-orange (10YR 6/6) where stained with limonite; fissile, laminated, brittle, no silt. Pyrite nodules, 4 cm., occur 4 feet below top and rarer, smaller (1-2 cm.) pyrite nodules, finely crystalline, lobate, flattened along bedding planes throughout rest of unit. Phosphate nodules, 2-3 cm., ovoid, with fossil core, at top of unit (sampled). Burrows, 4 mm. wide, along bedding planes, fairly straight, filled with light-olive-gray (5Y 6/1) mudstone. Vertical silica "dike" strikes 25° in ditch on west side of highway, 6-7 cm. wide, limonite-stained (sampled)	15.0
35. Siltstone, dark-gray (N3) where carbonaceous, grading to light-olive-gray (5Y 6/1), flecks of carbonaceous material and wispy dark streaks; abundant <u>Lingula</u> fragments. Distinct, irregular contact with less than 1 cm. of dark shale, like unit 36 with thin silt laminae less than 1 mm. thick and a few <u>Lingula</u> fragments (sampled).	0.05
34. Shale, grayish-black (N2), silty, laminated, pyrite, with very thin laminae of silt one or two grains thick. At top of unit is a trashy zone of <u>Lingula</u> fragments and conodonts (sampled). Basal contact sharp.	<u>0.05</u>
Total Sunbury Shale	<u>15.1</u>
Berea Sandstone:	
33. Sandstone, silty, medium-light-gray (N6) to light-olive-gray (5Y 6/1), weathers grayish-orange (10YR 7/4) to yellowish-gray (5Y 8/1); darker zones near top are pyritic; bed thickness increases upward from 0.7 foot to as much as 4 feet; at top is a 2-4 cm. pyrite bed	30.5
32. Sandstone and silty shale in equal amounts. Sandstone is like unit 33, except beds 0.1-0.2 foot thick. Upper bed surfaces are rippled; ripple crests strike 290-310°; wavelength is commonly 10 cm., wave height is commonly 1-2 cm.; cross laminae dip southwest in	

Mississippian (continued):	Thickness (feet)
Berea Sandstone (continued):	
lower parts of rippled beds and northeast in upper parts. Shale is greenish-gray (5GY 6/1), silty.	
Contacts sharp.	<u>14.5</u>
Total Berea Sandstone.	<u>45.0</u>
Bedford Shale:	
31. Shale (70 percent) and interbedded siltstone and very fine-grained sandstone (30 percent). Shale is greenish gray (5GY 6/1), silty, with some silt laminae. Siltstone and sandstone beds are less than 1 cm. thick, upper surfaces rippled and burrowed; complex burrow system on soles and load and flute casts (?). Amount of siltstone and sandstone increases in overlying units 32 and 33. Offset along basal contact of Bedford Shale 1.16 miles south along east side of Ohio Highway 32. .	20.0
30. Covered interval (thickness approximate)	<u>60</u>
Total Bedford Shale	<u>80</u>
Devonian:	
Ohio Shale (incomplete):	
29. Shale, dark-gray (N3) to brownish-black (5YR 2/1), weathers to very thin light-gray (N7) chips; brittle, fissile, subconchoidal fracture, tough when fresh, forms massive faces; no silt, pyritic; spores common throughout unit and increase in abundance upward; rare <i>Lingula</i> near upper contact. Uppermost 0.1 foot separated from main part of unit by 0.3 foot yellowish-brown (10YR 6/4) mudstone. Sampled at base and at 20 and 26 feet above base. Contact with underlying unit is sharp and slightly irregular.	61.1
Three Lick Bed:	
28. Shale, dark-greenish-gray (5GY 4/1) to greenish-gray (5GY 6/1), poorly laminated, soft, non-brittle, clayey; limonitic stain along bedding planes.	0.3
27. Shale, brownish-black (5YR 2/1), fissile, brittle, slightly silty, pyritic; rare spores.	0.2

Devonian (continued):

Ohio Shale (continued):

	Thickness (feet)
Three Lick Bed (continued):	
26. Shale, dark-greenish-gray (5GY 4/1) to greenish-gray (5GY 6/1), like unit 28. Sampled 0.7 foot below top	3.7
25. Shale, brownish-black (5YR 2/1), like unit 27	4.3
24. Shale, dark-greenish-gray (5GY 4/1) to greenish-gray (5GY 6/1), like unit 28.	0.2
23. Shale, brownish-black (5YR 2/1), like unit 27, slightly mottled. Sampled at base.	1.1
22. Shale, dark-greenish-gray (5GY 4/1) to greenish-gray (5GY 6/1), like unit 28; possible pyrite-filled burrows along bedding. Sampled 0.8 foot above base	2.2
21. Shale, brownish-black (5YR 2/1), like unit 27; abundant spores	3.0
20. Shale, dark-greenish-gray (5GY 4/1) to greenish-gray (5GY 6/1), like unit 28; abundant, tiny flecks of black carbonaceous matter.	0.2
19. Shale, brownish-black (5YR 2/1), like unit 27; 1 cm. clay shale parting 0.6 foot above base; rare spores. Sampled at 0.2 foot above base.	1.5
18. Shale, dark-greenish-gray (5GY 4/1) to greenish-gray (5GY 6/1), like unit 28. Sampled 0.5 foot above base.	<u>4.4</u>
Total Three Lick Bed	<u>21.1</u>
17. Shale, dark-gray (N3) to grayish-black (N2), weathers light gray (N7) to medium light gray (N6) chips, 1-2 cm; fissile, brittle, uniform, subconchoidal fracture, silty; numerous spores near base, decreasing in abundance upward; abundant flecks of black carbonaceous matter; few pyrite nodules, 2-3 cm., flattened along bedding planes in lower 3 feet of unit; pyritic zone 9 feet below top; two 0.1-foot thick, discontinuous cone-in-cone layers at 22 (sampled) and 33.5 feet below top. Unit weathers in ribbed fashion with ribs 0.5 foot thick separated by talus-covered slopes 0.2 to 0.5 foot thick.	

Devonian (continued):	Thickness (feet)
Ohio Shale (continued):	
Denser, more resistant bed at 40 feet above base. Sampled 6 and 43 feet above base	96.0
16. Shale, dark-greenish-gray (SGY 4/1), thinly laminated, poorly fissile, clayey, cohesive.	0.1
15. Shale, dark-gray (N3), fissile, brittle, fine; rare spores.	1.5
14. Shale, dark-greenish-gray (SGY 4/1), like unit 16. .	0.4
13. Shale, dark-gray (N3) to medium-dark-gray (N4), like unit 15. Contact with underlying gray shale sharp .	0.5
12. Shale, dark-greenish-gray (SGY 4/1), like unit 16. .	0.4
11. Shale, grayish-black (N2) to brownish-black (5YR 2/1), weathers to thin, small chips less than 1 cm. in diameter; laminated with laminae 1-2 mm. thick; poorly fissile, fine, pyritic; spores common to rare. . . .	1.1
10. Shale, greenish-gray (SGY 6/1) to dark-greenish-gray (GY 4/1), weathers to thin, fissile flakes; clayey to slightly silty; thinly laminated with laminae 1-2 mm. thick; flecks of black carbonaceous matter. Moderate-brown (5YR 4/4) iron-oxide stain along bedding. Interbedded with five thin, dark-gray (N3) shale beds at base and at 0.45-0.50, 1.1, 1.7, and 2.9 feet above base; contacts sharp. Upper 2 feet of this unit does not have dark-gray shale interbedded and is separated from lower 8.4 feet by a 0.6 foot zone of dark-gray shale with a thin (less than 5 mm.), silty, concretionary pyrite zone. Slightly sideritic concretionary zones, 0.5 foot thick, at 3.0, 4.0-4.5, and 7.5-8.0 feet above base; brittle, tough, dense, conchoidal fracture, weather dark yellowish orange (10YR 6/6). 2 cm.-thick cone-in-cone limestone layer 7.9 feet above base. In upper 2 feet, pyrite nodules are numerous, botryoidal, typically 1-2 cm. and up to 8 cm. long; flattened slightly along bedding, long axis parallels bedding; small pyrite-filled burrows (?) parallel to bedding. Sharp planar contact with underlying unit. Sampled 3 feet above base	11.0

Devonian (continued):

Ohio Shale (continued):	Thickness (feet)
9. Shale, brownish-black (5YR 3/1), slightly silty, thickly bedded, in beds 5-6 mm. thick, breaks along bedding with subconchoidal fracture, brittle, tough; 0.4 foot below top is a parting of greenish-gray (5GY 6/1) clay; abundant flecks of unidentifiable black carbonaceous debris, no spores, selenite rosettes along weathered bedding planes; about 1.0 foot below top are two fragments of coalified <u>Callixylon</u> (?) 1.2 feet long and 0.8 foot wide. . . .	6.0
8. Shale, grayish-black (N2) to brownish-black (5YR 2/1), weathers to thin chips, 3-4 cm., light-gray (N7) to medium-light-gray (N6); fissile, thinly laminated, brittle, subconchoidal fracture, slightly silty; where freshest, unit weathers into subround fragments up to 10 cm. across; rare pyrite nodules, 1-2 cm. in diameter; slightly pitted surface on some bedding planes. Abundant black <u>Foerstia</u> , lobate, especially conspicuous in weathered, lighter gray chips. Joints 3 feet apart strike 345° and dip 67° west. Sampled 1 foot above base and at top . . .	12.0
7. Shale, brownish-black (5YR 2/1) and olive-black (5Y 2/1), weathers medium light gray (N6) to light gray (N7) with pale-greenish-yellow (10Y 8/2) iron sulfate and dark-yellowish-orange (10YR 6/6) iron-oxide coatings; subconchoidal fracture, brittle, dense where fresh; spores absent to rare. Alternating massive and fissile-weathering beds in 0.5 to 0.8 foot couplets give outcrop a ribbed appearance; thin, brittle chips litter weathered slopes; sulphurous water seeps from near base of section	<u>4.2</u>
Total Ohio Shale in single exposure	<u>215+</u>
Section thickness in units 7 through 38 totals about 383 feet.	

Offset 4.1 miles to southwest on north side of Ohio Highway 32 near its junction with Ohio Highway 73 for description of basal 26.5 feet of section.

6. Covered; poor exposures of this interval along highway from Hackleslin Road to Ohio Highway 73, not measured.

Devonian (continued):

	Thickness (feet)
Ohio Shale (continued):	
5. Covered, with gravel cap to top of exposure; not included in section.	
4. Shale, light-brownish-gray (5YR 6/1) grading upward to greenish-gray (5GY 6/1); <u>Lingula</u> ; fish scales (?); burrows filled with greenish-gray clay.	3.0
3. Shale, olive-black (5Y 2/1), weathers light-brownish-gray (5YR 6/1), light gray (N7), to yellowish-gray (5Y 8/1); silty; pyrite-cemented layer in basal 2 cm. and some pyrite as flattened discs 2 cm. in diameter along bedding planes; <u>Tasmanites</u> common	<u>4.5</u>
Total lower Ohio Shale (incomplete).	<u>7.5</u>

Olentangy Shale(?):

2. Shale, greenish-gray (5G 6/1) to light-bluish-gray (5B 7/1); silty, non-calcareous; gray streak. 0.1 foot thick, approximately 7 feet above base; at base, pyrite layer, coarsely crystalline, 1-2 cm. thick with knobby, irregular upper surface contains fine, rounded quartz sand.	<u>7.0</u>
Total Olentangy Shale	<u>7</u>

Unconformity.

Silurian (incomplete):

Tymochtee Dolomite (incomplete):

1. Dolomite, yellowish-gray (5Y 7/2), weathers grayish-orange (10YR 7/4); silt-sized grains, uniform; irregular bedding; some pyrite nodules, 2-3 cm.; calcareous at top	<u>10.0+</u>
Total Tymochtee Dolomite (incomplete).	<u>10.0+</u>
Total thickness of lower part of section . . .	24.5

NOTE: Unit 6 (covered interval) is poorly exposed along Ohio Highway 32 between Ohio Highway 73 and the Hackleshin Road. This part of the section in other roadcuts and railroad cuts along Ohio Highway 73 and Portsmouth Road, southeast of the measured composite section, consists of black, fissile shale and greenish-gray shale with large, subrounded calcareous concretions as large as 2 feet in diameter. The thickness of this interval is not known, but Calvert (1968) indicates that the Ohio Shale in this area is nearly 300 feet thick; thus, as much as 70 feet of section may be missing from this description.

SECTION 3

TYPE SECTION OF THREE LICK BED

Interstate 64 Section Near Morehead Interchange

Complete section of Sunbury Shale, Bedford Shale, and Ohio Shale exposed in two large roadcuts along Interstate Highway 64; base of section is on south side of highway, 1.35 miles east of Bath-Rowan County line, 1,150 feet FNL x 900 feet FWL Sec. 1-T-71, Rowan County, Kentucky (Farmers quadrangle), at bridge across I-64 at west end of cut. Upper 83 feet of complete section (units 14 - 19) are described from exposures on north side of Interstate Highway 64, 3.20 miles east of Bath-Rowan County line, 1,200 feet FNL x 550 feet FEL Sec. 25-U-72, Rowan County, Kentucky (Farmers quadrangle). Described and measured by Linda J. Provo, Michael D. Lewan, and R. C. Kepferle using hand level and tape, April 28, 1976.

	Thickness (feet)
Mississippian (incomplete):	
Borden Formation (incomplete):	
Henley Bed of Farmers Member (incomplete):	
19. Mudstone, greenish-gray (5GY 6/1), silty; hackly fracture, limonitic stain; grass and vetch cover upper part of exposure. Basal contact sharp.	1.0+
Sunbury Shale:	
18. Shale, black (N1), very slightly silty, fissile, brittle; weathers medium gray (N6) to yellowish gray (5Y 8/1); fresh pieces have subconchoidal fracture; pyrite nodules along bedding planes at 4.5 and 5.5 feet above base; no spores; possible vertical and horizontal lens-shaped burrows indicated by lighter zones 2 to 3 mm. wide in uppermost part; lag concentrate at base 5 mm. thick, contains numerous <u>Lingula</u> , a few conodonts, rare spores. Both upper and lower contacts must be excavated to be seen.	
Sampled at base	<u>18.2</u>
Total Sunbury Shale.	<u>18.2</u>
Bedford Shale:	
17. Mudstone, olive-gray (5Y 4/1), slightly calcareous; weathers light olive gray (5Y 6/1); limonite seam along bedding plane 4.4 feet above base	14.8

	Thickness (feet)
Mississippian (continued):	
Bedford Shale (continued):	
16. Shale, black (N1), fine, even-textured, little silt; some spores; limonitic coating on sharp upper and lower contacts.	0.05
15. Mudstone, greenish-gray (5GY 6/1), silty, slightly calcareous; semispheroidal fracture; <u>Lingula</u> at 1 cm. above base. Basal contact sharp.	<u>0.2</u>
Total Bedford Shale.	<u>15.05</u>
Devonian:	
Ohio Shale:	
14. Shale, brownish-black (5YR 2/1); fissile, brittle; weathers progressively from medium light gray (N6) surfaces to moderate yellowish-brown (10YR 5/6), dusky yellowish-brown (10YR 2/2) with olive cast, and light brown (5YR 5/6) to dark yellowish-orange (10YR 6/6); morphology of weathered, near-vertical cuts characterized by smooth-weathering faces interbedded with splintery fissile-weathering faces to give outcrop a ribbed appearance; typical thicknesses are 0.1 to 0.3 foot for smooth faces and 0.5 foot for splintery faces; upper 22 feet of unit less well exposed in a steep talus-littered slope with occasional ledges about 0.5 foot thick well exposed; highly altered cone-in-cone limestone layer 1 to 2 cm. thick at 5.2 feet above base; spores small and inconspicuous near top, increase in size and abundance toward base; <u>Lingula</u> found at top. Basal contact with grayish-green shale sharp; offset on this contact to south side of Interstate Highway 64 in Sec. 10-T-71 to west for description of underlying units. Here flattened, amoebiform phosphate nodules 10 to 15 cm. long were found 31 and 33 feet above base of unit and a trash zone 2 to 3 mm. thick, with <u>Lingula</u> , fish bones, conodonts and small phosphate pebbles were found in the float on the slope of this unit	48.8
Three Lick Bed:	
13. Shale, grayish-green (5GY 4/1), iron-stained; basal contact gradational into black shale over 0.1 foot interval.	1.5

Devonian (continued):	Thickness (feet)
Ohio Shale (continued):	
Three Lick Bed (continued):	
12. Shale, olive-black (5Y 2/1), fissile; like unit 10; pyrite nodules in somewhat persistent zone about 1 foot above base; discontinuous cone-in-cone layer 1.9 feet above base, also observed at same horizon in roadcut to east. Basal contact sharp.	4.2
11. Shale, greenish-gray (5G 6/1), like unit 9.	0.9
10. Shale, olive-black (5Y 2/1), fissile; selenite rosettes on bedding planes; spores abundant; basal contact sharp	2.6
9. Shale, greenish-gray (5GY 5/1); secondary red (5YR 5/6) stain along bedding; basal 3-5 cm. burrowed, with burrows decreasing in abundance upward; <u>Lingula</u> at base; sharp basal contact.	<u>2.3</u>
Total Three Lick Bed	<u>11.5</u>
8. Shale, medium dark gray (N4) to medium-gray (N5); surface stained yellowish-brown; fissile; numerous spores on some bedding planes; discontinuous cone-in-cone layer attains maximum thickness of 0.2 foot about 5 feet below top of unit; pyrite nodules about 3 mm. thick concentrated along bedding plane about 22 feet above sharp basal contact	53.8
7. Shale, brownish-black (5YR 2/1); fissile; like unit 3; homogeneous; at top is a clay-shale seam, 1 cm. thick, which weathers light gray (N7); interlaminated with dark shale in couplets less than 1 mm. thick in 1-cm. interval below seam.	21.6
6. Interbedded light (60 percent) and dark (40 percent) shale. Light shale is greenish-gray (5GY 4/1) to light olive gray (5Y 6/1), argillaceous, micaceous, poorly fissile in 9 beds ranging from 0.2 to 1.5 feet thick; basal contacts sharp to gradational over 1 cm. Interbedded dark shale is olive black (5Y 2/1), in 8 beds 0.1 to 1.7 feet thick; well-preserved <u>Foerstia</u> common to abundant, some show lobate morphology; basal contacts sharp	8.3

Devonian (continued):	Thickness (feet)
Ohio Shale (continued):	
5. Shale, brownish-black (5YR 2/1), fissile, brittle; weathers blocky and massive in lower two-thirds, less resistant in upper one-third of unit; pyrite occurs along bedding planes; conodonts rare; possible <i>Foerstia?</i> (algae) in upper 0.1 foot of unit; spores in basal 0.1 foot. Sampled at sharp basal contact	20.3
4. Shale, interbedded, light (70 percent) and dark (30 percent). Light shale is greenish-gray (5GY 6/1), in beds ranging from 0.2 to 0.5 foot thick; top of uppermost bed is burrowed. Dark shale is brownish-black (5Y 3/1), like underlying unit, in beds 0.1 to 0.3 foot thick	9.1
3. Shale, brownish-black (5YR 2/1), brittle, fissile, laminated, with abundant reddish-brown <i>Tasmanites</i> spores and some flakes of chitinous (?) material; pyrite nodules well developed along selected bedding planes; prominent horizon 2.6 feet below top of unit, contains elongate nodules 1 to 3 cm. thick and 3 to 4 cm. wide; another 1-mm.-thick layer occurs at sharp basal contact	5.1
2. Shale, light olive-gray (5Y 6/1), greenish-gray (5GY 6/1) to dark greenish-gray (5G 5/1); weathers light gray (N7) to yellowish gray (5Y 8/1), joints stained with limonite; clayey to slightly silty; spores rare; contains interbeds 2 to 3 cm. thick of brownish-black (5YR 2/1) to dark gray (N4) shale with poorly defined contacts at 1.1 feet, 2.7 feet, and 2.9 feet below top. Basal contact is sharp, locally marked by pyritic sandy layer 1 cm. thick, but obscure where pyrite layer is absent.	<u>3.0</u>
Total Ohio Shale.	<u>181.5</u>
Unit may be equivalent of Olentangy Shale.	

Unconformity.

Silurian (incomplete):

Crab Orchard Formation (partially exposed):

1. Shale (85 percent) and dolomite (15 percent). Shale is olive-gray (5Y 5/1), clayey, dolomitic, poorly fissile; weathers to light gray (N7) thin flakes 1 to

	Thickness (feet)
Silurian (continued):	
Crab Orchard Formation (continued):	
2 cm. across and 2 mm. thick; in beds about 0.5 foot thick. Dolomite is light olive gray (5Y 6/1); weathers light brown (5YR 5/6) to moderate brown (5YR 4/4); silt-size grains; <u>Chondrites</u> -like burrows are mainly parallel to bedding, but a few are vertical in discontinuous thin beds and fairly continuous thicker beds up to 0.2 foot thick. Remaining part of Crab Orchard Formation not exposed below road level.	22.0+
Total thickness of section about 238 feet.	

(Note: Reconnaissance hand-level measurement above unit 13 in the western roadcut encountered 50 feet of Ohio Shale to the base of the Bedford Shale; the Bedford was measured as 13.5 feet thick, and the lower 7 feet of the Sunbury Shale was exposed at the top of the cleared roadcut.)

SECTION 4

Mountain Parkway Section Near Clay City

Nearly complete section of New Albany Shale exposed in two large roadcuts and one quarry along Mountain Parkway in Powell County, Kentucky (Clay City Quadrangle). Upper 54 feet of section are described from cut on east side of Kentucky Highway 1057, south of bridge over Mountain Parkway, 1725 feet FNL x 575 feet FEL Sec. 25-Q-68; the underlying units (1-14) are described from a quarry on the north side of Kentucky Highway 15, 0.1 mile northwest of its junction with Kentucky Highways 11 and 82, and from the large roadcut 0.15 miles farther west; base of section is on north side of Mountain Parkway, 0.25 miles west of overpass at Clay City interchange (Exit 16), 925 feet FSL x 900 feet FWL Sec. 11-Q-67. Described and measured by R. C. Kepferle, Michael D. Lewan, J. B. Maynard, P. E. Potter, and Linda J. Provo using hand level and tape, May 20, 1976.

	Thickness (feet)
Mississippian (incomplete):	
Nancy Member of Borden Formation (incomplete):	
23. Covered, to top of ridge overgrown by grass and small evergreen trees; not measured; contact with underlying unit is not exposed but is mapped at elevation 720+ feet (Simmons, 1967) and is believed to be near top of exposure, below.	

Devonian (incomplete):	Thickness (feet)
New Albany Shale:	
22. Shale, dark gray (N3), slightly silty, fissile; basal contact marked by underlying phosphate nodules. . . .	4.7+
21. Shale, dark gray (N3), slightly silty, uniform, fissile; elongate, flattened phosphate nodules as much as 0.3 foot long and 0.1 foot thick occur randomly along bedding planes; irridescent limonitic coating on bedding planes; fish scales and unidentifiable parts, rare; spore <u>Tasmanites</u> , common; contact with underlying cone-in-cone limestone layer sharp. Sampled at top of unit.	24.0
20. Shale, brownish-black (5YR 2/1), silty, fissile; yellowish-gray (5YR 7/2) powdery, weathered coating on bedding planes; at top is continuous cone-in-cone limestone layer, 0.1 foot-thick, heavily stained with limonite; spores abundant. Contact with underlying unit sharp.	19.2
Three Lick Bed:	
19. Mudstone, medium-light gray (N6), silty; poorly laminated, hackly fracture; selenite crystals and limonitic stain on weathered surfaces; unit sampled at westernmost cut. Basal contact sharp.	0.7
18. Shale, dark gray (N3) to medium-dark gray (N4), well laminated, with laminae about 1 mm. thick; few <u>Tasmanites</u> ; selenite rosettes and limonitic stain along bedding planes. Basal contact sharp.	2.7
17. Mudstone, medium-light gray (N6), like unit 18; sampled at westernmost cut. Basal contact sharp.	0.5
16. Shale, dark-gray (N3), like unit 17	1.7
15. Mudstone, medium-light gray (N6); like unit 18; base and top are gradational; sampled in westernmost cut. The alternation of gray mudstone and dark-gray shale imparts a ribbed appearance to the outcrops that includes units 18 to 14. Offset on this contact to quarry on north side of Kentucky Highway 15, 2.1 miles to northwest, in Sec. 11-Q-67 for description of the underlying unit	<u>0.6</u>
Total Three Lick Bed	<u>6.2</u>

Devonian (continued):	Thickness (feet)
New Albany Shale (continued):	
14. Shale, dark gray (N3), fissile, massive, uniform; interbedded with as many as six fairly continuous medium-gray (N5) to medium-dark-gray (N4) cone-in-cone limestone layers which are locally pyritic and are commonly less than 0.1 foot thick at base and top of unit and at 2.1, 7.3, 8.7, 12.2, 13.0, 14.3, 23.1, and 24.2 feet above base locally in this and adjacent exposure to west; cone-in-cone beds weather to limonite-stained light brown (5YR 5/6); lowest, highest, and bed 7.2 feet above base were sampled. Offset along contact to exposure 0.15 miles to west .	26.9
13. Shale, dark-gray (N3) to brownish-black (5YR 2/1); silty, well-laminated, with laminae 1-2 mm. thick; even fracture, tough; rare <u>Tasmanites</u> ; poorly formed selenite rosettes and irregular masses of selenite common common along bedding planes and fractures, which are also stained with limonite and sulfate. . .	17.3
12. Covered at road; probably similar to underlying unit 10; section offset across Kentucky Highway 15 to south	2.4
11. Shale, brownish-black (5YR 2/1), silty; more fissile than underlying units; red-brown <u>Tasmanites</u> spores abundant; <u>Foerstia</u> prominent in weathered zone 4.1 feet above base (sampled); limonite and sulfate stain on bedding and joint planes	12.2
10. Covered; probably similar to unit 8; slope littered with thin, medium gray shale chips.	1.7
9. Shale, grayish-black (N2), fine silt; fissile; weathers to splintery fragments; pyritic; 3.6 feet below top of unit is a highly weathered zone 0.4 foot thick containing abundant spores and iron-sulfide nodules which have finely crystalline, rounded bases and which mushroom upward into coarser octahedral crystals, with bedding draped around crystals (this zone is also identifiable in the quarry exposure to the east); limonite and sulfate stain on joint faces; sampled 5.2 feet below top of unit.	10.0

Devonian (continued):	Thickness (feet)
New Albany Shale (continued):	
8. Light and dark shale interbedded in subequal amounts in about 20 couplets. Light shale is olive gray (5Y 4/1) to greenish gray (5GY 6/1) and medium gray (N5) in beds commonly 0.1 foot thick and as much as 1.0 foot thick; burrows (?) common to rare along bedding planes, some ramose and straight, others fainter and meandering; coaly material in one bed near middle of unit. Dark shale is brownish black (5YR 2/1), dark gray (N3) to grayish black (N2) in beds ranging in thickness from 0.1 to 1.5 feet; pyritic; fossils include sparse <u>Tasmanites</u> spores and conodonts, rare <u>Lingula</u> and, near top, <u>Foerstia</u> (?) and <u>Zoophycos</u> -like burrows. Boundaries between beds sharp to gradational over 1 to 2 cm.	10.4
7. Shale, grayish-black (N2), fissile, like unit 4. . .	1.3
6. Covered, at first major bench above base; slope littered with light gray shale chips	2.0
5. Shale, grayish-black (N2), fissile, brittle, with subconchoidal fracture where fresh; weathers to light-gray (N7) chips which litter slopes; pyrite in irregular concentrations along bedding planes; some <u>Tasmanites</u> and <u>Lingula</u> ; heavily stained with limonite and sulfate; basal contact gradational over 0.1 foot	4.0
4. Dolomudstone, olive gray (5Y 4/1), weathers to rounded prisms less than 1 cm. on a side; clayey; lower contact sharp.	0.9
3. Interbedded shale and dolomudstone in descending order: shale, 1.9 feet; dolomite, 1.0 foot; shale, 1.1 feet; dolomite, 0.3 foot; shale, 0.2 foot; dolomite, 0.8 foot; shale, 0.3 foot (basal shale sampled). Shale is dark gray (N3), slightly silty, fissile, brittle, well-laminated, with laminae about 2 mm. thick; abundant <u>Tasmanites</u> spores; burrows (?) are gently curved, 0.5 to 1 cm. wide, locally pyritic, common on bedding planes. Dolosiltstone is olive gray (5Y 4/1), bioturbated. Basal contact is gradational	5.6

Devonian (continued):	Thickness (feet)
New Albany Shale (continued):	
2. Shale, olive gray (SY 4/1), silty, dolomitic near base; weathers to very light gray (N8), poorly fissile chips less than 1 cm. across; ribbed weathering pattern well-developed in upper 3 feet of unit in couplets 0.3 to 0.4 foot thick; blocky weathering zone occurs 2.5 feet above base; <u>Tasmanites</u> common; sampled 2.1 feet above base. Basal contact is sharp, unconformable, irregular, with local relief of about 0.1 foot.	<u>7.8</u>
Total New Albany Shale (see note).	<u>156.6</u>

Unconformity:

Boyle Dolomite (incomplete):

1. Dolomite, medium-light-gray (N6), silt-sized grains; weathers to grayish-orange (10YR 7/4); dense, with some wavy bedding and stylolites; chert nodules, medium-gray (N5), irregular to amoebiform, as much as 0.3 foot thick and 2 feet long; discontinuous clay parting 1.5 feet below top; calcite, pyrite, and sphalerite occur as irregular blebs in upper 0.5 foot, but appear to be unrelated to concentration of burrows (?) in same interval and which are parallel to bedding and a few centimeters wide; crinoids and other fossils weather out forming a pitted, irregular surface, suggesting that this unit may be a dolomitized limestone. Unit appears as single massive bed; remaining Boyle not exposed at road level in this section	<u>4.4</u>
Total thickness of section is about.	<u>161</u>

(Note: In the westernmost cut the inclusive interval between the lowest and highest greenish-gray mudstone beds (correlative with units 15 through 19 in the quarry part of the section) is 5.8 feet. Above this interval, a thickness of 21 feet of black shale is exposed on the steep face of the cut, and the uppermost 25 feet are covered. The uppermost 4 feet of the ridge is capped by the Nancy Member of the Borden Formation. Thus, the total thickness of the New Albany Shale at the westernmost section is about 152 feet.)

SECTION 5

Berea, Kentucky, Section

Nearly complete section of New Albany Shale exposed in series of cuts on east side of Interstate Highway 75 at and south of exchange and crossing of Kentucky Highway 21 west of Berea, Madison County, Kentucky. Top of section is south of overpass, 575 feet FNL and 600 feet FWL of Sec. 7-M-63; base of section is along entrance ramp to the northbound lanes of Interstate Highway 75 (Berea quadrangle). Section measured, described, and sampled, and its radioactivity profile measured using Jacob's staff, tape, Abney level, and scintillometer by R. C. Kepferle and Paul Edwin Potter, July 9, 1976.

	Thickness (feet)
Quaternary (?)	
15. Soil, olive-gray (SY 4/1) to yellowish-gray (SY 8/1), containing, near base, quartzite pebbles, siliceous geodes, and phosphatic nodules derived from nearby and underlying bedrock units; weathers to grassy flat. Erosional contact.	5+
Devonian:	
New Albany Shale (incomplete):	
14. Shale, brownish-black (5YR 2/1), weathers light gray (N7), with some iron oxide and sulfide stain on fractures and bedding planes along with rosettes and prisms of selenite 3 to 5 mm. long; silt in discontinuous laminae 1 to 2 grains thick; pyrite in discoidal concretions and disseminated grains; phosphate in nodules which are round to amoebiform, 2 to 3 cm. thick, elongate, some more than 13 cm. across, brownish-gray (5YR 4/1) and brownish-black (5YR 2/1), weather yellowish-gray (SY 8/1) on surface, with earthy luster and rough fracture; fossils include <u>Tasmanites</u> spores and a vitrain layer 3 mm. thick 5 feet above base. Top at or near contact with grayish-green shale of basal Borden Formation seen in outcrop less than 1 mile to the west. Basal contact placed at lowest phosphate nodule.	9
13. Shale, brownish-black (5YR 2/1) to grayish-black (N2), like unit above, except contains no phosphate nodules; 8 feet above base is zone of pyrite concretions 0.1 foot in diameter and 0.5 cm. thick, concentrated along bedding planes; shale weathers to fissile, brittle flakes and plates as much as 0.4 foot in diameter; <u>Tasmanites</u> abundant; possible fish scale, 1 mm. across,	

Devonian (continued):	Thickness (feet)
New Albany Shale (continued):	
near top of unit; silt laminae increase in abundance downward; tough and dense, with subconchoidal fracture where fresh. Sharp basal contact.	18
Three Lick Bed:	
12. Shale, greenish-gray (5GY 5/1-4/1), weathers yellowish-gray (5Y 8/1), clayey, subconchoidal fracture on joints and partings coated with limonite and sulfate stain. Sharp contact with underlying unit.	0.8
11. Shale, black (N1) to grayish-black (N2) and brownish-black (5YR 2/1); weathers light gray (N7), with iron oxide and sulfate stain; silt laminae 1 to 2 grains thick, commonly about 5 mm. to 1 cm. apart; brittle flakes litter outcrop; burrowed in upper 0.1 foot, burrows filled with greenish shale from overlying unit?; discontinuous cone-in-cone limestone layer, dark-gray (N5), 0.1 thick, about 0.6 below top (sampled); basal contact sharp.	1.2
10. Shale, greenish-gray (5GY 5/1 to 4/1) like unit 12; basal contact sharp	0.4
9. Shale, brownish-black (5YR 2/1) like unit 11; fish scale(?) 0.3 above base; <u>Tasmanites</u> sparse; upper 0.1 burrowed; pyrite up to 2 mm. in scattered blebs; basal contact sharp	0.9
8. Shale, greenish-gray (5GY 5/1) like unit 12; sharp contact with underlying unit. Offset north along contact to first cut south of interchange; and in borrow pit east of cut.	<u>0.2</u>
Total Three Lick Bed	<u>3.5</u>
7. Shale, black (N1), grayish-black (N2), and brownish-black (5YR 2/1); slightly silty; some silt laminae 1 to 2 grains thick about 5 mm. apart; burrowed in upper 0.2 feet; burrows are gently curving, burrow-fill is medium dark gray (N4); as much as 0.5 cm. wide along bedding planes; <u>Tasmanites</u> sparse to abundant; some scattered black organic shreds; pyritic; slightly more resistant-weathering rib at about 20 feet above base (near base of cut); in upper 15 feet is rhythmic alternation of massive- and	

Devonian (continued):	Thickness (feet)
New Albany Shale (continued):	
fissile-weathering shale in sets 0.5 foot thick that impart ribbed appearance to otherwise littered slope. Poorly preserved <u>Foerstia</u> in 2.5 feet thick zone 8.9 feet above base of unit; weathered chips typically have slight depressions on surfaces, where <u>Foerstia</u> have weathered out. All but lower 10 feet described up slope from middle light pole of north cut; basal 10' described from borrow pit to east	37
6. Interbedded light (60 percent) and dark shale. Light shale is greenish-gray (5Y 6/1) in 7 beds decreasing downward in thickness from 2.4 to 0.1 feet; thickest gray shale contains 4 thin brown-shale streaks. Dark shale is brownish-black (5YR 2/1) to dusky brown (5YR 2/2); silty in thin laminae in 6 beds 1.3 to 0.1 feet thick; lowest dark shale burrowed (dug this section out)	5.6
5. Shale, black (0.1+ foot), and covered Offset to north-bound entrance ramp to I-75	16
4. Dolomudstone, greenish-gray (5G 6/1), weathers to yellowish-gray (5Y 8/1) prisms with spheroidal sides. Basal contact sharp. (Top covered in grass on west side; may be black shale recoverable across to west) .	2.7+
3. Organic dolomitic mudstone, olive-black (5Y 2/1), weathers yellowish-gray (5Y 8/1); laminated; base marked by 0.05-thick rippled(?) sandy layer. Basal contact sharp	1.7
2. Dolomitic mudstone, laminated, olive-black (5Y 2/1); base sharp, irregular, relief of about 0.1 foot; weathers yellowish-gray (5Y 8/1)	<u>1.2</u>
Total New Albany Shale	<u>94.7</u>

Unconformity.

Boyle Dolomite (incomplete):

1. Dolomitic limestone, dark gray (N3), olive gray (5Y 4/1), to light-olive-gray (5Y 6/1); weathers yellowish-brown (5YR 5/4) to dark yellowish-orange (10YR 6/6); locally conglomeratic, with lighter olive pebbles 1 to 6 cm. long in a darker matrix; scattered white calcite-filled pockets and massive chert in

Devonian (continued):	Thickness (feet)
Boyle Dolomite (continued):	
some beds; bed thickness 0.9 to 2.5 feet, accentuated by weathering along stylolitic bedding planes. Base not exposed	9.2+
Total thickness of section, approximate. . . .	<u>109</u>

(Note: The slopes of the Interstate cuts lie at about 30° and are mainly mantled by a thin talus which can be removed by some trenching with mattock or shovel. The uppermost part of the New Albany Shale is well exposed about 1 mile west of the southern cut. There the shale is overlain by about 0.6 foot of brownish-gray to olive-gray shale, about 0.05 foot of black shale and then by the greenish-gray shale of the basal Borden.)

SECTION 6

Big Clifty Creek Section

Complete section of Chattanooga Shale exposed in small unnamed tributary to Big Clifty Creek and along Ringgold Road, 4.1 miles north-west of its junction with Old Kentucky Highway 80 at West Somerset, Pulaski County, Kentucky (Delmer quadrangle). Base of section is in unnamed tributary, 2,850 feet FSL x 2,400 feet FEL of Sec. 19-H-58; top of Chattanooga Shale is along unpaved road, 3,000 feet FSL x 2,425 feet FWL of Sec. 19-H-58. Section measured, described, and sampled using Jacob's staff, Abney level, and tape and its radioactivity profile measured using scintillation counter by R. C. Kepferle, P. E. Potter, and Linda J. Provo, August 3, 1976.

Mississippian (incomplete):	Thickness (feet)
Borden Formation (incomplete):	
Nancy Member (incomplete):	
7. Shale, greenish-gray (5G 5/1), weathers light olive gray (5Y 7/1) to greenish-gray (5G 7/1); silty; rounded phosphate nodules along bedding planes approximately 1.4 and 2.8 feet above base, with glauconite around nodules	15+
Total Nancy Member (incomplete)	<u>15+</u>

	Thickness (feet)
Devonian (incomplete):	
Chattanooga Shale:	
6. Shale, brownish-black (5YR 2/1) to olive-black (5Y 2/1), weathers to light gray (N7) plates and chips; bedding planes and joints coated with sulfates of iron; <u>Tasmanites</u> common; abundant olive-gray (5Y 4/1) phosphate nodules, weather gradationally to chalky white, earthy luster, ovoid and elongate or amoebiform, typically 3-5 cm. thick and up to 1 foot long, somewhat flattened along bedding planes, bedding contorted over nodules; base of unit is at lowest occurrence of phosphate nodules; silica "dike", 2 cm. wide, vertical, geodiform, extends 15 feet laterally in ditch along unpaved road and 3 feet vertically into overlying unit. Contact with overlying Nancy Member is abrupt; a 0.2-foot-thick zone of phosphate nodules (sampled) in glauconite-stained mudstone (possibly equivalent to Maury Formation) occurs at top of this unit.	7.0
5. Shale, brownish-black (5YR 2/1), like unit 3.	7.0
Three Lick Bed:	
4. Mudstone and shale, interbedded. Mudstone is olive gray (5Y 4/1), weathers moderate brown (5YR 4/4); clayey, pyritic; in three beds, less than 0.1 foot thick, occurring between 32.7 and 35 feet above base of section. Shale is brownish-black (5YR 2/1), like unit 3, with <u>Tasmanites</u> and sparse <u>Lingula</u> ; burrowed immediately below mudstone beds; burrows curved, smooth-sided, up to 1 cm. wide, filled with light-brownish-gray clay (5YR 6/1), decrease in abundance upward to gray shale.	<u>2.3</u>
Total Three Lick Bed.	<u>2.3</u>
3. Shale, olive-black (5Y 2/1), weathers to medium-light-gray (N6) fissile chips and plates; pyrite in burrows in basal 0.5 foot and as stellate nodes which disrupt bedding and stand in relief on bedding planes, abundant pyrite as cubes and accretions at 24 to 26 feet above base with abundant lanceolate fish scales(?); <u>Lingula</u> common to abundant to 3.5 feet above base (oriented sample at 3.0 feet above base), long axes oriented at 206°, 283°, 291°, 300°, 301°, 304°, and 323°; thin clay shale seams, yellowish-brown (10YR 5/2), weathering yellowish-gray (5Y 8/1) and slightly recessed, less than 0.1 foot thick, occur 5.3, 15.8.	

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
16.7, and 17.7 feet above base; <u>Tasmanites</u> rare to abundant; rounded, medium-sized grains (20-30%) occur near base of unit; weathered outcrop has ribbed appearance due to alternating resistant and nonresistant beds in couplets 0.3 foot thick. Offset along bedding plane 5 feet below top to tributary to east. Basal contact sharp, paraconformable.	31.7
2. Sandstone, Duffin layer, olive-black (5Y 2/1) to brownish-black (wet, 5YR 2/1), weathers yellowish-gray (5Y 7/2) to moderate yellowish-brown (10YR 5/4); sand grains medium-sized, well-rounded, frosted; phosphatic, dolomitic; basal 0.2 foot contains phosphate pebbles 2-3 cm. wide which stand out in relief; pyrite as nodules 2 cm. wide near top; conodonts and fish(?) remains observed. Contact with underlying unit, disconformable (sampled)	0.9
Total Chattanooga Shale ^{1/}	<u>48.9</u>
Unconformity.	
Boyle Limestone (incomplete):	
1. Dolomite, olive-gray (wet, 5Y 4/1) weathers medium light gray (N6) to light gray (N7), limy, medium-grained, pyritic, few glauconite grains; fluted- and rounded-weathering beds 0.6-0.7 foot thick; 1.3 feet below top is 0.5-foot-thick bed of chert, mottled yellowish-gray (5Y 7/2) and olive-gray (5Y 4/1); weathers moderate brown (5Y 4/4) to dusky red (5R 3/4), iron oxide stain; dolomite contains solitary corals and brachiopods, locally calcite-filled. Base covered. . .	2.6
Total Boyle Limestone (incomplete).	<u>2.6+</u>
Total thickness of section, approximate	<u>67</u>

^{1/} NOTE: Compares with 47.4 feet of Chattanooga Shale measured by Bass (1956, p. 27) at the same locality (Conant and Swanson, 1961, loc. 6).

SECTION 7

Creelsboro Section

Complete section of Chattanooga Shale along east side of Kentucky Highway 379 and in gulley along old road east of Highway 379, 2.9 miles west of Creelsboro, Russell County, Kentucky (Creelsboro quadrangle). Base of measured section is 1,900 feet FNL x 2,225 FEL in Carter coordinate, Sec. 15-E-52. Section measured and described using Jacob's staff, Abney level, and tape and its radioactivity profile measured using scintillation counter by R. C. Kepferle, P. E. Potter, and Linda J. Provo, August 3, 1976.

Mississippian (incomplete):	Thickness (feet)
Ft. Payne Formation (incomplete):	
12. Mudstone, greenish-gray (SGY 6/1), silty, glauconitic	5.0+
11. Mudstone, olive-gray (SY 4/1), shaly.	<u>0.2</u>
Total Ft. Payne Formation (incomplete).	<u>5.2+</u>
Devonian:	
Chattanooga Shale:	
10. Shale, brownish-black (5YR 2/1), petroliferous odor, abundant pyrite; contact with overlying Ft. Payne Formation is sharp and conformable.	0.4
9. Phosphatic nodules, concentrated in layer	0.1
8. Shale, brownish-black (5YR 2/1), slightly silty, slightly pyritic, weathers to medium-light-gray fissile flakes and chips; phosphate nodules occur 4.4 feet above base and extend to top with long axes oriented at 183°, 188°, 190°, 193°, 200°, 207°, and 215°.	15.9
7. Shale and mudstone. Shale is brownish-black (5YR 2/1), like unit 6, and burrowed. Mudstone occurs as three very thin seams, less than 1 cm. thick; unit possibly equivalent to Three Lick Bed.	1.7

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
6. Shale, brownish-black (SYR 2/1), weathers to medium-light-gray (N6) fissile flakes and chips; slightly silty with a few silt laminae one or two grains thick; slightly pyritic; <u>Tasmanites</u> common, and show upward increase in abundance; unit forms distinct, massive face; at 4.0 feet above base is a light-brown (SYR 5/6) clay parting 1 cm. thick; discontinuous dolomitic and pyritic layer, 0.1 foot thick, occurs 8.4 feet above base of unit.	13.1
5. Mudstone (70 percent) and shale (30 percent). Mudstone is brownish black (wet, SYR 2/1) to medium dark gray (dry, N4), occasionally mottled with burrows parallel to bedding; beds range from 0.1 to 0.8 foot in thickness. Shale is brownish black (SYR 2/1), pyritic; contains <u>Tasmanites</u> , a few clay partings, and burrows; upper 0.2 foot is a "varved" bed of black shale and silt laminae 1 mm. thick.	4.2
4. Shale, black (wet, N1) to brownish-black (SYR 2/1), weathers to medium-gray (N5) to light gray (N7) thin, fissile flakes and plates; strong petroliferous odor from freshly broken surface; pyrite in stellate nodes; abundant conodonts on bedding plane near top of unit; burrowed along bedding planes near base; discontinuous conglomerate 0.2 above base, 0.1 foot thick, contains phosphate pebbles and bone fragments in sandy matrix. Basal contact sharp	<u>3.5</u>
Total Chattanooga Shale	<u>38.9</u>
Unconformity.	
Kiddville (?) Bed:	
3. Chert-pebble conglomerate in medium-grained, poorly sorted, well-rounded, sand matrix; iron-stained, discontinuous	0-0.5
Boyle (?) Limestone:	
2. Limestone residuum of silt and clay weathered and oxidized to moderate brown (SYR 4/4) to dark yellowish-brown (10YR 4/2); identifiable by chert content and position; chert occurs in three fairly continuous layers of olive-gray (5Y 4/1) to yellowish-gray (5Y 8/1), locally banded and mottled irregular nodules, which range in thickness from 0.2 foot to over 1.0 foot.	<u>2-3.0</u>
Total Boyle (?) Limestone residuum.	<u>2-3.0</u>

	Thickness (feet)
Unconformity.	
Ordovician (incomplete):	
Cumberland Formation (incomplete):	
1. Limestone, olive-gray (wet, SY 4/1), light-gray (dry, N7), weathers to light olive gray (SY 7/1) to yellowish-gray (SY 8/1); silt-sized grains; sparse glauconite; uniform, laminated; semi-conchoidal fracture; unfossiliferous except as burrows indicated by slight mottling; upper contact abrupt and uneven with relief as great as 1 foot in 10-foot-wide exposure	3.0+
Total Cumberland Formation (incomplete)	<u>3.0+</u>
Total section, about.	<u>50</u>

Note: Complete section occurs along highway at 1900 feet FNL x 2,225 feet FEL of Sec. 15-E-52 and extends to gully beside highway; top is not clearly exposed in gully, but is well-defined. Orientations of phosphate nodules were taken from gully exposure. Description of units 7 through 12 was made along main highway cut, a few hundred feet north, where exposures were better.

SECTION 8

Pleasant Grove Section

Complete section of Chattanooga Shale exposed in cut on north side of parking lot at Pleasant Grove Recreation Area of Dale Hollow Lake, 3.75 miles northeast of Tennessee Highway 53 bridge over Obey River at Celina, Clay County, Tennessee (Dale Hollow Dam quadrangle). Base of section is located 1,675 feet FNL x 150 feet FWL in Carter coordinate, Sec. 19-A-49E. Section measured and described using Jacob's staff, Abney level, and tape and its radioactivity profile measured using scintillation counter by R. C. Kepferle, P. E. Potter, and Linda J. Provo, August 4, 1976.

	Thickness (feet)
Mississippian (incomplete):	
Ft. Payne Formation (incomplete):	
11. Limestone (grainstone), medium-light-gray (N6), weathers to yellowish-gray (SY 8/1); coarse-grained, crinoidal, stylolitic bedding, dolomitic and glauconitic in basal 0.3 foot; silicified in discontinuous bands of chert up to 0.3 foot thick and less than 1.0 foot apart; chert is medium light	

Mississippian (continued):	Thickness (feet)
Ft. Payne Formation (continued):	
gray (N6), weathers light gray (N7); basal contact erosional and disconformable. Overlying this 9-foot-thick unit are a mudstone bank (10 feet), crinoidal packstone (2 feet), and greenish-gray shale interbedded with thin dolomitic and cherty wackestones (16 feet)	37.0+
Total Ft. Payne Formation (incomplete).	<u>37+</u>
Maury Shale:	
10. Phosphatic nodules in matrix of yellowish-gray (SY 7/2) shale. Nodules are spherical to elongate and oriented at 117°, 121°, 124°, 134°, 139°, 146°, 170°, 203°, and 218°.	0.6
Total Maury Shale	<u>0.6</u>
Devonian (?):	
Chattanooga Shale:	
9. Shale, grayish-black (N2), weathers dark greenish-gray (SGY 4/1); occasional silt laminae; phosphate pebbles abundant in upper 0.2 foot; slightly pyritic with fairly continuous zone of 1-3 cm. pyrite nodules about 0.3 foot above base and scattered throughout; translucent, white conodonts common; sparse <u>Lingula</u> about 1.0 foot below top.	5.3
8. Shale, like unit 9. In this unit occur three burrowed zones, 2 cm. thick, at base, 0.1 foot above, and at top; burrows are 2-3 mm. wide, with dusky yellow (SY 6/4) fill, and some vertical burrows extend downward into underlying black shale as much as 0.1 foot; basal burrowed zone characterized by greater abundance of and smaller size of burrows; probable correlative of Three Lick Bed	0.7
7. Shale, grayish-black (N2), like unit 9, with silty blebs (burrows?); base is marked by lowest occurrence of phosphate nodules.	4.4
6. Shale, grayish-black (N2), like unit 9, several thin pyrite seams and silt laminae; wood fragments oriented at 72° and 104°, 3.8 feet above base; 2.8 feet above base is a zone of elongate, 1-2 mm. tetragonal(?) crystals and crystal casts (sampled).	5.1

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
5. Burrowed zone, with burrows not well-defined.	0.4
4. Shale, black (N1), dense.	0.7
3. Shale, olive-black (5Y 2/1)	<u>0.4</u>
Total Chattanooga Shale	<u>17.0</u>
Unconformity.	
Boyle (?) Dolomite (incomplete):	
2. Limestone layer, pyritic, glauconitic	0.1
1. Dolomite, olive-gray (5Y 5/1), weathers light brown (5YR 5/6); cherty; silicified brachiopods stand out in relief	<u>0.7+</u>
Total Boyle (?) Dolomite (incomplete).	<u>0.7+</u>
Total section, about	<u>55</u>

This section is near section 16 of Conant and Swanson (1961, pl. 1), where 16.2 feet of shale are assigned to the Gassaway Member (Conant and Swanson, 1961, pl. 12). Thus, unit 3 above may correlate with the Dowlletown Member to the south.

SECTION 9

Flat Gap Road Section

Incomplete section of Chattanooga Shale and Grainger Formation exposed for 0.55 mile in roadcuts and creek beds along northeastern side of Tennessee Highway 31 (Flat Gap Road); top of Chattanooga Shale is located 4.25 miles north of junction of U.S. Highway 11W and Tennessee Highway 31 at Mooresburg, Hawkins County, Tennessee (Lee Valley quadrangle), 2,475 feet FSL x 2,875 feet FWL in Carter Coordinate, Sec. 24-1S-76E. Section measured, described, and sampled, and its radioactivity profile measured using Jacob's staff, Abney level, tape, compass, and scintillation counter by R. C. Kepferle, P. E. Potter, and Linda J. Provo, August 5, 1976.

Mississippian (incomplete):	Thickness (feet)
Grainger Formation (incomplete):	
Basal siltstone member (incomplete):	
27. Interbedded siltstone (90 percent) and shale (10 percent). Siltstone is olive-gray (5Y 5/1), weathers dark yellowish-orange (10YR 6/6), uniform micaceous, noncalcareous; beds with sharp, planar bases; bed thickness increases upward from 0.1-0.3 foot at base to as much as 1.4 feet at 6 feet above base; possible Bouma sequences T _{abc} in some beds; lumpy sole marks and low-relief flute marks rare, oriented at 207° with blunt end toward northeast. Shale is olive-gray (5Y 4/1), silty, with grain size fining upward, poorly laminated, with thin elongate and flattened siderite nodules in fossiliferous beds commonly less than 0.3 foot thick. Basal parts of shale beds may represent T _e in Bouma (1962) sequence. Strike, 85°; dip, 26°S	10+
Total Grainger Formation (incomplete)	<u>10+</u>

Devonian (incomplete):

Chattanooga Shale (incomplete):

26. Shale (90 percent) and siltstone (10 percent). Shale is medium dark gray (N4) with olive-gray cast, weathers medium light gray (N6) to light gray (N7); thinly laminated, noncalcareous; 50 feet below top shale is medium dark gray (dry, N4) to olive-black (wet, 5Y 2/1), pyritic, weathers subconchoidally and to small splinter; rare, noncalcareous nodules with limonitic crust, 2 feet long and 0.2 foot thick, along some bedding planes; bedding cut by joints and fractures.

Siltstone is olive-gray (wet, 5Y 4/1) and medium light gray (dry, N6), weathers light gray (N7) with moderate yellowish-brown (10YR 5/4) limonitic stain, micaceous, pyritic, with fine specks of disseminated organic (?) debris; laminated, with T_{ab} Bouma (1962) sequences in beds commonly less than 0.2 foot thick, slightly graded; in upper part of unit sole marks include flute casts at 244° with blunt end toward east; siltstone beds increase in abundance upward in unit, with a bundle of siltstone beds less than 2 feet thick occurring 3 to 5 feet below top of unit. Discontinuous clay ironstone nodules, 2-3 cm. thick occur throughout unit. Beds strike 68°, dip 26°S. 90

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
25. Covered interval between end of highway cut and creek bed to northeast.	40
24. Shale, brownish-black (dry, 5YR 2/1) to black (wet, N1), weathers light gray (N7), slightly silty, pyritic, rare <u>Tasmanites</u> , and fish scale (?) fragments; joints coated with moderate reddish-brown (10R 4/6) limonitic material; exposed in stream east of culvert, where beds strike 95°, dip 30°S. Sampled about 1 foot below top.	6
23. Covered interval along road to north, probably shale like unit 24.	20
22. Shale, like unit 24, highly weathered exposure in farm lane east of Tennessee Highway 33 about 50 feet from road.	5+
21. Siltstone, very light olive-gray (5Y 7/1), muddy; limonite-stained joints; sharp contact with overlying shale; strike 78°; dip 29°S	3
20. Covered	35
19. Siltstone, light olive-gray (5Y 6/1), weathers yellowish-gray (5Y 7/1), noncalcareous, coarse-silt-sized grains, limonitic stain on weathered surfaces; bedding irregular and disrupted, suggesting burrowing; dark, clayey laminae are olive-gray (5Y 4/1); bedding thins and grain-size fines toward base of exposure, grading into siltstone interbedded with silty shale containing discontinuous clay ironstone nodules. Exposure, opposite Gordon home, weathers to elongate plates and chips with irregular, lumpy surfaces.	25
18. Covered; projected along road from base of overlying unit.	105
17. Siltstone, medium light gray (N6) to medium dark gray (N4) when dry, olive-gray (5Y 4/1) when wet; pyritic, burrowed, somewhat laminated, parting surfaces commonly less than 0.1 foot thick; steeply dipping fault plane bounds lower limit of unit. . . .	8
Fault.	

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
16. Siltstone, like unit 17, in a thinning-upward cycle in which beds in upper half part along muddy layers less than 1 cm. thick; bedding surfaces burrowed, with curly, meandering trace fossils (<i>Scalarituba missouriensis</i>); lower half of unit is massive-weathering with slickensided surfaces. Wood fragment, 10 cm. long, oriented at 282°. Strike 85°, dip 31°S.	13±2
15. Siltstone, like unit 17, in a thinning upward sequence in which basal 4 feet are massive with slickensided face and upper 3 feet are shaly-weathering owing to laminae of darker, argillaceous material; burrowed.	7
14. Siltstone, light gray (N7) with interlaminated medium dark gray (N4) clayey silt, ripple-cross-laminated in massive, blocky-weathering beds; sole marks; burrows near tops of beds, medium-dark gray (N4) to olive-black (5Y 2/1) argillaceous and carbonaceous partings about 0.3 foot thick. Basal 10-12 feet is more carbonaceous and weathers to thin plates and fissile chips. As a whole, unit 14 is a thickening upward sequence interrupted by two or three platy-weathering zones less than a foot thick.	45
13. Deformed zone. Shale and siltstone contorted; likely that disturbance is associated with shalier portions of this zone	20
12. Siltstone (80 percent) and shale (20 percent). Siltstone is medium gray (N5) to light olive-gray (5Y 6/1), limonitic weathering stain, micaceous along bedding planes; planar lamination common, ripple lamination less common, T _{ab} and possible T _{abc} sequences of Bouma (1962); maximum bed thickness 2 feet. Shale is medium gray (N5) to olive-gray (5Y 4/1); shaly-weathering ledge, 1.2 feet thick at base, vitrain layer at top. Unit 12 is a sequence in which beds thicken toward middle of unit from lower and upper boundaries; two thinning upward cycles each about 10 feet thick occur in basal 20 feet.	50

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
11. Shale and siltstone interlaminated in subequal amounts (90 percent), and mudstone (10 percent). Siltstone is medium gray (N5) to light olive-gray (5Y 6/1) in beds less than 1 cm. thick. Mudstone is dark greenish-gray (5GY 6/1), weathers yellowish-gray (5Y 8/1), silty, micaceous, beds occur 2.1, 4.9, 10.2, 15.6, 16.2, 16.8, 17.3, 18.7, 20.1, and 20.4 feet above base of unit. Basal and upper contacts of unit sharp; basal 0.2 foot is olive-black (5Y 2/1) shale.	21
10. Shale and interlaminated siltstone, like unit 11 but less resistant and less carbonaceous. Silt laminae are medium gray (N5) and are typically less than 2 mm. thick, rarely in beds up to 2 cm. thick. Clay laminae are dark gray (N3) and less than 1 mm. thick. Two greenish-gray (5GY 6/1) mudstone and shale beds, 0.1 foot thick, occur at 31 and 37 feet above base. Near base, unit is shalier and pale yellowish-brown (5YR 6/2), weathers light brown (5YR 6/4). <i>Foerstia</i> (sampled) common to abundant in zone, 43 feet thick, beginning 13 feet above base	57
9. Covered; offset to creek bed to northeast	97
8. Mudstone with interbedded siltstone exposed in creek. Mudstone is olive-gray (5Y 7/1), slightly silty, in beds 0.1 to 0.2 foot thick. Siltstone is grayish-orange (10YR 7/4), with limonitic stain, planar lamination; evenly bedded with beds lensing locally	1+
7. Shale, brownish-black (5YR 2/1), fissile, brittle, with silty laminae one or two grains thick; unidentifiable black (fish part?) debris and conodonts; limonite-stained joints and parting surface; sampled.	1.5
6. Clay mudstone, like unit 8.	0.1
5. Shale, brownish-black (5YR 2/1), like unit 7.	0.5
4. Mudstone, olive-gray (5YR 4/1) to dusky brown (5YR 2/2), slightly silty	0.3

Devonian (continued):	Thickness (feet)
Chattanooga Shale (continued):	
3. Shale, brownish-black (5YR 2/1), like unit 7, rare, black spores; dip 40°	11
2. Covered	90
1. Exposure at dip slope opposite green dumpster. Shale, like unit 7, spores abundant; interbedded at base with greenish-gray mudstone. Dip 37°	10+
Total Chattanooga Shale (incomplete).	<u>761.4</u>
Total section, about.	<u>771</u>

[Note: Units 22 through 26 may be equivalent to Big Stone Gap Member as used by Hasson (1973, p. 21).]

SECTION 10

Mountain Branch Section

Incomplete section of Ohio Shale and Berea Sandstone exposed in drainage of Mountain Branch of Elkhorn Creek and along access road to Johnson Brothers Limestone Quarry, off Kentucky Highway 197, 4.7 miles south of junction with Kentucky Highway 80 in Elkhorn City, Pike County, Kentucky. Base of section is in gully 1,000 feet FNL x 100 feet FWL of Sec. 24-J-86; top of section is along access road 1,950 feet FNL x 100 feet FEL Sec. 25-J-86 (Hellier quadrangle). Base of supplementary section is in fault contact with Pennsylvanian sandstone also exposed along access road 700 feet FNL x 925 feet FEL Sec. 25-J-86. Section measured, described, and sampled using Jacob's staff, tape, Abney level, and Brunton compass and its radioactivity profile measured using scintillometer by R. C. Kepferle, P. E. Potter, and Linda J. Provo, June 15-16, 1976.

Mississippian:	Thickness (feet)
Berea Sandstone (incomplete):	
29. Covered to top of interval with float blocks of Berea Sandstone exposed in ditch and on slope above ditch	45+
28. Siltstone (90 percent) and shale (10 percent). Siltstone is medium gray (N5) to light olive gray (5Y 6/1), weathers yellowish gray (5Y 7/2) to grayish yellow (5Y 8/4); massive; load casts	

Mississippian (continued):	Thickness (feet)
Berea Sandstone (continued):	
on soles; maximum bed thickness 2.5 feet with bed thickness generally increasing upward. Interbedded shale is greenish gray (5Y 5/1), weathering to yellowish gray (5Y 6/1)	47
27. Shale (90 percent), greenish-gray (5Y 5/1), as above; with a few siltstone interbeds (10 percent) containing black, carbonaceous debris, as above; siltstone beds typically 0.3 foot thick; contact with underlying Ohio Shale is sharp and conformable	<u>9</u>
Total Berea Sandstone	<u>101+</u>
Devonian:	
Ohio Shale (incomplete):	
26. Shale, brownish-black (5YR 2/1), fissile, with some dark gray (N3) siltier beds which are less fissile and weather spheroidally; orbiculoid and linguloid brachiopods sparse to common in upper 12 feet; lowermost 10 to 12 feet are covered; sampled at upper contact and 28 feet above base . . .	39
25. Disturbed zone of contorted black shale beds.	7
24. Shale, olive-black (5Y 2/1), silty, micaceous, brittle, laminated but not fissile in lower 15 feet with fissility improving upward, blocky weathering; red-brown <u>Tasmanites</u> spores, <u>Lingula</u> sparse near base; black carbonaceous debris as sand- and silt-sized flecks, throughout, interbedded with thin, 0.1 foot lenticular to nodular, dark-gray (N3) to medium dark-gray (N4) siltstone beds throughout. Maximum thickness of siltstone beds is 1.0 foot at 70 feet above base (sampled). Shale sampled at base and 50 feet above base.	77
23. Siltstone and mudstone. Siltstone is light bluish-gray (5B 7/1), weathers grayish-orange (10YR 7/4), uniform, argillaceous; micaceous; abundant flecks of black carbonaceous debris; planar and cross-lamination and rare, faint current lineation on soles of beds commonly 0.1 to 0.5 foot thick; siltstone beds best developed and most abundant 5-25 feet above base of unit where it makes up	

Devonian (continued):

Thickness
(feet)

Ohio Shale (continued):

- 60 percent of unit; less abundant upward in unit; interbedded and intergradational with mudstone. Mudstone is light olive gray (5Y 5/2) to olive gray (5Y 3/2) to dark greenish gray (5GY 4/1), in beds 0.1 to 1.0 foot thick; slightly silty and micaceous; subconchoidal fracture, incipient shaly parting poorly developed; limonitic stain. More resistant beds of silty mudstone in beds 0.1 to 0.4 foot thick have uneven fracture, locally sharp-based, mottled due to bioturbation (?); rare, small flecks of shiny black carbonaceous matter; ovoid limonitic, clayey nodules 0.2 foot in diameter at 45 and 110 feet above base. Mudstone beds more abundant in upper 120 feet of unit and gradually become more fissile upward in section; mudstone sampled at 7 and at 142 feet above base; siltstone sampled at 10 and 143 feet above base. . . . 147
22. Shale, olive-black (5Y 2/1) to olive-gray (5Y 3/1), micaceous; silty, with numerous very thin silt laminae one or two grains thick; silty laminae are more abundant in a zone 10 to 12 feet above base of unit, intermediate in color between pale yellow brown (10YR 5/2) and brownish-gray (5YR 4/1); burrowing in silty laminae in uppermost foot of unit with a 0.1-foot-thick, light-olive-gray (5Y 6/1) siltstone bed; abundant black coaly plant remains as much as 1 cm. in length along bedding planes; few dark brown to black spores. About 18 feet above base of unit is a low angle fault which offsets bedding. Sampled black shale at 7 feet above base. Ravine enters from east just above base of this unit. 34
21. Dark shale (80 percent) and light mudstone (20 percent), interbedded in about 25 couplets. Dark shale is brownish-black (5YR 2/2), rarely medium gray (N5), in beds ranging from less than 1 foot to as much as 9 feet thick; micaceous; quartzose silt in lighter colored laminae, which may pinch and swell; abundant resinous Tasmanites spores; and rare silt-filled burrows. Mudstone is greenish gray (5GY 5/1) to medium light gray (N6), weathering to grayish yellow green (5GY 7/2), subconchoidal to flaggy fracture; fractures coated

Devonian (continued):	Thickness (feet)
Ohio Shale (continued): with hematite, dark yellowish-orange (10YR 6/6) to pale reddish-brown (10R 5/4); fine flecks of black organic matter. Boundaries between beds sharp. Couplets are thinnest in a zone 5 feet thick beginning 23 feet above base of unit. Unit is more resistant and hackly in appearance on slope than is underlying unit 20. Sampled greenish-gray mudstone 15 feet above base and brownish-black shale 15.5 feet above base	63
20. Mudstone (70 percent) and siltstone to very fine- grained sandstone (30 percent). Mudstone is light gray (N7), micaceous, contains very fine black shreds of organic matter; contact gradational with overlying brownish-black shale; thin, car- bonaceous shale near middle of unit. Siltstone is light olive gray (5Y 6/1), laminated, in discrete beds less than 0.1 foot thick in lowest 5 feet of unit and becoming less well defined upward in the unit. Sampled siltstone 7 feet above base and mudstone at 6.5 feet above base. . . .	20
19. Covered interval.	7
18. Shale, dusky brown (5YR 2/2) to dusky yellowish brown (10YR 2/2), weathers dark yellowish brown (10YR 4/2) to grayish brown (5YR 3/2), silty, laminated, micaceous; sampled 3 feet above base . . .	5
17. Covered interval.	18
16. Mudstone (60 percent) and siltstone (40 percent). Mudstone is greenish gray (5GY 5/1), weathers light greenish gray (5GY 7/1). Siltstone and silty shale are light olive-gray (5Y 6/1), weather moderate yellowish brown (10YR 5/4), planar lamination, in beds 2-4 cm. thick. Eight feet above base is a 1-foot thick limonite- cemented zone which may be related to a fault along bedding plane; sampled limonitic zone 8 feet above base and mudstone 10 feet above base . . .	18
15. Covered interval.	12

Devonian (continued):	Thickness (feet)
Ohio Shale (continued):	
14. Mudstone, greenish-gray (5GY 5/1, like unit 16; and siltstone, light olive-gray (5Y 6/1), like unit 16; sampled mudstone 2 feet above base of unit and siltstone 3 feet above base of unit.	25
13. Covered by recent (?) slide material.	125
12. Mudstone (80-90 percent), greenish-gray (5GY 5/1), and thin siltstone (10-20 percent), light olive-gray (5Y 6/1), poorly indurated, massive bedding; sampled siltstone 21 feet above base and mudstone at 21.5 feet above base	40
11. Covered interval, may be mudstone. Underlying units are measured and described from unnamed gulley.	84
10. Mudstone (80 percent), greenish-gray (5GY 6/1) and thin interbeds of dark shale (20 percent); sampled mudstone at top of unit	6
9. Mudstone, olive-gray (5Y 4/1) to greenish-gray (5GY 5/1) interbedded with equal amounts of shale, black (N1) to olive-black (5Y 2/1); fissile, brittle, fractured, micaceous, carbonaceous, <u>Tasmanites</u> spores; sampled dark shale 3 feet above base	7
8. Shale (80 percent), black (N1); with three interbedded greenish-gray shale beds ranging in thickness from less than 0.1 foot to 0.4 foot and separated by at least 1 foot of black shale; sampled 7 feet above base	13
7. Shale and mudstone in equal amounts; shale like unit 4 and mudstone like unit 5; beds 0.1 to 0.3 foot thick in 5 or 6 couplets; numerous minor fractures crosscut unit obliquely with offset up to 0.1 foot; sampled.	5
6. Mudstone (70 percent), like unit 5, interbedded with black shale beds like unit 4 less than 0.1 foot in thickness; mudstone beds 0.3 to 0.8 foot thick; sampled 4 feet above base.	12

Devonian (continued):	Thickness (feet)
Ohio Shale (continued):	
5. Mudstone, olive-gray (5Y 4/1) to greenish-gray (5GY 5/1), brittle; partly covered; sampled 3 feet above base	15
4. Shale, black (N1) to olive-black (5Y 2/1), fissile, brittle, fractured, carbonaceous; micaceous, <u>Tasmanites</u> spores; sampled 5 and 15 feet above base	22
3. Covered interval.	25
2. Shale, grayish-black (N2), highly fractured, carbonaceous; top of unit covered; sampled.	5
1. Covered interval, to stream gulley below.	<u>20</u>
Total Ohio Shale (incomplete)	<u>851+</u>
Total section measured:	<u>952</u>

APPENDIX B--SAMPLE NUMBER, URANIUM CONTENT, AND LOCATION OF OUTCROP
AND CORE SAMPLES ANALYZED FOR URANIUM OXIDE

APPENDIX B —SAMPLE NUMBER, URANIUM CONTENT, AND LOCATION OF OUTCROP
AND CORE SAMPLES ANALYZED FOR URANIUM OXIDE.

SAMPLE NUMBER	U_{308} (ppm)	LOCATION
17317	74	Roadcut in Chattanooga Shale on Kentucky Highway 90, 2 mi east of bridge over Cumberland River at Burkesville, Cumberland, County, Kentucky; 0.1 m above basal contact.
17318	47	Same location; at upper contact of Chattanooga Shale.
17319	36	Outcrop of Chattanooga Shale in Pulaski County Park, on Kentucky Highway 1248, 1.3 mi north of its junction with Kentucky 80 (7.2 mi west-southwest of West Somerset, Pulaski County, Kentucky).
17320	19	Outcrop of Chattanooga Shale at dead end of Ringgold Road, 4.2 mi from its junction with Cumberland Parkway at Somerset, Pulaski County, Kentucky; 1.75 m below upper contact.
17321	36	Roadcut in New Albany Shale on west side of U. S. Highway 127, about 1.3 mi northeast of Liberty, Casey County, Kentucky.
17322	26	Outcrop in New Albany Shale on dirt land, just before descent to Dix River Valley, 0.5 mi north of U. S. Highway 150 about 0.75 mi east of Crab Orchard, Lincoln County, Kentucky.
17323	37	Outcrop of New Albany Shale in bed of Mason Fork of Flint Lick Creek, on unnamed secondary road off Kentucky Highway 954, 3 mi southwest of Berea, Garrard County, Kentucky.
17324	11	Outcrop of New Albany Shale on west side of Dogwood Drive, north of Kentucky Highway 21 about 0.6 mi west of Berea, Madison County, Kentucky; 0.9 m above basal contact.
17325	20	Roadcut in New Albany Shale on north side of unnamed road 0.9 mi east of its junction with U. S. Highway 421, about 0.1 mi south of junction of U. S. 421 and Kentucky 21, Big Hill, Madison County, Kentucky.

SAMPLE NUMBER	U_3O_8 (ppm)	LOCATION
17326	29	Roadcut in New Albany Shale 0.1 mi east of Madison-Estill County line, on Kentucky Highway 594, 7.8 mi east of its junction with U. S. 421, northeast of Big Hill, Estill County, Kentucky.
17327	27	Roadcut in New Albany Shale on north side of Kentucky Highway 499, 1.8 mi west of Dug Hill, Estill County, Kentucky.
17328	33	Railroad cut in New Albany Shale on north side of Kentucky Highway 1571, 0.4 mi beyond its junction with Kentucky 52 at Revenna, Estill County, Kentucky (north of Kentucky River).
17329	19	Roadcut in Ohio Shale on Kentucky Highway 10, 1.1 mi west of junction of Kentucky 8 and 10 at Vanceburg, Lewis County, Kentucky; 1 m above base of measured section.
17330	28	Same location; 2.2 m above base of measured section.
17331	29	Outcrop of Ohio Shale in stream bed on gravel road up Rock Camp Run, 1.1 mi north of Kentucky Highway 344, 0.3 mi east of Petersville, Lewis County, Kentucky.
17332	17	Roadcut in Ohio Shale 0.4 mi north on the east side of Spring Road, 0.7 mi east of Wallingford, Fleming County, Kentucky.
17333	62	Roadcut in Sunbury Shale, Bedford Shale, and Borden Formation on north side of Interstate 64, 4.3 mi west of Morehead (Kentucky Highway 32) interchange, Rowan County, Kentucky; sampled Sunbury Shale 0.6 m below upper contact.
17334	27	Same location; sampled Sunbury Shale 2 m below upper contact.
17335	25	Roadcut in Ohio Shale on south side of Interstate 64, 6.0 mi west of interchange at Morehead, Rowan County, Kentucky; at base of Ohio Shale.
17336	28	Roadcut in New Albany Shale on north side of Mountain Parkway just west of Clay City interchange (Exit 16), Powell County, Kentucky; 2.1 m above basal contact.

SAMPLE NUMBER	U_3O_8 (ppm)	LOCATION
17337	31	Same location; 7.6 m above basal contact.
17338	42	Same location; 9.6 m above basal contact.
17339	47	Same location; 10 m above basal contact.
17340	35	Same location; 18 m above basal contact.
17341	36	Same location; 23 m above basal contact.
17342	19	Roadcut in New Albany Shale on east side of Kentucky Highway 1057 at Stanton (Kentucky 213) interchange of Mountain Parkway, Powell County, Kentucky; 9.1 m below upper contact.
17343	6	Brazil core.
17344	44	Brazil core.
17345	32	New cut in New Albany Shale at building site on west side of Kentucky Highway 11, about 1 mi north of junction Kentucky 11 and 15 at Clay City, Powell County, Kentucky.
17346	81	Roadcut in Chattanooga Shale on east side of Interstate 65, 1 mi south of junction I-65 and U. S. 64 at Pulaski, Giles County, Tennessee; .88 m above basal contact.
17347	77	Roadcut in Chattanooga Shale on east side of Tennessee Highway 7, 1.8 mi southeast of Snow Creek, near Santa Fe, Maury County, Tennessee.
17348	79	Roadcut in Chattanooga Shale on U. S. Highway 64, 2.4 mi east of city limits of Kelso, Lincoln County, Tennessee; .4 m above basal contact.
17349	106	Roadcut in Chattanooga Shale on east side of U. S. Highway 231, 10.7 mi north of Fayetteville, Lincoln County, Tennessee; 0.5 m below upper contact.
17350	58	Roadcut in Chattanooga Shale on both sides of U. S. Highway 41, 1.1 mi northwest of Noah Fork Bridge, near Noah, Coffee County, Tennessee; 0.67 m above basal contact.

SAMPLE NUMBER	U ₃ O ₈ (ppm)	LOCATION
17351	50	Same location; 2 m below upper contact.
17352	49	Roadcut in Chattanooga Shale on east side of Tennessee Highway 53, 6.2 mi south of Dekalb-Cannon County line, Cannon County, Tennessee; 0.72 m above basal contact.
17353	23	Same location; 2 m below upper contact.
17354	23	Roadcut in Chattanooga Shale and Maury Shale on north side of U. S. Highway 70, 3.2 mi west of Smithville, Dekalb County, Tennessee; 0.47 m below Dowelltown-Gassaway contact.
17355	43	Same location; 1.75 m below upper contact of Gassaway member.
17356	33	Same location; in Maury Shale, 0.1 m below upper contact.
17357	95	Highway cut in Chattanooga Shale and Maury Shale at east end of Sligo Bridge over Center Hill Reservoir, U. S. Highway 70, east of Smithville, Dekalb County, Tennessee; in Maury Shale, 0.15 m below upper contact.
17358	95	Same location; in Maury Shale, 0.4 m below upper contact.
17359	72	Same location; in Chattanooga Shale at basal contact of Gassaway member.
17360	49	Same location; in Chattanooga Shale, 0.3 m above basal contact of Dowelltown member.
17361	66	Highway cut in Chattanooga Shale on Tennessee Highway 53, 0.7 mi north of entrance to Dale Hollow Dam overlook (west side), north east of Celina, Clay County, Tennessee; 0.1 m above basal contact.
17362	51	Roadcut in Chattanooga Shale near north end of Dale Hollow Dam, opposite overlook, near Celina, Clay County, Tennessee; 3.1 m above basal contact.
17363	34	Same location; 1.75 m below upper contact.

SAMPLE NUMBER	U_{38} (ppm)	LOCATION
17364	64	Highway cut in Chattanooga Shale 0.4 mi west of west end of bridge over Obey River, on Tennessee Highway 53, near Celina, Clay County, Tennessee; 0.5 m above basal contact.
17365	40	New roadcut in Chattanooga Shale on west side of Tennessee Highway 53 just beyond Dry Fork, south of Celina, Clay County, Tennessee; 0.84 m below upper contact.
17366	82	Same location; 3.5 m below upper contact.
17367	23	Same location; 0.2 m above basal contact.
17368	14	Roadcut in Chattanooga Shale on Tennessee Highway 135, 8.7 mi east of the junction of Tennessee 135 and 53 at Gainesboro, Jackson County, Tennessee; at basal contact.
17369	34	Same location; 1.0 m below upper contact.
17370	83	Outcrop of Chattanooga Shale in bed of Flint River, along Upcreek Road near Sulphur Springs, Madison County, Alabama.
17371	95	Roadcut in Chattanooga Shale on Buddy Williamson Road about 0.35 mi east of its intersection with Mint Springs Road, 2.8 mi west of Plevna, Madison County, Alabama.
17372	69	Outcrop of Chattanooga Shale 0.1 mi. east of bridge over unnamed creek on Carriger Road, 1 mi east of Fisk, Madison County, Alabama.
17373	40	Roadcut in Chattanooga Shale on Tennessee Highway 56 at south approach to Hurricane Bridge over Center Hill Reservoir, 1.6 mi south of the bridge and about 0.7 mi north-northeast of Smithville, DeKalb County, Tennessee; at upper contact.
17374	59	Same location; 4.5 m below upper contact.
17375	32	Same location; 0.5 m below Dowelltown-Gassaway member contact.

SAMPLE NUMBER	U ₃ O ₈ (ppm)	LOCATION
17377	30	Core of Ohio Shale: Lew Bates, Jr. No. 2 Kocheiser Sec. 30, Washington Twp., 422 ft FSL x 550 ft FEL Richland County, Ohio 60.5-ft below top.
17378	34	Same location; 78.5 ft below top.
17379	24	Same location; 416 ft below top.
17380	7	Same location; 433 ft below top.
17381	20	Core of Ohio Shale: Kentucky-West Virginia Gas No. 7239 Combs 1690' FNL x 325' FWL of Sec. 19-K-76 Perry County, Kentucky 8.6 ft below top.
17382	25	Same location; 41.5 ft below top.
17383	6	Same location; 77.2 ft below top.
17384	6	Same location; 175 ft below top.
17385	30	Same location; 240.4 ft below top.
17386	38	Same location; 292.6 ft below top.
17387	13	Same location; 302 ft below top.
17388	10	Same location; 319.8 ft below top.
17389	4	Same location; 333 ft below top.
17390	38	Same location; 229.7 ft below top.
19893	22	Nearly complete section of Ohio Shale, Bedford Shale, Berea Sandstone and Sunbury Shale exposed for 5.1 miles in roadcuts along both sides of Ohio Highway 32 near Peebles, Franklin Township, Ohio (Adams County); sampled Ohio Shale 210 feet below upper contact.
19894	35	Same location; 200 feet below upper contact.

SAMPLE NUMBER	U_3O_8 (ppm)	LOCATION
19895	26	Same location; 174 ft below upper contact.
19896	27	Same location; 132 ft below upper contact.
19897	8	Same location; 76 ft below upper contact.
19898	6	Same location; 62 ft below upper contact.
19899	20	Same location; 61 ft below upper contact.
19900	28	Same location; 33 ft below upper contact.
19901	48	Same location; 18 ft below upper contact.
19902	19	Same location; at upper contact.
19903	28	Same location; 77.6 ft below upper contact.
19904	23	Same location; 70.9 ft below upper contact.
19905	33	(Duplicate of 19899.)
19906	15	Incomplete section of Ohio Shale and Berea Sandstone exposed in drainage of Mountain Branch of Elkhorn Creek and along access road to Johnson Brothers Limestone Quarry, off Kentucky Highway 197, 4.7 mi south of its junction with Kentucky Highway 80 in Elkhorn City, Pike County, Kentucky. Base of section is in gully 1,000 ft FNL x 100 ft FWL of Sec. 24-J-86; top of section is along access road 1,950 ft FNL x 100 ft FEL of Sec. 25-J-86 (Hellier quadrangle); sampled Ohio Shale 796 ft below upper contact.
19907	6	Same location; 760 ft below upper contact.
19908	8	Same location; 752 ft below upper contact.
19909	7	Same location; 731 ft below upper contact.
19910	6	Same location; 385 ft below upper contact.
19911	4	Same location; 352 ft below upper contact.
19912	8	Same location; 276 ft below upper contact.

SAMPLE NUMBER	U_3O_8 (ppm)	LOCATION
19913	18	Same location; 56 ft below upper contact.
19914	3	Same location; 11 ft below upper contact.
19915	1	Same location; at upper contact.
19916	10	Same location; 786 ft below upper contact.
19917	10	Same location; 751 ft below upper contact.
19918	4	Same location; 384.5 ft below upper contact.
19919	9	Same location; 351.5 ft below upper contact.
19920	7	Same location; 53 ft below upper contact.
19921	8	Incomplete section of Chattanooga Shale and Grainger Formation exposed for 0.55 mi in roadcuts and creekbeds along northeastern side of Tennessee Highway 31 (Flat Gap Road); top of Chattanooga Shale is located 4.25 mi north of junction of U. S. Route 11W and Tennessee Highway 31 at Mooresburg, Hawkins County, Tennessee (Lee Valley quadrangle); sampled Chattanooga Shale 131 ft below upper contact.
19922	18	Same location; 649 ft below upper contact.