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Geology of the Devonian black shales of the Appalachian Basin

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Abstract—Black shales of Devonian age in the Appalachian Basin are a unique rock sequence. The high content of organic matter, which imparts the characteristic lithology, has for years attracted considerable interest in the shales as a possible source of energy. The recent energy shortage prompted the U.S. Department of Energy through the Eastern Gas Shales Project of the Morgantown Energy Technology Center to underwrite a research program to determine the geologic, geochemical, and structural characteristics of the Devonian black shales in order to enhance the recovery of gas from the shales. Geologic studies by Federal and State agencies and academic institutions produced a regional stratigraphic network that correlates the 15 ft black shale sequence in Tennessee with 3000 ft of interbedded black and gray shales in central New York. These studies correlate the classic Devonian black shale sequence in New York with the Ohio Shale of Ohio and Kentucky and the Chattanooga Shale of Tennessee and southwestern Virginia. Biostratigraphic and lithostratigraphic markers in conjunction with gamma-ray logs facilitated long-range correlations within the Appalachian Basin. Basinwide correlations, including the subsurface rocks, provided a basis for determining the areal distribution and thickness of the important black shale units. The organic carbon content of the dark shales generally increases from east to west across the basin and is sufficient to qualify as a hydrocarbon source rock. Significant structural features that involve the black shale and their hydrocarbon potential are the Rome trough, Kentucky River and Irvine-Paint Creek fault zone, and regional decollements and ramp zones.

INTRODUCTION

The U.S. Government, response to the energy shortage of the 1970s, sponsored research programs to develop unconventional hydrocarbon resources. In 1976, under the auspices of the Energy Research and Development Administration, now the U.S. Department of Energy (DOE), the Eastern Gas Shales Project was organized to study the Devonian black shales in order to enhance their gas production. The U.S. Geological Survey, under interagency agreement No. EX-76-C-01-2287 with DOE's Morgantown Energy Technology Center was responsible for the compilation of the regional geology of the Devonian black shales. In addition to the financial support of the Morgantown Energy Technology Center, the writer wishes to acknowledge the State geological surveys and universities who, in co-operation with the Eastern Gas Shales Project, supplied much of the basic data for this regional study.

Interest in the economic development of the Devonian shales has prompted a variety of geochemical studies to help define areas for hydrocarbon exploration. As an aid to those studies, this paper presents a summary of the basinwide stratigraphic framework of the principal Devonian black shale units in the Appalachian Basin and specific regional tectonics of the Appalachian Basin that may affect hydrocarbon production from the black shales. The area of study is defined by the outline of the regional stratigraphic network prepared for the Devonian shales of the Appalachian Basin (Fig. 1). The nomenclature and the areal extent of the stratigraphic units as used here does not necessarily conform to the usage of the U.S. Geological Survey.

STRATIGRAPHY

Regional setting

The wedge of Paleozoic sedimentary rocks in the Appalachian Basin is the result of a general cyclic repetitive deposition of certain rock types in an asymmetric, eastward-deepening downwarp in the earth's crust. Modification of Colton's (1970) cross-section showing the stratigraphic and lithologic relations to the sedimentary wedge of the Appalachian Basin indicates a cyclic repetition of three noticeable rock types: organic-rich rocks, predominantly black shale; clastic rocks, mostly silty shale, siltstones and sandstones; and carbonate rocks (Fig. 2). The obvious cycle, not always complete, is a basal carbonaceous shale overlain by clastics which in turn are overlain by carbonates. Three, and possibly four, cycles may be identified in the basin fill (Fig. 2).

The third cycle contains at its base the Devonian black shales. These shales are a facies within a large westward- and southward-thinning sequence of sedimentary rocks. In eastern Pennsylvania the sequence is over 5000 ft and thins westward across the basin where in central Ohio the thickness is about 600 ft. Southward, in central Tennessee, the thicknesses range from 0 to about 50 ft. Throughout the length of the basin, the sequence thickens from the central

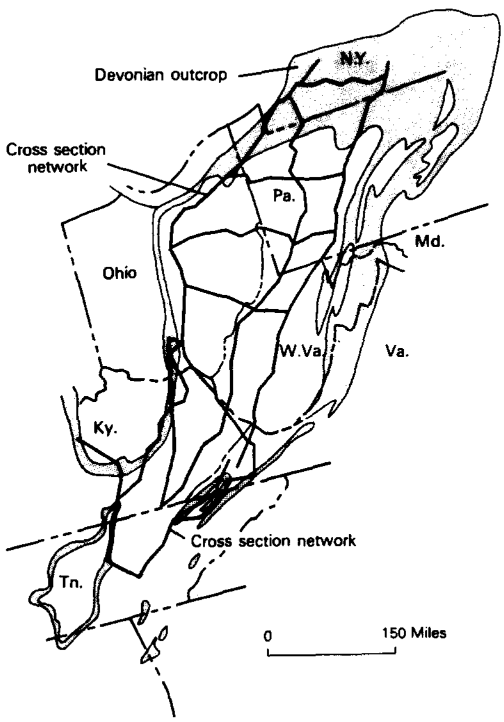

Fig. 1. Index map showing location of stratigraphic cross-sections and the Devonian outcrop belt in the Appalachian Basin. Cross-section network outlines the area of study.

region eastward to the outcrop belt in the folded Appalachians.

The principal lithologic components of this Devonian wedge are marine clastics with minor amounts of carbonate rock and nonmarine clastics. The marine facies includes black shale, gray shale, siltstone and sandstone, and lesser amounts of argillaceous limestones. The nonmarine facies consists of reddish colored shale, siltstone, sandstone and conglomerate. This facies, which was not studied for this report, is the eastern terrestrial component of a large delta system that grades westward into progressively finer grained marine turbidities. The siltstones and sandstones of the turbidite sequence are either thin-bedded sheet deposits, indicate of a relatively low energy, distal basin deposit or thicker-bedded sandstones with current and channel structures, indicative of a proximal, higher energy, slope or shelf environment. These turbidites are interbedded with, and grade basinward, to dark, organic rich shales. The dark colored shales represent the extreme distal portions of the deltaic wedge. The dark gray, brownish-black to black shales are thought to have accumulated in tranquil anoxic basinal waters. Their euxinic depositional site allowed the preservation of the finely macerated organic detritus which imparts the dark color to the shale. Sporadic limestone beds with pelagic and benthic faunas are suggestive of a higher energy, oxygenated water, shoal environment. The regional facies relationship of the black shales and contiguous rocks within the Appalachian Basin are shown on the generalized cross-section (Fig. 2).

The basic repetitive depositional cycle recognized within the Paleozoic section of the basin is also recognizable within the Devonian shale sequence. Although much reduced in thickness and not without the expected variation due to missing units, the lithologic sequence of the Devonian cycle is similar to the larger Paleozoic cycle of the basin. In New York, de Witt and Colton (1959) recognized this cyclic sedimentation pattern. A complete cycle consists of a basal black shale overlain by lighter gray shale, siltstone, and sandstone with a limestone at the top.

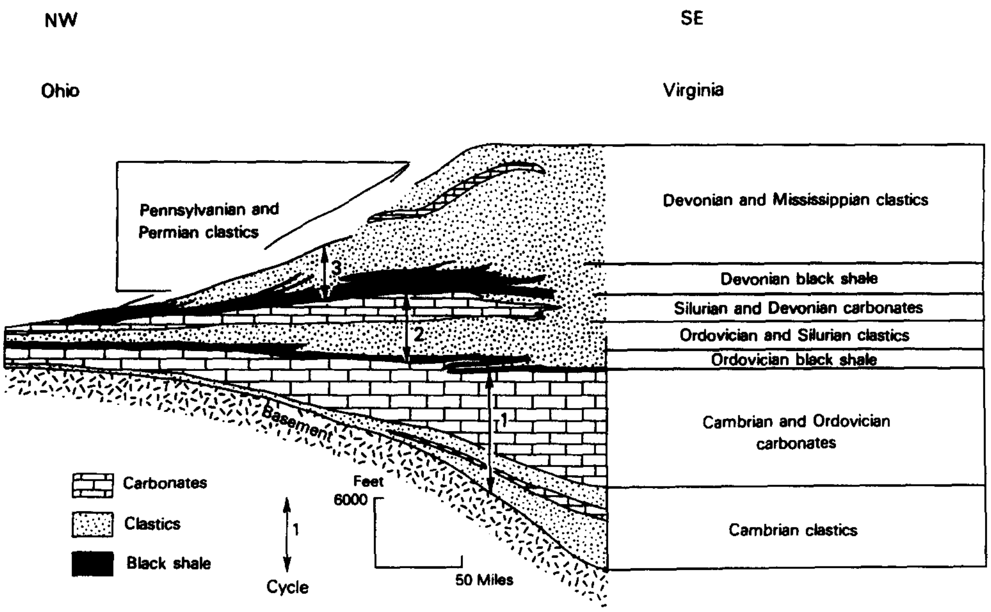

Fig. 2. Stratigraphic cross-section of the Appalachian Basin showing the cyclic relationship of the basin fill. The Devonian black shale is the basal sequence of cycle 3. Modified from Colton (1970).

A complete cycle is represented by the Hamilton Group at the base of the Devonian black shale sequence. The cycle includes the basal black Marcellus and Skaneateles Shales, the overlying Moscow and Ludlowville Shales and the Tully Limestone at the top. A few thin limestone beds within the thick Hamilton sequence suggests the presence of a few incomplete subcycles. Above the Hamilton Group in the northeastern part of the basin there are several recognizable cycles; however, only the basal black shale and the overlying gray shale and coarser clastics are present. Toward the western and southern part of the basin the cycles become compressed losing the gray clastics, and in areas such as central Tennessee the cycles are represented almost entirely by black shale.

Lithology and related properties

The color of the Devonian shales ranges from medium light gray (N 6) to black (N 1) with variations of brownish black (5 YR 2/1) and olive black (5 Y 2/1). The color value notations are from the Rock Color Chart of Goddard *et al.* (1948). In general reference to the Devonian black shales, "black" includes the color value of dark gray (N 3), grayish black (N 2), black (N 1), brownish black (5 YR 2/1), and olive black (5 Y 2/1).

The most conspicuous lithologic feature of the organic-rich Devonian shales is the dark color, the principal cause of which is the organic carbon content of the shale. To a lesser extent, and in part dependent on the organic carbon content, iron in the reduced state can contribute to the dark color (Potter *et al.* 1980). Calcium content also tends to darken the color value of organic-rich shales (Hosterman and Whitlow, 1981a, b).

The amount of carbon relative to the color value is represented by an exponential curve (Hosterman and Whitlow, 1981a, Fig. 1). The curve flattens above a carbon content of 3–4% such that there is no noticeable decrease (darkening) in the color value as the carbon content increases.

The mineralogic constituents of the black shale are quartz, feldspar, mica, clay minerals, sulfides, organic matter, and minor amounts of carbonate, phosphate, and accessory minerals. The lithologic data presented here are, in part, from the petrographic studies by Conant and Swanson (1961), Larese and Heald (1977) and Stenbeck (1981). Additional data on the framework and clay minerals are from the X-ray studies of Hosterman and Whitlow (1981b).

Quartz is nearly always present as a primary constituent in amounts as much as 25%. Generally, the quartz composes 10–20% of the rock. It is usually extremely fine grained ranging from very fine sand size (0.125 mm) to clay size (0.004 mm). A few isolated, floating, fine (0.125 mm) to medium (0.27 mm) grained, well-rounded quartz grains are found at, or near, the base of some black shale units. To date, these well-rounded quartz grains have only been found in the southern part of the basin. The quartz is most always angular to subangular having an equant to elongate shape. The extremely fine grained nature generally precludes anything other than the monocrystalline variety of quartz. Also, because of the very fine grained character of the quartz, it is difficult to determine authigenic quartz, secondary overgrowths, and to interpret possible multicycle sedimentation. Some of the quartz-rich silt laminae contain a few overgrowths and other forms of secondary quartz.

Feldspar is present in amounts less than that of quartz; probably less than 10%. The shape and grain size of the feldspar is similar to that of the quartz. Differentiation between feldspar and quartz is difficult because of the very fine grain size. The grain size also precludes determination of the type of feldspar. However, sporadic plagioclase grains are identified by their albite twinning.

Variable amounts of mica are found in the black shale. Conant and Swanson (1961) report as much as 10% muscovite or sericite; Stenbeck (1981) reports about 5–30% chlorite, muscovite, and other micaceous minerals contained in the black shale. Biotite appears to be present in recognizable amounts only in association with ash beds found in the black shale sequence. As much as 30–40% biotite is found within the ash bed; however, only a few percent is found in the enclosing black shale. The 0.5–2 mm, bronze-weathering flasks may be identified megascopically in outcrop or in core material. They are generally oriented parallel or subparallel to bedding.

Clay minerals found by X-ray diffraction methods are illite, chlorite, kaolinite, and two mixed-layer clays (Hosterman and Whitlow, 1981b). The clay fraction of the Upper Devonian black shales throughout the basin averages about 60%. Of the fraction, the clay minerals have the following average ratio: illite, 59; chlorite, 17; mixed-layer illite–smectite, 23; kaolinite, 1; mixed-layer illite–chlorite, trace (modified from Hosterman and Whitlow, 1981b). The Middle Devonian black shales are similar in clay composition but contain calcite at the expense of the total clay fraction. The amount of calcite in the Middle Devonian black shales averages 25% whereas the Upper Devonian black shales contain only a trace, except for the Geneseo Shale Member of the Genesee Formation that contains an average of 15%.

Iron sulfides in the form of pyrite and marcasite are ubiquitous in the black shale. Marcasite is a small percentage of the total iron sulfide (Stenbeck, 1981). Most investigations do not distinguish between the two, and as pyrite is in greater quantity, the iron sulfides are referred to as pyrite.

Pyrite in the black shales occurs as microscopic to megascopic single subhedral to euhedral cubes or pyritohedrons, masses of crystals, framboidal clusters, cavity linings, laminae and coatings, and after organic remains such as spores and brachiopods.

Most of the pyrite is present as very fine submicroscopic particles disseminated throughout the shale. The diameter of the largest particles may be as much as several mm. In some siltstones or very fine grained sandstones the pyrite forms lenses several cm long and 1–2 cm thick. Commonly the sulfide weathers to white or yellowish masses or coatings of sulfate.

The organic material in the black shales is both marine and terrestrial in origin. Relative proportions of each type of organic matter at a particular site is dependent on the location of the site relative to the open marine areas, terrestrial source areas, and prevailing water currents and wind directions. The terrestrial material consists of woody and/or coaly fragments, cuticles, spores, pollen, and other herbaceous remains. The marine fraction includes algal material, algal palynomorphs, and soft body parts of marine faunal groups such as fish and invertebrates. *Tasmanites*, believed to be a spore case from a marine algae, is a common form found in the black shales from certain localities.

The amount of organic carbon in the Devonian shale sequence rantes from less than 0.5% to nearly 20%. The average organic carbon content for the black shales having a color value of N 1–N 3 is about 4% by weight. Those shales lighter in color than N 3 have an average of about 0.8% organic carbon. These averages were computed for this report from more than 400 organic carbon determinations from 67 wells and surface localities in the basin (Claypool and Stone, 1979; Claypool, *et al.*, 1980; Claypool, written communication, 1981; Maynard, 1981). Throughout much of the basin, the average organic carbon content of the Devonian black shale sequence exceeds the lower limit of organic carbon generally established for hydrocarbon source rocks.

The areal distribution of organic carbon in the black shales and the lighter colored, gray shales is not covarient. The carbon content of the organic-rich black shales generally increases from east to west across the basin (Fig. 3), whereas the carbon content of the lighter colored gray shales is variable showing high concentrations in the central part of the basin that appear to decrease toward the east and west.

Carbonate, generally calcite, occurs in quantities of usually less than 1% in most of the black shale units. Only the Geneseo Shale Member of the Genesee Formation and the Marcellus and Skaneateles Shales have appreciable amounts of calcite throughout. X-ray analysis indicates that calcite is present in those units in amounts of 10–20% (Hosterman and Whitlow, 1981b). Where recognizable megascopically, the carbonate occurs as nodules, concretions, small crystals and veins.

Phosphate is present in minor amounts in the black shale sequence as detrital material and as an au-

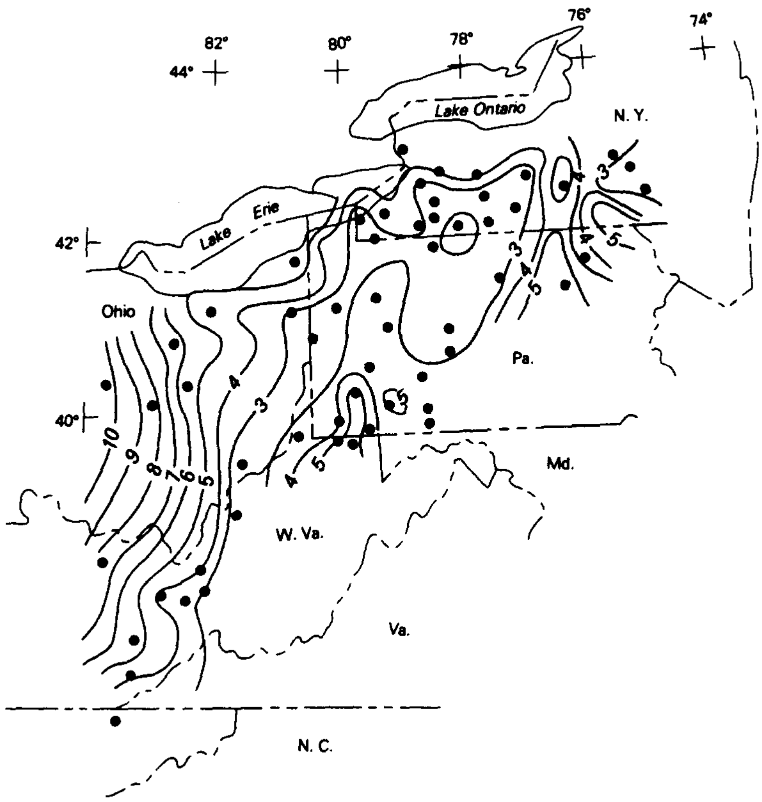

Fig. 3. Average organic carbon of the black shales of Middle and Late Devonian age (numbers and contours indicate %). Analyses from Claypool and Stone (1979), Claypool *et al.* (1980), Claypool (written communication, 1981) and Maynard (1981). Sample locations shown by black dots.

thigenic precipitate. The detrital phosphate is in the form of phosphatic bones, shells, conodonts, and other unidentifiable phosphatic hard parts of organisms. This form of phosphate is probably widespread laterally and vertically in the shale sequence throughout the basin. Authigenic phosphate occurs as nodules as large as 3–4 in at the top of the black shale sequence in the southern part of the basin.

Stratification in the black shale consists of very thin laminae less than a millimeter thick to very thin beds a few centimeter thick. Visual recognition of stratification in fresh outcrops or samples is dependent on variations in color and/or lithology. The darker colored, thin laminae are usually composed of clay and varying amounts of organic material. Thin, wispy, or lenticular lighter colored laminae are composed of very fine quartz and feldspar silt. The unweathered rock generally shows little or no fissility. Weathered shale is fissile, usually parting into brittle pieces ranging from 1 mm to 1 cm in thickness.

The rock fabric is dependent on the quantity of organic matter contained in the rock. Shale containing increased amounts of organic matter tends to be massive and less fissile. Instead of easily parting when struck, these highly organic shales break with a conchoidal fracture. Shales containing a large amount of organic material in relatively fresh outcrops are easily recognized by their massive blocky and resistant character. This characteristic resembles the blocky nature of bituminous coal beds.

Development of stratigraphic nomenclature

There are 10 regionally extensive black shale units within the Devonian shale sequence of the Appalachian Basin. Although these units are distinctive and form the regional stratigraphic framework, their stratigraphic nomenclature is not consistent throughout the basin.

Different nomenclature systems were devised for the Devonian shale sequence because early studies were essentially confined to the readily accessible and well-exposed outcrop areas in the basin. Within each of these areas, the shale sequence was divisible in a manner peculiar to that sequence with the adoption of local geographic nomenclature. The principal areas where the different nomenclature systems were developed are: central and western New York, along the outcrop belt from Lake Erie to south-central Ohio, central Tennessee, and south-western Virginia. Each system, which is uniquely applicable to its local region, has developed into a usable format that has stood the test of time. Areally, these outcrop regions are only a small percentage of the total extent of the Devonian shale sequence. The greatest portion lies within the subsurface of the basin (Fig. 1). The stratigraphy of the subsurface area was largely unknown until relatively recently when the stratigraphy of the early study areas was projected into the subsurface of the basin.

The widespread continuity of the black shales and their characteristically sharp basal contact have provided an easily recognizable basis for stratigraphic subdivision. The gray shales, siltstones and sandstones have gradational contacts and are difficult to delineate and map. In addition, the clastic rocks between the black shale units grade into and intertongue with the upper beds of the black shale units. This feature precludes accurate and consistent mapping of the upper contacts of the black shale unit. Consequently, the base of one widespread black shale to the base of a stratigraphically higher black shale provides a convenient sedimentary sequence or cycle that can be accurately mapped as a stratigraphic unit. These units have been mapped at the surface in New York and have been extended southward and westward into the subsurface of the Appalachian Basin. In the south-central part of the basin, the basic cycle cannot be recognized because of the disappearance of the intervening lighter colored clastics.

Regional stratigraphy

Thirteen stratigraphic cross-sections (Fig. 1) across the Appalachian Basin form the basis for the regional correlation of the principal black shale units in the Devonian shale sequence. These sections, in addition to local detailed studies, were used to compile regional distribution maps for the stratigraphic units and areas of appropriate nomenclature (Fig. 7–11). The regional stratigraphy is summarized by the correlation chart (Fig. 4) which shows the principal black shale units, their nomenclature, and their correlatives for different regions within the basin. The stratigraphic positions of the black shale units in a longitudinal section through the basin is shown in Fig. 5.

The cross-section network was prepared primarily using gamma-ray logs from wells drilled for oil and gas. The gamma-ray logs were compared where possible with lithologic logs to establish stratigraphic control and maintain a direct relationship with the rock type and the log response. The utility of the gamma-ray is based on the fact that different types of rocks contain varying amounts of radioactive elements which emit proportionate amounts of radioactivity that are recorded on the log. Figure 6 is an abstracted section from the network shown in Fig. 1. It illustrates the use of the gamma-ray log in establishing long-range subsurface correlations. The section covers a 400 mile distance from New York through Pennsylvania and Ohio to Kentucky and shows the continuity of similar log signatures for six principal black shale units in the basin. These characteristic log traces provide the basis for regional black shale correlations.

Lower Mississippian–Upper Devonian black shales

Although the black shale sequence is generally referred to as Devonian in age, the uppermost black shale unit of the sequence is the Sunbury Shale of

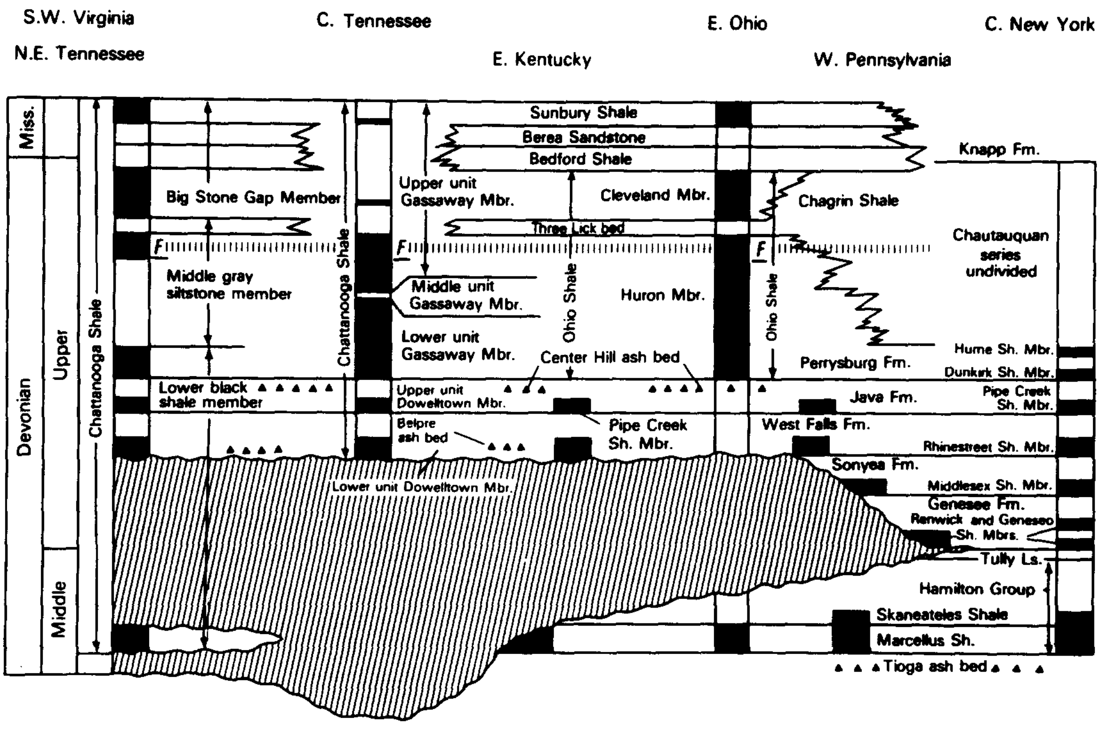

Fig. 4. Correlation chart of the Devonian black shale units in the Appalachian Basin. Solid black pattern, black shale units; | | |*F*.| | |, zone of fassil algae *Foerstia*; ▲, ash beds.

Early Mississippian age. The Sunbury is exposed in Ohio along Lake Erie, in the north-trending Devonian outcrop belt in central Ohio, and in central-eastern Kentucky (Fig. 1). Eastward, in the central part of the basin, the Sunbury Shale is in the subsurface. In central-eastern Kentucky, the Bedford Shale and Berea Sandstone, which separate the overlying Sunbury Shale from the underlying Ohio Shale, thin to extinction allowing the two black shale formations to merge. In central-eastern Kentucky and southward into Tennessee, where the Sunbury and Ohio Shales have thinned and merged, they form the Gassaway Member, the upper member of the Chattanooga Shale (Fig. 4). In south-western Virginia, the Sunbury thickens along with the underlying beds equivalent to the Bedford Shale and/or Berea sandstone. Here the Sunbury Shale can be identified on gamma-ray logs as an equivalent to the upper beds of the Big Stone Gap Member of the Chattanooga Shale of north-eastern Tennessee and south-western Virginia (Fig. 4). The thickness of the Sunbury and equivalent rocks, determined from the gamma-ray logs, ranges from 0 to approximately 200 ft. The isopachs define a north-trending belt in eastern Ohio extending southward to the area of known maximum thickness in south-western Virginia (Fig. 7).

The Ohio Shale is divided into two members. The upper unit is the Cleveland Member; the lower unit is the Huron Member. These two black shale mem-

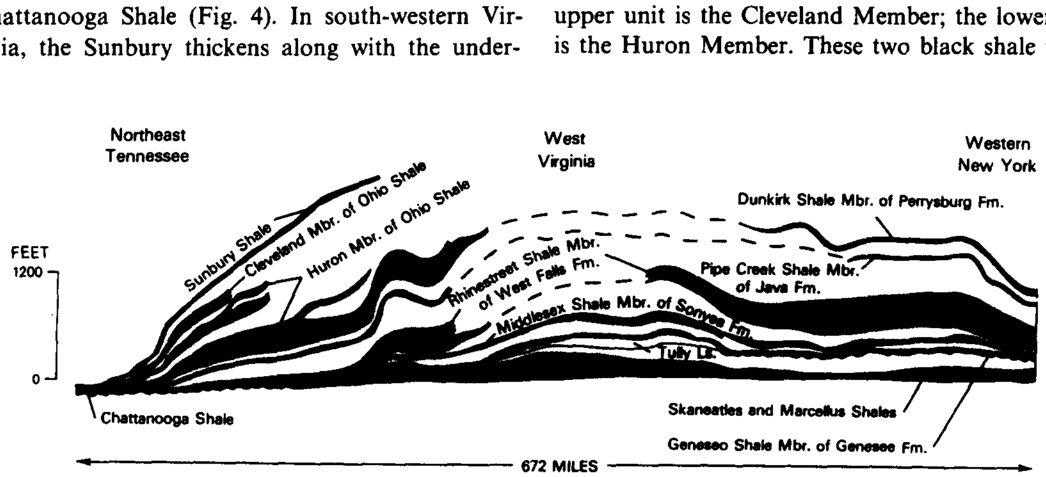

Fig. 5. Longitudinal cross-section through the central part of the Appalachian Basin showing the regional stratigraphic relationship of the Middle and Upper Devonian black shale units. In part diagrammatic. Modified from the center longitudinal cross-section shown in Fig. 1.

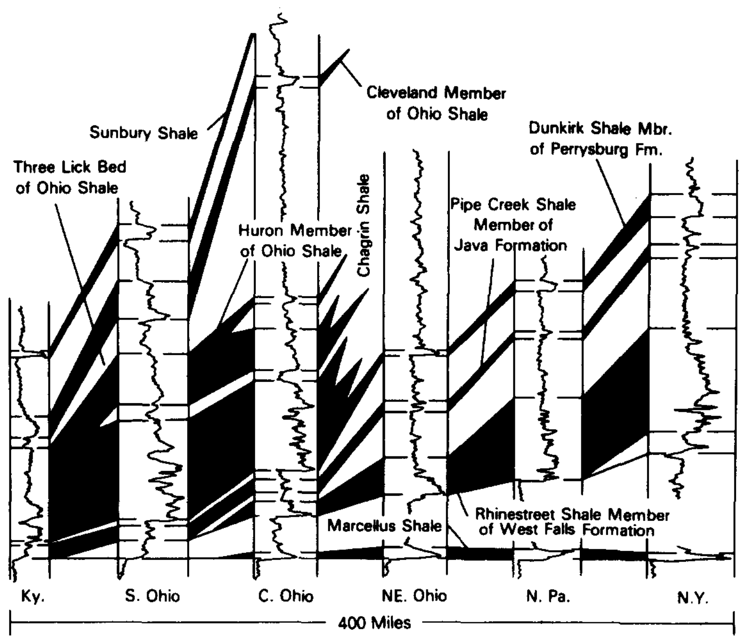

Fig. 6. Selected gamma-ray logs from the westernmost longitudinal cross-section (Fig. 1) illustrating long-distance regional correlations and characteristic log signature for black shale units.

bers are separated by the greenish-gray siltstone and shales of the Chagrin Shale, the 20–30 ft thick distal part of which is the Three Lick Bed of the Ohio Shale (Fig. 4). The Cleveland Member is exposed along Lake Erie in Ohio. Its western extent is limited by its north-trending outcrop that follows the exposed belt of Devonian rocks in central Ohio. Southward, in eastern Kentucky and central Tennessee where the Ohio Shale is not recognized, paleontological evidence (Conant and Swanson, 1961; Hass, 1956) suggests that beds in the upper unit of the Gassaway Member of the Chattanooga Shale are equivalent to the Cleveland Member (Fig. 4). Similar paleontological data, in conjunction with subsurface gamma-ray log correlations, indicate that the Cleveland beds (and the equivalent beds in the Gassaway Member of the Chattanooga Shale of Tennessee) are present as the black shale beds in the lower part of the Big Stone Gap Member of the Chattanooga Shale of north-eastern Tennessee and south-western Virginia (Fig. 4). The eastern limit of the Cleveland, as mapped from gamma-ray log data, is delineated by the zero isopach line (Fig. 7). The isopach map indicates that the radioactive black shale of the Cleveland Member occupies a north-trending belt in the basin, with the maximum thickness of approxi-

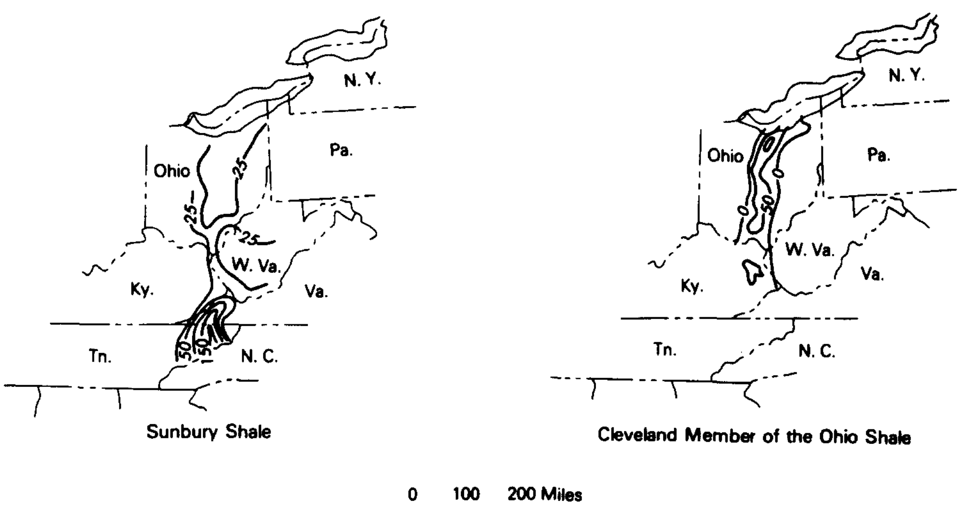

Fig. 7. Isopach map of the Sunbury Shale and the Cleveland Member of the Ohio Shale; contour interval as shown, thickness in feet.

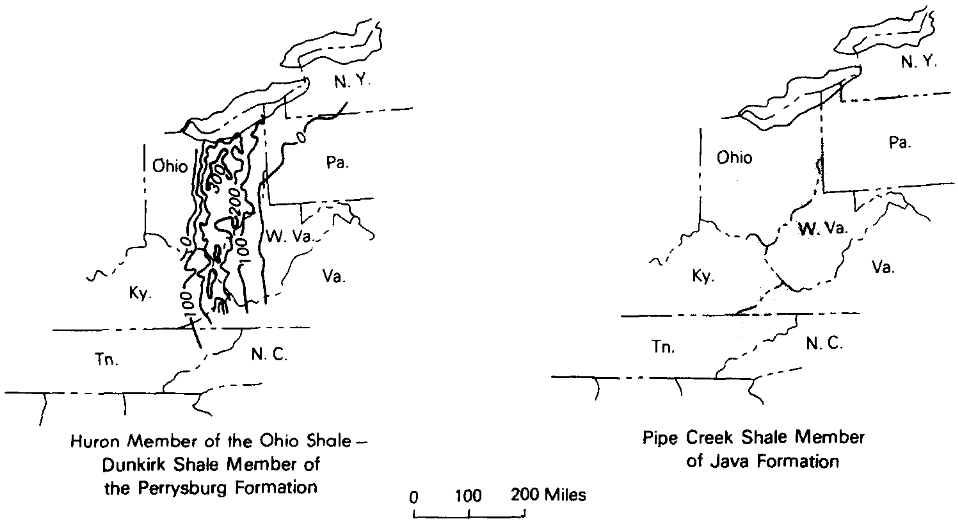

Fig. 8. Isopach map of the Huron Member of the Ohio Shale and its equivalent, the Dunkirk Shale member of the Perrysburg Formation; contour interval as shown, thickness in feet. Distribution of the Pipe Creek Shale Member of the Java Formation shown by shading.

mately 100 ft in north-central Ohio. Although not mapped for this report because of the lack of thickness data, the sequence equivalent to the Cleveland in south-western Virginia is approximately 80 ft thick.

The lower division of the Ohio Shale, the Huron Member, is divided into an upper and lower part by tongues of the Chagrin Shale (Figs 5 and 6). The upper black shale part of the Huron splits and interfingers with the Chagrin in central Ohio and thins to extinction in north-eastern Ohio (Fig. 6). The lower black shale also thins towards the east; however, it can be continuously traced through the subsurface of north-western Pennsylvania into western and central New York. In New York, the basal portion of the Huron Member is the Dunkirk Shale Member of the Perrysburg Formation (Fig. 6).

In a similar fashion of intertonguing and thinning with the Chagrin and equivalent rocks, the Huron Member extends from central Ohio into south-eastern Ohio and to central West Virginia. The upper part of the Huron grades into lighter gray shales and siltstones of the Chagrin in south-east Ohio; the lower part continues towards central West Virginia where it is no longer recognizable in the subsurface well records.

Southward and westward from central Ohio, the distal portion of the Chagrin Shale thins to extinction allowing the upper and lower parts of the Huron to merge. In addition, the upper and lower parts of the Huron thin southward into Kentucky and north-eastern Tennessee. In central Kentucky and central Tennessee, the Huron Member of the Ohio Shale is equivalent to the lower and middle units, and part of the upper unit of the Gassaway Member of the Chattanooga Shale. Eastward, in south-western Virginia, the beds equivalent to the Huron Member thicken, become intercalated with gray shale and siltstone, and are equivalent to the upper part of the lower black shale member and the middle gray siltstone member of the Chattanooga Shale of south-western Virginia and eastern Tennessee (Fig. 4).

The Huron Member is exposed along the Devonian outcrop belt from eastern Kentucky to north-east Ohio (Fig. 1). In Pennsylvania and part of New York, the Huron Member is in the subsurface. The equivalent of the basal beds of the Huron, the Dunkirk Shale Member of the Perrysburg Formation, emerges from the subsurface along Lake Erie and is exposed within the Devonian outcrop belt in the south-western part of New York. Southward, its correlative, the Gassaway Member of the Chattanooga Shale, follows the Devonian outcrop belt in central Kentucky and Tennessee. Also, the equivalent beds in the unnamed lower black shale member and unnamed middle siltstone member of the Chattanooga Shale follow the outcrop pattern in south-western Virginia and eastern Tennessee (Fig. 1).

The Huron and its correlatives are the most widespread and thickest black shale unit of Late Devonian age in the basin. The unit occupies a north-trending belt that covers eastern Ohio, the western parts of Pennsylvania and New York, western West Virginia, western Virginia, eastern Kentucky and eastern Tennessee. It is composed of at least 300 ft of radioactive black shale in the central part of this belt and more than 300 ft in western Virginia (Fig. 8).

The determination of the regional stratigraphy of the Ohio Shale and related rocks has been facilitated by the presence of the stratigraphically restricted, widespread (Hass, 1956; Schopf and Schwietering, 1970; Roen, 1981) fossil algae *Foerstia*. It occurs in the Huron Member of the Ohio Shale below the Three Lick Bed (Fig. 4). Recently, *Foerstia* has been reported in the upper unit of the Gassaway Member, negating a previous correlation of the Three Lick Bed with the middle unit of the Gassaway (Kepferle *et al.*, 1983). *Foerstia* also occurs in the upper part of the middle gray siltstone member of the Chattanooga Shale of south-western Virginia (Fig. 4).

The black shale unit below the Ohio Shale is the Pipe Creek Shale Member of the Java Formation of New York. It is a thin unit, 25 ft or less, and apparently insignificant. However, its thinness, characteristic gamma-ray log response (Fig. 6), and remarkable widespread continuity from New York through Pennsylvania, Ohio, West Virginia, Kentucky, and Virginia to Tennessee (Fig. 8) make it a useful and significant stratigraphic marker bed. In addition, its association with the Center Hill ash bed in various parts of the basin (Roen, 1980) enhances its utility as a key stratigraphic marker bed (Fig. 4).

Correlatives of the Pipe Creek are within the lower black shale member of the south-western Virginia Chattanooga Shale and possibly in the upper unit of the Dowelltown Member of the Chattanooga Shale of central Tennessee (Fig. 4).

The Rhinestreet Shale Member of the West Falls Formation of New York is exposed within the Devonian outcrop in the western part of the State. Elsewhere, except for outcrops in south-western Virginia and parts of eastern Tennessee, the Rhinestreet and its correlatives are in the subsurface of the basin. In south-western New York and north-western Pennsylvania, it is present in the subsurface, reaching its maximum thickness of more than 200 ft of radioactive black shale. In western Pennsylvania, the Rhinestreet intertongues eastward with gray shales and siltstone and is not recognized on the gamma-ray logs near the central part of the State. South-westward in central West Virginia, the Rhinestreet is not recognized because it thins into and intertongues with a thick wedge of gray shale and siltstone (Fig. 5). In Ohio and eastern Kentucky, the black shale of the Rhinestreet thins westward, losing progressively its lower beds by lapping out against a regional unconformity that separates the rocks of Middle and Late Devonian age.

The correlatives of the Rhinestreet in the southern part of the basin are within the Chattanooga Shale of south-western Virginia, north-eastern Tennessee and central Tennessee. Except for the basal few feet, the lower part of the lower black shale member of the Chattanooga in the south-western Virginia–north-eastern Tennessee area is equivalent to the Rhinestreet of New York (Fig. 4). In central Tennessee, the beds of the Rhinestreet Shale Member are probably equivalent to the lower unit of the Dowelltown Member of the Chattanooga Shale (Fig. 4).

The long-distance extension of the Rhinestreet beds from New York to Tennessee is based on the utility of the gamma-ray log, paleontological studies, and the Belpre ash bed. The Belpre is a significant marker bed that is found in the Rhinestreet of northern Ohio and most of the southern half of the areal distribution of the Rhinestreet (Roen, 1980; Roen and Hosterman, 1982). Its position is close to the base of the Rhinestreet, and where the Rhinestreet has been confused with Marcellus Shale, the Belpre was thought to be the older Tioga ash bed. The Rhinestreet Shale Member forms a 150 mile wide belt that trends slightly east of north. The maximum thickness of more than 250 ft occurs in the northern part of the belt. The belt of Rhinestreet lies eastward of the Huron–Dunkirk sequence in the northern part of the basin. Southward, in Ohio and

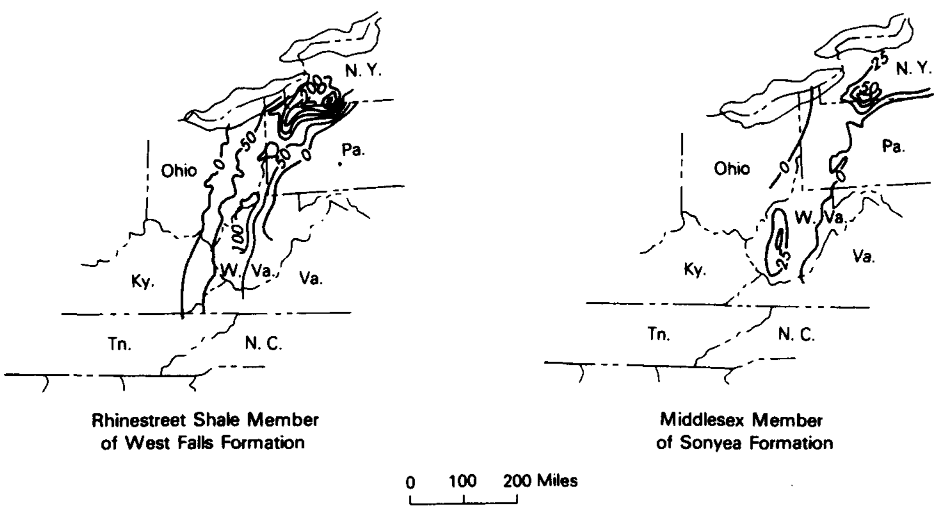

Fig. 9. Isopach maps of the Rhinestreet Shale Member of the West Falls formation and the Middlesex Shale Member of the Sonyea Formation; contour interval as shown, thickness in feet.

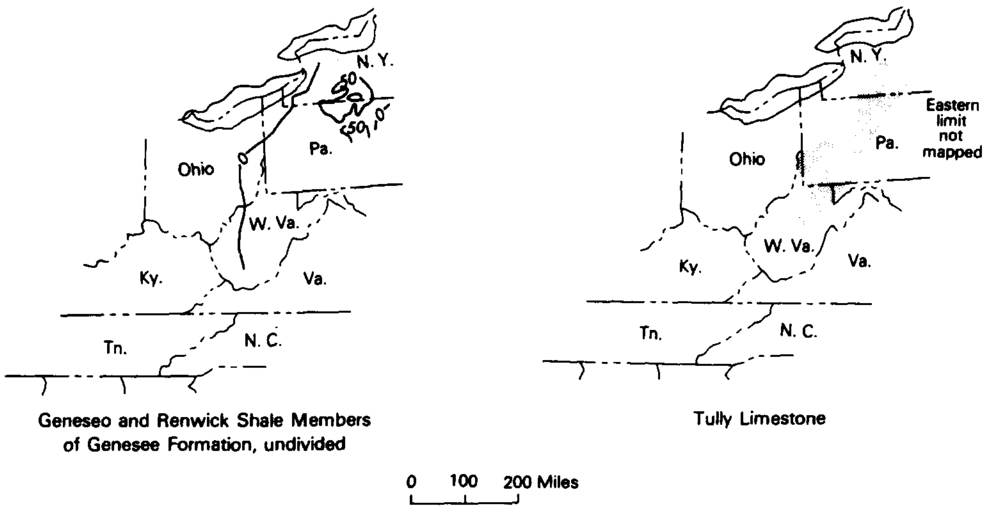

Fig. 10. Isopach map of the Geneseo and Renwick Shale member of the Genesee Formation, undivided; contour interval as shown, thickness in feet. Distribution of the Tully Limestone shown by shading.

West Virginia, the depocenters of the Rhinestreet and the Huron–Dunkirk shales are superimposed (Fig. 8 and 9).

The Middlesex Shale Member of the Sonyea Formation is only exposed in western and central New York State. Elsewhere it is in the subsurface of the basin. In the subsurface it extends southward through western Pennsylvania into western and central West Virginia (Fig. 9). Eastward, in western Pennsylvania and central West Virginia, the black shales of the Middlesex interfinger with the gray shale and siltstone units of the Sonyea Formation. Westward, the black shale thins by nondeposition against the underlying unconformity separating Middle and Upper Devonian rocks in north-western Pennsylvania and eastern Ohio (Fig. 9). It attains its maximum thickness of about 75 ft in a circular area along the New York–Pennsylvania border. Although not as thick, an isolated lobe of Middlesex is as much as 50 ft in south-western West Virginia. The maximum thickness of the Middlesex lies east of the maximum thickness of the overlying Rhinestreet in the northern part of the basin. In the southern part of the basin, the black shales of the Middlesex coincide with the maximum thickness of the Rhinestreet and Huron.

The radioactive black shale of the Geneseo Formation is predominantly within the Renwick Shale Member and the basal Geneseo Shale Member. These black shale members are separated by gray shales, silty shales, siltstone, and very fine grained sandstones in central and western New York. Southward, the intervening rocks thin and the two members merge with some part, or all, of the merged unit being a correlative of the Burket Black Shale Member of the Harrell Shale (not shown in Fig. 4) of central-western Pennsylvania. Except for their exposures in New York and along the westernmost folded belt of Devonian rocks in Pennsylvania, Maryland, and West Virginia, the Renwick and Geneseo are in the subsurface of the basin (Fig. 1). The units are present in a combined thickness of less than 50 ft in western Pennsylvania, central-eastern Ohio and central West Virginia. The sequence thins to extinction westward and southward from its area of maximum thickness of 100 ft along the New York–Pennsylvania border (Fig. 10). The Geneseo Shale Member overlies the Tully Limestone of Middle Devonian age in central New York. The Geneseo is separated from the Tully by a regional unconformity that represents an increasing hiatus southward and westward between rock of Middle and Late Devonian age.

Middle Devonian rocks

The Tully Limestone is a regionally significant marker bed within the Devonian shale sequence. Its areal extent as defined by the regional stratigraphic network (Fig. 1) is shown in Fig. 10. The eastern limit of the Tully is beyond the network and was not mapped. Within the approximate 100 mile north-east-trending belt delineated here the Tully attains a maximum thickness of about 90 ft. It thins to extinction southward in West Virginia and westward in Pennsylvania and New York. It is limited in central New York by its outcrop belt.

The basal black shales of the Hamilton Group are the Skaneateles Shale and the underlying Marcellus Shale (Fig. 4). The two units are generally lithologically similar and are separated by the relatively thin Stafford Limestone Member (not shown in Fig. 4), the basal member of the Skaneateles Shale. The sequence is exposed within the Devonian outcrop belt (Fig. 1) from the eastern tip of Lake Erie eastward to the Allegheny Front and southward within the folded Middle Devonian rocks of the eastern part of the basin. Basinward from the outcrop belt, the Skaneateles–Marcellus sequence is in the subsurface.

The Skaneateles is less extensive than the Marcellus. From its outcrop belt is extends westward to

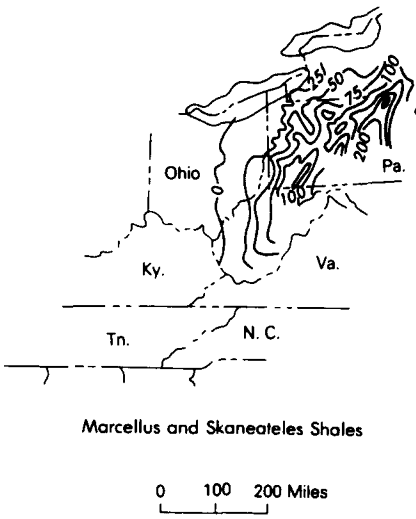

Fig. 11. Isopach map of the Marcellus and Skaneateles Shales, undivided; contour interval as shown, thickness in feet.

north-east Ohio where it pinches out. Southward it pinches out in western Pennsylvania just east of the West Virginia panhandle. It is not present in the western half of West Virginia. The western limit of the more extensive Marcellus approximates a north-trending line from central Ohio southward along the Kentucky–West Virginia border to southwestern Virginia (Fig. 11). The thickness of radioactive black shale in the Skaneateles–Marcellus sequence is as much as 200 ft in the eastern part of the study area (Fig. 11). The Skaneateles–Marcellus sequence is areally extensive and relatively thick containing probably the largest volume of organic-rich shale in the Devonian shale sequence; however, most of the sequence is beneath 7000 ft or more of overburden.

The Tioga ash bed, an areally extensive stratigraphic marker, occurs very near, or just below, the base of the Marcellus Shale in New York, Pennsylvania, Ohio and West Virginia (Fig. 4). Locally the Belpre ash bed has been confused with the Tioga causing miscorrelation of the Rhinestreet Shale Member of the West Falls formation with Marcellus Shale.

STRUCTURE

Regional setting

Rocks of Devonian age are exposed in an elongated elliptical belt that generally outlines the Appalachian basin (Fig. 12). Within this outcrop belt, and primarily in the subsurface, is the Middle and Upper Devonian sequence which includes the dark gray to black organic-rich shales of this report.

The eastern outcrop belt of Devonian shale is included in a series of elongated folds of Paleozoic rocks extending from north-east Pennsylvania in a swath that narrows to fewer folds south-westward to north-eastern Alabama (Fig. 12). In Pennsylvania, the Devonian outcrop belt lies predominantly to the east of the Allegheny front. Southward, in Maryland, Virginia and West Virginia, the belt straddles the Allegheny front with part of the exposure within the broadly folded rocks of the Appalachian plateau region and part within the more tightly folded rocks of the Valley and Ridge province. In south-western Virginia, Tennessee and Alabama, the eastern outcrop belt is mainly in the Valley and Ridge province to the east of the Allegheny front. From north-western Pennsylvania to central New York in the northern Appalachian plateau region, the rocks of Devonian age form their broadest exposure belt. Westward, in Ohio, the Devonian rocks crop out along the east side of the Cincinnati arch in a belt that narrows southward to central Kentucky. This belt nearly coincides with the western margin of the Appalachian Basin. In Kentucky, the exposed Devonian rocks wrap around the Jessamine dome trending westward to the Illinois Basin (Fig. 12). Southward, in central Tennessee, a comparatively thin sequence of Devonian rocks, composed primarily of black shale, forms a narrow outcrop belt encircling the Nashville dome (Fig. 12). Within the Appalachian Basin, the Devonian shale sequence underlies approximately 128,000 square miles.

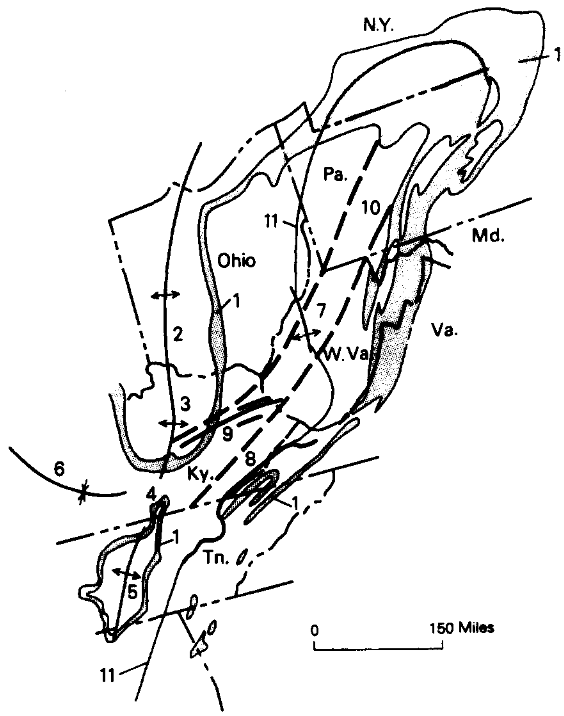

Fig. 12. Map showing structural elements and Devonian outcrop belt in the Appalachian Basin. (1) Devonian outcrop belt, (2) Cincinnati arch, (3) Jessamine dome, (4) Cumberland saddle, (5) Nashville dome, (6) Illinois Basin, (7) Burning Springs anticline, (8) Pine Mountain fault, (9) Kentucky River, Irvine–Paint Creek fault zone, (10) Rome trough, heavy dashed lines represent faults bounding the graben, (11) western limit of thrusting.

Much of the exposed Devonian shale sequence, except along the eastern folded margin, has a low regional dip into the central portion of the Appalachian Basin. The dip for the base of the Devonian shale sequence ranges from approximately 80 ft per mile in central new york to approximately 40 ft per mile in Ohio and Kentucky. Because of the folding along the eastern margin of the basin, the dip of the exposed rocks is considerably steeper and more variable than other parts of the basin.

Significant tectonic features

The major tectonic features within that part of the Appalachian Basin underlain by the Devonian black shale sequence are the Rome trough, the Kentucky River and Irvine–Paint Creek fault zones, and decollements and their associated features (Fig. 12). All of these features, to varying degrees, have some structural effect on the black shale sequence.

The Rome trough is a linear normal fault-bounded graben in pre-Cambrian basement rocks of the basin (Fig. 12). The north-east-trending structure is about 30–50 miles wide and 600 miles long. It extends from central Kentucky through West Virginia into central Pennsylvania. A general configuration of the structure has been defined by deep-drilling records in Kentucky and western West Virginia; however, in northern West Virginia, Ohio and Pennsylvania, basement tests are lacking and the configuration of the Rome trough is less well known (Harris, 1978). Harris suggests that the Rome trough is part of a much larger structure which may extend to the Moorman syncline of western Kentucky and the Mississippian embayment area. He referred to this combined graben structure as the Eastern aulacogen.

Hoffman *et al.* (1974) describe a series of development stages for the aulacogens of the Canadian Shield. Harris (1978) recognized and applied the stages of aulacogen development of Hoffman *et al.* (1974) to the Rome trough. Generally, the graben, transitional, and broad downwarp stages are recognized by Harris as having taken place from Cambrian to Silurian time. In Devonian time, the southern half of the trough was apparently locked, however, in the northern part; stratigraphic evidence in the form of abrupt thickening of the Middle and Upper Devonian shale sequence across the trough suggests that some reactivation took place. Reactivation appears to have taken place later in the southern half of the trough where surface rocks of Pennsylvanian age have been cut by normal faults.

Aside from the effects on the sedimentation of the rocks of Middle and Late Devonian age deposited across its northern half, the Rome trough may be related to the natural fracture system in the Devonian shales in the vicinity of the Kentucky–West Virginia State line. Because of low permeability and porosity of the black shales, the necessity of natural fractures is critical to their gas production. The position of the Devonian black shale gas fields in eastern Kentucky and West Virginia relative to the Rome trough suggests that the fracture porosity in the Devonian shales is a result of reactivation of the trough faults (Harris, 1978).

The Kentucky River and the Irvine–Paint Creek fault systems (Fig. 12) of central and eastern Kentucky are part of the Rome trough complex. These fault systems are the only known surface manifestation of the high-angle normal faults of Rome trough graben complex. The Kentucky River system forms the north-west boundary of the Rome trough. The Irvine–Paint Creek system, which is south of the Kentucky River fault zone, is within the trough and is probably the surface expression of faults bounding a stair step block in the trough. These fault systems intersect the Devonian black shales at the surface where the shales crop out around the Jessamine dome. Eastward, at the surface, the faults cut progressively younger rocks which overlie the Devonian shales. Along the surface trace of these faults the thickness of rock overlying the Devonian increases eastward to about 3000 ft. Any fracture system associated with these faults that would increase the Devonian shale porosity and permeability would probably allow the gas to bleed to the surface through the 3000 ft of cover. The faults were probably active during all stages of the aulocogen development throughout the Paleozoic.

Near the close of the Paleozoic, the compressive forces of the Alleghenian orogeny produced a structural style of deformation characterized by low-angle, bedding-plane decollements and associated splay faults, fractures and folds.

In the eastern part of the basin, outside the study area, the master decollements are found in the lower Paleozoic rocks translating those rocks westward to a point where movement could no longer be sustained at that stratigraphic level. Movement was then accomodated by smaller cross-cutting overthrusts and splays and/or by transferring the decollement by ramping to a stratigraphically higher incompetent zone that will accomodate the thrusting. On the basis of the stratigraphic position of these decollements, Milici (1980) categorized the detachments into lower- and upper-level decollements. The lower-level decollements rise along cross-cutting ramps and repositioned in a higher stratigraphic sequence to become upper-level decollements. Lower-level decollements generally are found east of the Allegheny front and east of the study area in Cambrian and Ordovician rocks. West of the Allegheny front the detachments are upper-level that involve thrust sheets of Silurian, Devonian, and younger Paleozoic rocks. The approximate western limit of the effects of the upper-level thrusting is shown as No. 11 in Fig. 12. Locally these upper-level decollements and associated deformations create significant structures critical to the hydrocarbon potential of the Devonian black shales and related rocks. Milici (1980) delineates the areal extent and stratigraphic position of the major decollements. There are three areas where upper level decollements in upper Paleozoic rocks have, to varying degrees, an influence on the Devonian black shales. The first and largest area includes those parts of West Virginia, Pennsylvania, and New York within the study area and east of the western limit of thrusting (Fig. 12). In this area, the main decollement is in the upper part of the evaporite deposits of late Silurian age. Splay faulting, folding, and fracturing resulting from the detachment produced structures that shattered and fractured the Devonian black shales. The Burning Springs anticline (Fig. 12) and its associated folds and splay faults is an example of such structures that are a result of impedence of movement in an upper-level decollement near the western edge of the incompetent Silurian transport beds. Structure–contour maps that show dislocations of selected black shale units are indicative of deformation associated with the formation of the Burning Springs anticline. Faults mapped in the black shales of western New York and Pennsylvania are also the result of thin-skinned deformation above the decollement zone in the Silurian.

East of the area of this report, in Fayette, Mercer, Monroe and Summers Counties in eastern West Virginia, is a relatively smaller region where Milici (1980) indicates a decollement in the Middle Devonian rocks. A third area is the pine Mountain Overthrust block (Milici, 1980) (Fig. 12). Here the upper-level decollement is within the lower part of the black Chattanooga Shale of Devonian age.

The structural effects that decollements might have on black shales are better understood by knowing some of the significant deformation features of thin-skinned tectonics. Important are the structural features of the decollement zone in the allochthonous plate and the structures resulting from abondonment or change of stratigraphic level by a decollement.

Decollement zones of the thin-skinned style of deformation in the southern Appalachians have a consistent recognizable strain fabric. Harris and Milici (1977) first called attention to this characteristic fabric of thin-skinned deformation in their study of an upper-level decollement zone near Dunlap, Tennessee. They defined the fabric of this zone as consisting of a basal detachment fault overlain by two distinct zones of deformed strata.

The lower zone, termed the broken formation zone, is bounded by subsidiary thrusts or detachment faults and is composed of segmented and distorted elongate bodies or rock cut by shear and rotational faults in addition to a pervasive fracture system.

The upper fractured zone is considerably less deformed, grading from the more intensely deformed lower broken zone upward through a zone dominated by splay and normal rotational gravity faults. The intensity of deformation decreases upwards to the point where the strata are relatively undeformed above the upper-fractured zone. The larger the amount of movement, the greater the thickness of the total disturbed zone above the decollement (Harris, 1981).

Harris (1981) applied these stress patterns of the deformed zone above the Pine Mountain thrust fault (Fig. 12), in south-western Virginia and eastern Kentucky, to explain the gas production from the Devonian shales in the thrust-sheet sequence. In the north-eastern part of the thrust block, the black organic-rich Chattanooga Shale is overlain by the Bedford Shale and Berea Sandstone. The decollement is positioned near the base of the incompetent Chattanooga Shale. Gas production is from the fractured Berea Sandstone, regardless of the position of the wells relative to local folds within the thrust sheet. According to Harris (1981), the black shale is the source of the gas and the Berea is a fractured-blanket-reservoir in the fractured formation zone above the Pine Mountain thrust fault. The identification of structural patterns in the deformed zone above decollements (Harris and Milici, 1977; Harris, 1981) elsewhere in the basin may identify fractures formed by thin-skinned upper-level detachments that may favorably affect gas production by increasing the porosity and permeability of the Devonian black shale and associated brittle beds.

Abandonment takes place when the rocks above the decollement can no longer continue lateral translation along the present stratigraphic position of the detachment. All possible variations may be found from total abandonment of movement along a specific detachment zone to partial abandonment with translation accommodated in part along the existing detachment and in part by newly created faults and folds. Complete abandonment takes place when the translation along a lower-level decollement is transferred by a tectonic ramp to an upper-level decollement. Abandonment is due to an impediment causing a deflection and in some instances a bifurcation of the detachment surface. Causes of impediment are (1) tectonic melanges formed in the detachment zone, (2) ramps in the basement reflected in the sedimentary rock of the detachment zone, and (3) increased friction due to lithologic change or variation in the detachment zone strata.

The abandonment process, in which the decollement seeks another stratigraphic level conducive to more efficient translation, creates rootless folds, antithetic and synthetic splay faults, and associated fractures (Harris and Milici, 1977, Figs. 8–10, Plates 2, 5, and 7; Milici, 1980, Plate 1). Abandonment structures that involve the Devonian black shale source beds produce fracture porosity and permeability, thus freeing and mobilizing the adsorbed gas. The fracture prosity and permeability create reservoirs within the source beds as well as migration pathways to other fracture-induced or previously existing reservoirs. A significant example is the Burning Springs anticline at the western limit of thrusting (Fig. 12). The decollement is within the Silurian evaporite sequence which is changing facies causing an impediment. The restricted westward translation along the decollement is compensated by antithetic and synthetic splay faulting and fracturing that enhances the Devonian shale gas production in the allochthonous plate. Similar tectonics evolved with the decollement in the Silurian evaporite section in New York and is most likely responsible for the faulting of the Devonian black shales in that area.

REFERENCES

Claypool G. E. and Stone A. W. (1979) Organic carbon content of Devonian black shale sequence sampled in drill cuttings from eighteen wells in western Pennsylvania. *U.S. Geol. Sur. Open-File Rep.*, No. 79-1665, 10 pp.

Claypool G. E., Hosterman J. W., Malone D. R. and Stone A. W. (1980) Organic carbon content of Devonian shale sequence sampled in drill cuttings from twenty wells in southwestern New York. *U.S. Geol. Surv. Open-File Rep.*, No. 80–810, 23 pp.

Colton G. W. (1970) The Appalachian basin—its depositional sequences and their geologic relationships. In *Studies of Appalachian Geology, Central and Southern* (Edited by Fisher G. W., Pettijohn F. J., Reed J. C. and Weaver K. N.), pp. 5–47. John Wiley, New York.

Conant L. C. and Swanson V. E. (1961) Chattanooga Shale and related rocks of central Tennessee and nearby areas. *U.S. Geol. Surv. Prof. Pap.*, No. 357, 91 pp.

Goddard E. N., Trask P. D., Deford R. K., Rove O. N., Singewald J. T. Jr and Overbeck R. M. (1948) Rock Color Chart. Washington, D.C., National Research Council, 6 pp. (Republished by Geological Society of America, 1951.)

Harris L. D. (1978) The eastern interior aulacogen and its relation to Devonian shale-gas production. In *Second Eastern Gas Shales Symposium*, Preprints, Vol. 2, pp. 55–72. U.S. Department of Energy, Morgantown Energy Technology Center, METC/SP-78/6.

Harris L. D. (1981) Fracture system in the eastern overthrust belt. *U.S. Geol. Sur. Open-File Rep.*, No. 81-1129, 19 pp,

Harris L. D. and Milici R. C. (1977) Characteristics of thin-skinned style of deformation in the southern Appalachians and potential hydrocarbon traps. *U.S. Geol. Sur. Prof. Pap.*, No. 1018, 40 pp.

Hass W. H. (1956) Age and correlation of the Chattanooga Shale and Maury Formation. *U.S. Geol. Surv. Prof. Pap.*, No. 286, 47 pp.

Hoffman P., Dewey J. F. and Burke K. (1974) Aulacogens and their genetic relationship to geosynclines, with a proterozoic example from Great Slave Lake, Canada. In *Modern and Ancient Geosynclinal Sedimentation* (Edited by Dott R. H. Jr and Shaver R. H.), pp. 38–55. Society of Economic Paleontologists and Mineralogists, Special Publication, No. 19.

Hosterman J. W. and Whitlow S. I. (1981a) Munsell color value as related to organic carbon in Devonian shale of Appalachian basin. *Am. Assoc. Pet. Geol. Bull.* **65**, 333–335.

Hosterman J. W. and Whitlow S. I. (1981b) Clay mineralogy of Devonian shales in the Appalachian basin. *US Geol. Surv. Open-File Rep.*, No. 81-585, 170 pp.

Kepferle R. C., Pollock J. D. and Barron L. S. (1983) Organic-matter preservation in Chattanooga shale: revised Late Devonian correlations, Kentucky and Tennessee (abstr.). *Am. Assoc. Pet. Geol. Bull.* **67**, 495.

Larese R. E. and Heald M. T. (1977) Petrography of selected Devonian shale core samples from the CGTC 2043 and CGTC 11940 wells, Lincoln and Jackson Counties, West Virginia. *U.S. Energy Research and Develop. Admin., Morgantown Energy Res. Cent. Contractor Rep.*, No. MERC/CR-77/6, 27 pp.

Maynard J. B. (1981) Some geochemical properties of the Devonian–Mississippian Shale sequence. In *Geological Society of America Field Trip Guidebooks* (Edited by Roberts T. G.), Vol. 2, pp. 336–343.

Milici R. C. (1980) Relationship of regional structure to oil and gas producing areas in the Appalachian basin. *U.S. Geol. Surv. Misc. Invest. Ser.*, Map I-917F.

Potter P. E., Maynard J. B. and Pryor W. A. (1980) *Sedimentology of Shale*, 306 pp. Springer-Verlag, New York.

Roen J. B. (1980) A preliminary report on the stratigraphy of previously unreported ash-fall localities in the Appalachian basin. *U.S. Geol. Surv. Open-File Rep.*, No. 80–505.

Roen J. B. (1981) Regional stratigraphy of the Upper Devonian black shales in the Appalachian basin. In *Geological Society of America Field Trip Guidebooks* (Edited by Roberts T. G.), Vol. 2, pp. 324–330.

Roen J. B. and Hosterman J. W. (1982) Misuse of the term "bentonite" for ash beds of Devonian age in the Appalachian basin. *Geol. Soc. Am. Bull.* **93**, 921–925.

Schopf J. M. and Schwietering J. F. (1970) The *Foerstia* zone of the Ohio and Chattanooga shales. *U.S. Geol. Surv. Bull.*, No. 1294-H, 15 pp.

Stenbeck T. V. (1981) Petrology. In *Stratigraphy of the Chattanooga Shale (Upper Devonian and Lower Mississippian) in Vicinity of Big Stone Gap, Wise County, Virginia* By Kepferle R. C., Potter P. E. and Pryor W. A.). *U.S. Geol. Surv. Bull.*, No. 1499, pp. 13–18.

deWitt, W. Jr and Colton G. W. (1959) Revised correlations of lower Upper Devonian rocks in western and central New York. *Am. Assoc. Pet. Geol. Bull.* **43**, 2810–2828.