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Frank R. Ettensohn and Lance S. Barron

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Prepared for

UNITED STATES DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
Morgantown, West Virginia 26505

Under Contract No. DE-AC21-76ET12040

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DOE/METC/12040-2
Distribution Category UC-92a

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DEPOSITIONAL MODEL FOR THE DEVONIAN-MISSISSIPPIAN BLACK-SHALE SEQUENCE OF NORTH AMERICA: A TECTONO-CLIMATIC APPROACH

by

Frank R. Ettensohn[1] and Lance S. Barron[2]

ABSTRACT

The Devonian-Mississippian black-shale sequence of North America is a distinctive stratigraphic interval that reflects a low rate of clastic-sediment influx, high organic productivity, and development of anaerobic conditions in a stratified water column within an inland, equatorial, epicontinental sea. The origin of these conditions apparently is related to the interaction of tectonism and climatic conditions unique to North America at this time.

Black-shale deposition was coincident with and related to the continent-continent collision that caused the Acadian Mountains. This rising mountain belt developed across the equator just east of the "Black-Shale Sea", and effectively completed enclosure of the sea and became the major source of clastic sediments. Collision and resulting uplift, however, were apparently episodic. During periods of uplift, the mountains acted as a barrier to the moisture-laden trade winds converging on the equator; this caused rainshadow conditions west of the mountains and reduced clastic influx into the "Black-Shale Sea." In the absence of clastics, organic-rich muds were deposited throughout the sea.

Concurrent with and related to the periods of uplift and subduction, were episodes of widespread cratonic subsidence and transgression, which were especially effective in the linear peripheral or foreland (Appalachian) basin west of the mountains. During these periods of subsidence and transgression, the sediment-starved "Black-Shale Sea" migrated eastward over parts of the Catskill Delta and westward over exposed parts of the craton. During intervening periods of tectonic quiesence, subsidence abated and the mountains were lowered by erosion to the point that trade winds crossed unimpeded and delivered precipitation to western parts of the mountains near the equator. This resulted in a vast influx of clastics and rapid westward deltaic progradation into the "Black-Shale Sea." Seven such major cycles of alternating of black shale and coarse clastics are present in the Catskill Delta complex.

Few of the deltaic progradations migrated westward beyond the peripheral basin because of its confining effects, so that even during rainy periods, sediment-starved conditions persisted in cratonic portions of the

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sea. Progressive deepening in cratonic portions of the sea combined with the equatorial nature of the sea caused a stratified water column (pycnocline) to develop which prevented oxygenation of the deeper bottom waters. The organic-rich muds deposited in the sea were preserved in the anaerobic, azoic conditions that resulted. Eventually the sea deepened to the point that upwelling oceanic waters entered from the continental margin in the Ouachita area.

The "Black-Shale Sea" and its organic-rich muds were essentially the result of subsidence and sediment-starved conditions created by the collisional event which formed the Acadian Mountains. The interaction of these mountains with the atmospheric circulation patterns of the time is an important aspect of black-shale deposition which apparently has never been examined before.

This study was supported under contract number DE-AC21-76ET12040 from the Department of Energy, Morgantown Energy Technology Center.

KEY WORDS: Devonian-Mississippian black-shale sequence, North America, sediment-starved, high organic productivity, anaerobic, stratified water column, "Black-Shale Sea", rainshadow, upwelling, Acadian Mountains.

INTRODUCTION

Although black shales are not uncommon in the geologic record, the Devonian-Mississippian black-shale sequence of North America is unusual in its widespread distribution and homogeneity. This black-shale sequence, though known by many stratigraphic names, forms a significant and easily recognized stratigraphic marker horizon that is continuous throughout much of midcontinental United States with extensions into the Southwest and into west-central Canada. These shales are thickest in the area of the Appalachian Basin where they may compose as much as one-fourth of the Devonian sedimentary sequence. These shales are also unusual because of their high organic-matter content, high radioactivity, and paucity of fossils, especially benthic forms. In addition, they are important sources of natural gas (Avila, 1976) and may in time be economically viable sources for some radioactive elements (Glover, 1959; Conant and Swanson, 1961; Breger and Brown, 1962) and some forms of synthetic fuel. Yet, despite the long-standing interest in these shales and much intensive study, the origin of these shales is still uncertain. Basically, there are two schools of thought regarding the origin of these shales: one suggesting a shallow-water origin (Linney, 1882, 1884; Grabau, 1917; Branson, 1924; Hard, 1931; Twenhofel, 1939; Stockdale, 1939; Campbell, 1946; Wells, 1947; Conant, 1955; Conant and Swanson, 1961; Hallam, 1967; Lewis and Schwietering, 1971; Schwietering, 1978) and another suggesting a deep-water origin (Newberry, 1873; Shaler, 1877; Clarke, 1903; Schuchert, 1910; Reudemann, 1934, 1935; Woodward, 1943; Rich, 1951; Byers, 1977, 1979). Some workers, (Hard, 1931; Provo, 1977), however, suggested that water depth is not necessarily a controlling factor in the deposition of these shales. They emphasize instead the necessity of a model which can account for the production and preservation of abundant organic matter in a marine environment. The marine conditions conducive toward the production and preservation of abundant organic matter have been discussed recently by Heckel (1977) and Byers (1977), but more fundamental yet, are the regional controls that permit such conditions to develop. These controls will also be examined.

Since these interpretations were originally published, much additional information on the sedimentological, paleontological, stratigraphic, tectonic, and paleoclimatic framework of these shales has accumulated. Much of this information has accumulated as a result of the Eastern Gas Shales Project under Department of Energy sponsorship. However, this additional information has also made us more aware of problems which must be explained before the origin of these shales can be fully understood. Foremost among these problems are:

1.) A means of producing and preserving the vast amounts of organic debris present in the shale.

2.) The widespread, homogeneous nature of the shale.

3.) The unusual concentrations of various heavy metals in the shale.

4.) The unusual nature of the fauna and flora found in the shales.

5.) The presence of prominent and widespread green-shale horizons in the black-shale sequence.

6.) The relationship between the black shales and contiguous units.

This study integrates both new and old evidence to provide new lines of evidence, explain the above problems, and develop a depositional model which can explain the origin of the shale in terms of the known sedimentologic, paleontologic, stratigraphic, tectonic, paleoclimatic, and paleogeographic framework. The presently available evidence in each of these areas will be examined briefly in following sections. The model is developed with particular reference to eastern Kentucky where much of the new evidence was collected.

ACKNOWLEDGEMENTS

We wish to give special thanks to Dennis R. Swager, Michael L. Miller, Scott B. Dillman, and Gerald Markowitz, former research assistants in the black-shale program at the University of Kentucky, whose theses provided valuable new data for our model. We also wish to thank Roy C. Kepferle, Edward N. Wilson, and Philip H. Heckel for their trips into the field with us and valuable discussion. Our special gratitude goes to Jane T. Wells who typed and proofed the manuscript and to Danna L. Antoine, who drafted the figures.

Funding for this study was provided under contract number DE-AC21-76ET-12040 from the Department of Energy, Morgantown Energy Technical Center.

Sedimentary, Paleontologic, Stratigraphic Framework

The Upper Devonian-Lower Mississippian black-shale sequence is one of the most distinctive and well-known stratigraphic intervals in east-central and midwestern United States. The sedimentology and stratigraphy (Campbell, 1946; Ellison, 1950; Hoover, 1960; Conant and Swanson, 1961; Oliver and others, 1967), and petrology (Patchen and Larese, 1976; Miller, 1978; Harvey and others, 1978; Samartojo and Waldstein, 1978; Potter and others, 1980) of these shales are fairly well-known and suggest some of the characteristics below as being most distinctive.

The black-shale sequence is nearly everywhere unconformable with underlying units, which range in age from Middle Ordovician to Middle Devonian. Moreover, the unconformity surface is relatively flat and smooth, and over some areas the black shales exhibit uniformity in thickness and composition, suggesting a pre-depositional peneplain (Conant and Swanson, 1961). In some areas, this surface may have been karstic (Carmen and Shillhan, 1930). Basal parts of the black-shale sequence that overlie this surface typically exhibit a basal lag, sandstone or "bone bed" varying in thickness from a few millimeters to a few meters (Fig. 1). Locally, this part of the sequence may be thick enough that it has a member or formational status (e.g., Misener, Sylamore, Hillsboro (?), Hardin, Duffin/Harg/Ravenna facies). These basal beds vary in composition from a silty clay to a distinct sandstone containing fine to very coarse sand-size quartz grains, phosphatic pellets and nodules, glauconite rock fragments, plant spores, small pyritized gastropods, fish bones and teeth, conodonts, and wood fragments. The cement may be calcareous, siliceous, siliceous-pyritic, or phosphatic. Not only do lag horizons occur at the bases of the black-shale sequences, but we have noted their presence wherever major black-shale units sharply overlie green-shale units

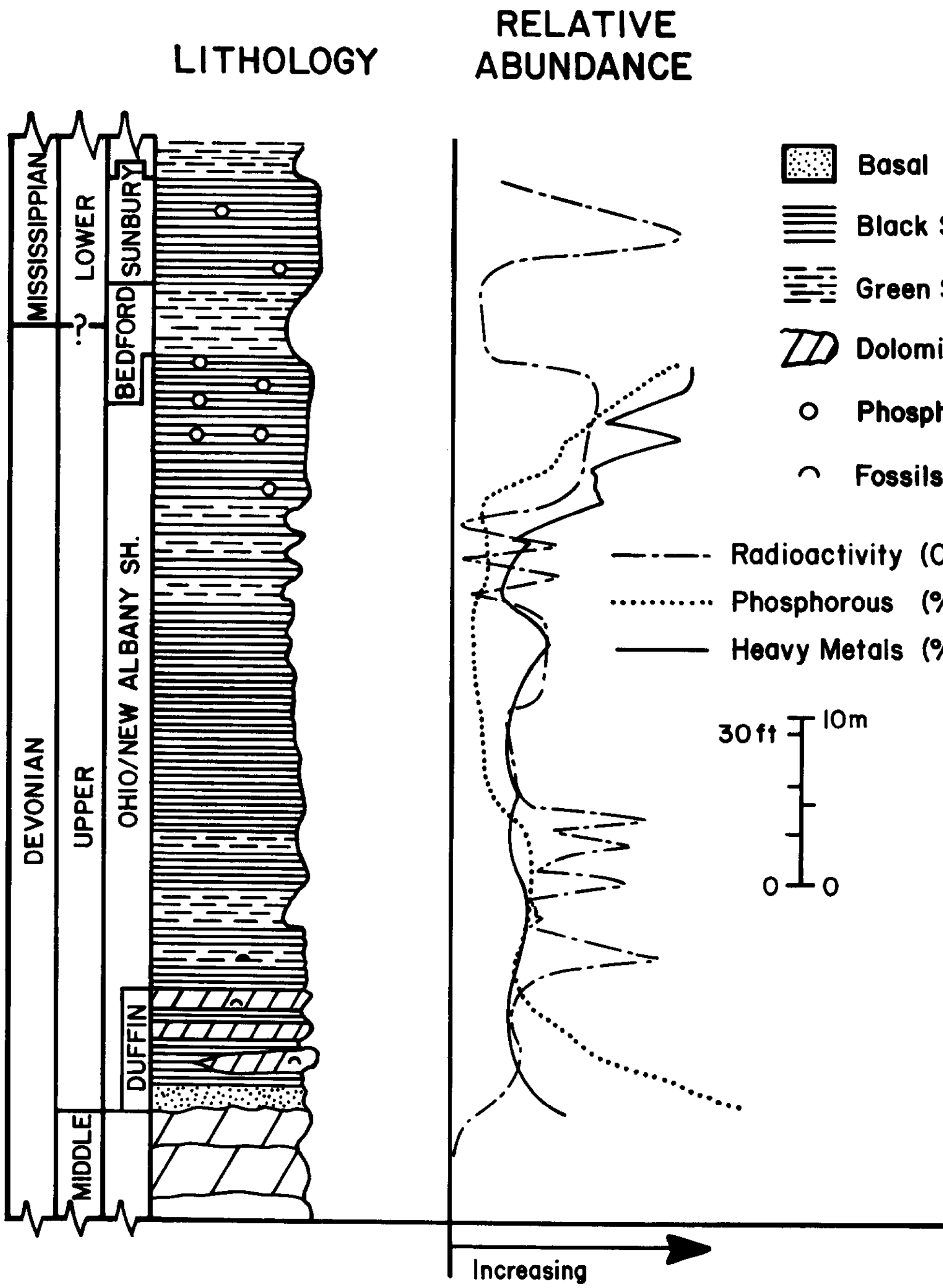


Figure 1. Generalized, composite black-shale sequence from east-central Kentucky showing the distribution of lithologies and the relative vertical abundances of radioactivity, substances, phosphorous, and heavy metals (data from Swager, 1978, and Markowitz, 1979).

within the black-shale sequence itself. Conkin and Conkin (1975) suggest that these lag horizons mark paracontinuities or diastems representing periods of little sedimentation followed by rapid transgression. Although Conkin and Conkin suggest that paracontinuities reflect very shallow, near-shore conditions, we suggest that in parts of the black-shale sequence they may also represent deeper, subaequeous sedimentational diastems.

The black-shale sequence is generally characterized by two dominant lithologies, an organic-rich, brownish-black to black, fissile shale and an organic-deficient, gray to green clayey shale. The brownish-black to black shales are highly carbonaceous and owe their dark coloration to the dominance of organic matter over clay. The shales are also notable for their high radioactivity and high concentrations of trace elements. By volume, organic matter comprises approximately a third of the rock, which is consistent with the 15 to 20 percent organic matter by weight and by petrographic analysis (Conant and Swanson, 1961, p. 43-44; Potter and others, 1980, Table 4). The organic matter consists primarily of organic films on clay-particle aggregates, spores, algae, woody material, and opaque macerals (Miller, 1978). This organic material always occurs in close association with angular, silt-size and clay-size quartz grains. The quartz occurs either randomly dispersed within the organic matter or as paper-thin laminae, which give the black shale a pronounced fissility upon weathering. Individual laminae range in thicknesses from .01 to 5.0 mm. Unweathered shale seen in cores is typically massive and uncleavable, exhibiting little of the fissility seen in outcrops. Most of the quartz appears to be concentrated in the black organic-rich shales; quartz comprises 20 to 25 percent of these shales (Conant and Swanson, 1961). Although clays may compose up to 50 percent of some black shales (Potter and others, 1980), clays are generally much less abundant, usually around 10% (Conant and Swanson, 1961; Miller, 1978).

Finely disseminated, microscopic phosphate occurs throughout most of the black shale (Conant and Swanson, 1961), but in upper parts of the black-shale sequence, the phosphate also occurs as concretionary bodies which vary in shape from small spheroidal concretions and ellipsoidal nodules a few centimeters in diameter to large, irregular amoebaform bodies with long dimensions approaching a meter (Fig. 1). A phosphate-rich zone of phosphatic nodules, pellets, fossils and cements also typically occurs at the base of a sequence associated with the basal lag (Fig. 1). The basal contacts of black-shale units are almost always sharply defined, whereas vertical and lateral contacts are typically gradational into gray or green shales.

Much has been written about the paleontology of this shale sequence, and this is the topic of an extensive bibliography by Barron and Ettensohn (In press). Marine body fossils are relatively rare in the black shales, but those that are found usually indicate a nektic, planktic, epiplanktic, or necroplanktic life mode. Benthic forms are especially rare throughout most of the black shales. When benthic forms do occur, however, they always occur near the base of the sequence (Savage, 1930, 1931; Campbell, 1946; Lineback, 1968; Fig. 1) or in the eastern, shoreward intertonguings with the Catskill Delta complex (Sutton and others, 1970; Byers, 1977). These low-diversity communities are typically composed of eurytopic brachiopods, gastropods and pelecypods. *Lingula* and other inarticulate brachiopods which are commonly associated with the black shales were probably epiplanktic on logs (Rudwick, 1965).

The basal parts of cratonic black-shale sequences may also exhibit interbedded, fossiliferous carbonates and coarser clastics (basal lag?)

exhibiting ripple marks and flaser beds. The Duffin/Harg/Ravenna facies of eastern Kentucky is an example of this (Foerste, 1906; Campbell, 1946).

Interbedded with the black shales in many areas are irregular bedded green to gray, organic-deficient mudstones and shales (Fig. 1). In the green to gray shales, laminae are absent or poorly developed. In contrast to the black shales, the organic content in these shales decreases to approximately five percent, whereas the percentage of clays increases to nearly 80 percent. Except for local siltstone lenses and beds, the percentage of quartz is drastically reduced, generally averaging 5 to 10 percent (Miller, 1978). These shales are also relatively nonradioactive (Fig. 2). Compared to the black shales, the diversity of life in these shales is markedly increased. Although, similar nektic, planktic, epiplanktic, and necroplanktic forms still occur, they are not as abundant as in adjacent black shales. Unlike the black shales, however, benthic fossils do occur, and include _in situ_ _Lingula_ and a variety of trace fossils, as well as a micromorph fauna consisting of ostracods, cephalopods, pelecypods, gastropods, and Foraminifera (Barron and Ettensohn, 1980).

Stratigraphically, even the most homogeneous black-shale sequence can be divided into distinctive units based on radioactivity (Ettensohn and others, 1979). Seven of these units were initially designated in the Ohio-New Albany-Chattanooga shale sequence (Fig. 2) from the subsurface of Ohio and eastern Kentucky by Provo (1977). These units were subsequently correlated with named surficial units and traced into the black-shale outcrop belts of Kentucky and Ohio (Swager, 1978; Provo and others, 1978), as well as eastward into the subsurface of Virginia, West Virginia, eastern Ohio, Pennsylvania, and New York where they pinch out into coarser basinal and slope-edge clastics (Chagrin, Brallier, and "Portage Facies"), which in

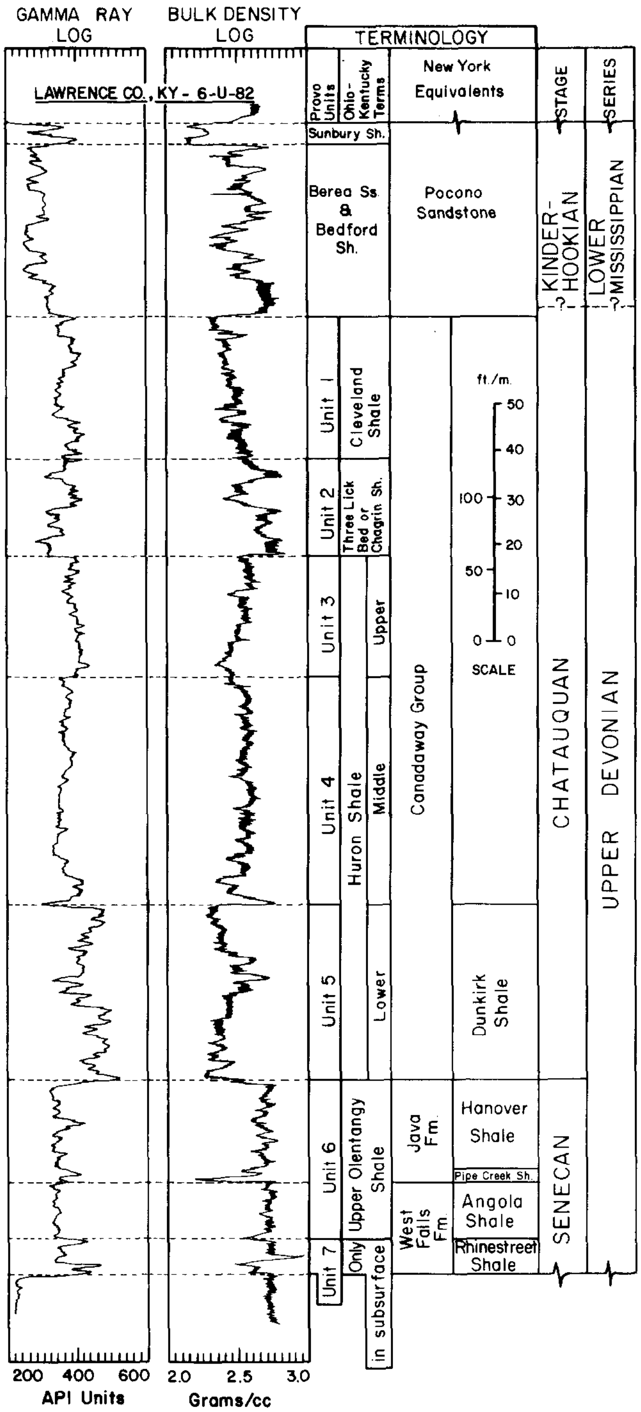


Figure 2. Radioactive stratigraphy and stratigraphic nomenclature from eastern Kentucky showing correlations with the New York section. Units 2 (Three Lick - Chagrin) and 6 (Upper Olentary - Angola Shale/Hanover Shale) and the Bedford-Berea sequence contain significant amounts of less radioacitve green shale and are represented by prominent negative deviations.

turn grade eastward into even coarser marginal-marine and terrestrial shelf-edge clastics ("Chemung and Catskill" facies) (Piotrowski and Krajewski, 1977; Wallace and others, 1978; Kepferle and others, 1978; Roen and others, 1978a,b; Potter and others, 1980). Of course, this sequence of transitions represents major time-transgressive facies changes that occurred during deposition of the Catskill Delta in the Middle and Late Devonian and in the Early Mississippian and this has been well documented in many earlier studies (e.g., Barrell, 1913, 1914; Caster, 1934; Broughton and others, 1962; Rickard, 1975).

Because the Catskill delta experienced periods of progradation, punctuated by periods of transgression, a distinct sequence of cyclic lithologies developed (Fig. 3). Because of varying distances from the source area and differences in the amount of clastic input during different phases of deltaic progradation, the vertical sequences are not everywhere similar throughout the distribution of the black shale,as might be expected. Figure 3 demonstrates some of the regional variations in the black-shale sequence..

Near the eastern source area, the sequence consists of cyclic alternations of unfossiliferous, black, fissile shale with intervals of green to gray shale, siltstone and sandstone, which may be very fossiliferous; locally, fossiliferous limestones may be interbedded with the green to gray shale. In an eastward direction, the black shales eventually tongue out into the coarser clastics, whereas the coarser, clastic intervals pinch out westwardly into the black shales. In general, there is an eastward change to coarser and coarser clastics and a gradation from black shales in the west to redbeds in the east.

Because few of the coarser clastic intervals prograded beyond the Appalachian Basin, the black-shale sequence in eastern and east-central parts of the adjacent craton are largely unfossiliferous fissile black

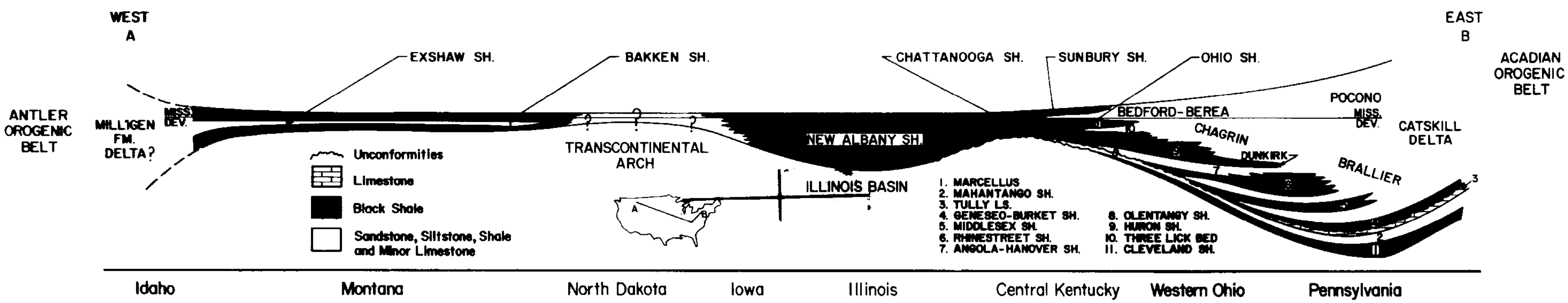


Figure 3. Schematic cross section showing the distribution of black shales and related facies from New York to Idaho. The thin Pipe Creek black shale separates the Angola and Hanover Shale (7), but is too thin to show on the section. Not drawn to scale (adapted from Gutschick and Moreman, 1967; and Potter and others, 1980

shales with two or three, thin unfossiliferous, but bioturbated, green-shale intervals. In central and western parts of the craton, where the green shales and coarser clastics from eastern sources have pinched out (Fig. 3), the sequence may be composed entirely of black, fissile shale. Some of these black-shale sequences on western parts of the adjacent craton may contain thin green-shale intervals derived from sources other than the Catskill Delta.

In the Catskill Delta and adjacent parts of western Pennsylvania and Ohio, seven major black-shale units (Marcellus, Geneseo, Middlesex, Rhine-street, Huron-Dunkirk, Cleveland, and Sunbury) and intervening clastic units occur. Each successive black-shale unit overlaps underlying black-shale units on the western margin of the Appalachian Basin as they were progressively displaced westwardly by prograding wedges of green shale and coarser clastics (Fig. 3). Only the last three black-shale units (Huron-Dunkirk, Cleveland, and Sunbury) and the last three coarser clastic wedges (Upper Olentangy-Hanover-Angola, Chagrin-Three Lick, and Bedford-Berea) effectively migrated beyond the Appalachian Basin onto parts of the Cincinnati Arch and beyond. The earlier black-shale units and intervening coarser clastic intervals are essentially restricted to the Appalachian Basin (Fig. 3).

Tectonic Setting

It is difficult to discuss a depositional model for the Upper Devonian-Lower Mississippian black shales of the east-central United States without some reference to the regional tectonic framework, for much of the black-shale deposition occurred during and at the end of a major continent-continent collisional event known as the Acadian Orogeny. This collisional event not only created the Acadian highlands in what is now New England and the Maritime provinces of Canada, from which most of the Upper Devonian clastics in this area were derived, but also probably caused reactivation of certain basement structures and periods of broad epeirogenic uplift and subsidence which influenced black-shale deposition.

Devonian-Mississippian black-shale deposition occurred during a period of global transgression or submergence which accompanied the Acadian and other coeval tectonic events characterized by convergence at craton margins. The correspondence of global transgression with periods of plate convergence probably is not coincidental. Both Johnson (1971) and Sloss and Speed (1974) related periods of global transgression to periods of plate convergence during which spreading rates were accelerated. The relationship is twofold. During periods of accelerated spreading, spreading centers and adjacent ocean bottoms are typically elevated causing upward displacement of ocean waters and hence transgression (Johnson, 1971). At the same time, subduction beneath the involved continents caused differential subsidence of the craton and transgression (Sloss and Speed, 1974).

Although the Acadian event has been ascribed to a number of different plate-tectonic models, some involving different plates, we have chosen a model developed by McKerrow and Ziegler (1972) and later expanded on by Dewey and Kidd (1974) as best fitting the present evidence. Their tectonic scenario began with the Caledonian Orogeny in the Upper Silurian and lowermost Devonian. At this time, the Baltic Shield (Baltica) collided with North America-Greenland (Laurentia) thereby partially closing the Proto-Atlantic or Iapetus Ocean from northern Scandanavia to Ireland. This resulted in the formation of the Caledonides and a larger continental mass known as Laurussia (see Ziegler and others, 1979, for reconstructions; Fig. 4). According to McKerrow and Ziegler (1972) and Dewey and Kidd (1974), however, the southern portion of the Proto-Atlantic did not close completely during the Caledonian Orogeny, which left the southern part of the former Baltica extending southwestward as a long peninsula. This peninsula is known as the Avalon-Massachusetts Peninsula (McKerrow and Ziegler, 1972) or as the Avalon Prong (Dewey and Kidd, 1974) and consisted of present-day eastern Newfoundland, eastern Nova Scotia, and eastern Massachusetts (Fig. 4). During the Middle Devonian, this peninsula was impacted against North America by collision with northwestern South America from Peru to Venezuela (Gondwanaland) resulting in the Acadian Orogeny (McKerrow and Ziegler, 1972; Dewey and Kidd, 1974; Fig. 4). Most major deformation was confined to the northern Appalachians from eastern Newfoundland to Pennsylvania (Rodgers, 1967) where the continent-continent collision had occurred. Collision occurred first to the northeast and with time extended to the southwest. According to Donohoe and Pajarie (1973) the orogenic event in the northeast may have begun as early as the late Early Devonian, but the main collisional event occurred during the late Middle and early Late Devonian. Nonetheless, the event apparently continued episodically into the Early Mississippian farther to the southwest (Rodgers, 1967). With the Acadian Orogeny, Baltica was completely welded to Laurentia and the last phase in the formation of the Old Red Sandstone Continent (Fig. 4) was completed.

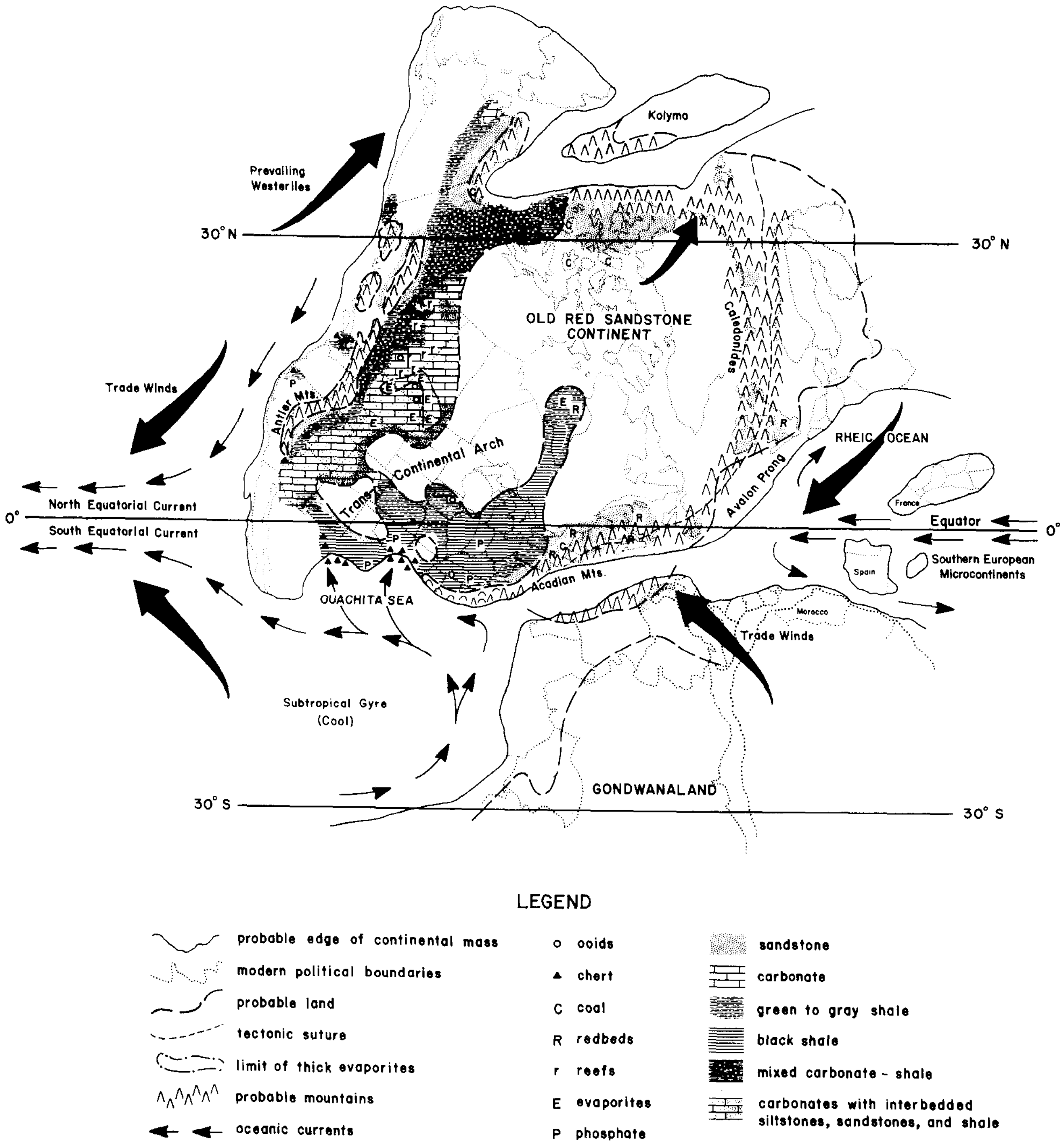


Figure 4. Generalized Late Devonian paleogeography and lithofacies for North America. Paleogeography summarized from McKerrow and Ziegler (1972), Seyfert and Serken (1973), Badham and Halls (1975), and Heckel and Witzke (1980); lithofacies largely from heckel and Witzke (1980).

In the southern Appalachians, there is also evidence of an Acadian orogenic event but the intensity of the event was less and the style of tectonism differed from that to the north. The Avalon Zone has been traced into the southern Appalachians (Williams, 1978) and evidence of deformation (e.g., Hatcher, 1978), volcanism (Dennison and Textoris, 1970, 1978) and granitic intrustion (e.g., Plavlides,1976) is present. Nonetheless, deformation and accompanying relief were not as great in the southern Appalachians as to the north, for very little post-orogenic sediment was produced. Most of the Upper Devonian sediments in the foreland basin of the southern Appalachians are either black shales or clastics derived from the northeast (Rodgers, 1967). It is unlikely that Acadian orogenic activity in the southern Appalachians resulted from continent-continent collision as in the north. A more likely cause is westward subduction beneath an island-arc system, microcontinents (rifted continental fragments), or a peninsular continental fragment (Hatcher, 1978).

In the northern Appalachians where continent-continent collision occurred, the sites of most intense deformation and tight suturing corresponded with projections or promontories in the irregular North American continental margin; in adjacent structural re-entrants, deformation was less intense and subsidence may have predominated (Dewey and Kidd, 1974; Thomas, 1977). Such promontories collided first and more intensely creating areas of great tectonic relief (Dewey and Burke, 1974; Dewey and Kidd, 1974). In this context, it is interesting to note that the position of the Catskill Delta, which apparently provided much of the fine-grained detritus found in the black shales, corresponds to the New York promontory (see Williams, 1978). Thick sequences of post-orogenic clastics derived from the tectonic highlands associated with this promontory accumulated in parts of the foreland or peripheral basin associated with adjacent structural re-entrants (Dewey and Kidd, 1974; Thomas, 1977). This accounts for the great thickness of Middle and Upper Devonian clastics found in the Catskill delta of Pennsylvania and southeastern New York (see Meckel, 1970; Thomas, 1977).

According to McKerrow and Ziegler (1972) and Dewey and Kidd (1974), the collisional event producing the Acadian Orogeny was followed by rifting, separation and south westward rotation of South America during the Late Devonian and Early Carboniferous. At the same time, however, the northwestward movement of Africa toward the southern European microcontinents (Fig. 4) caused these microcontinents to collide with east-central portions of Laurussia (Badham and Halls, 1975) and thereby maintained the compressional regime in the Acadian area. As a result, pulses of clastic progradation, some with a more northerly source area, continued to be debouched into adjacent parts of the foreland or peripheral basin. Not until the Late Carboniferous-Early Permian did extensive continental collision occur again, when northern Africa (Gondwanaland) collided with European and North American parts of Laurussia in the Hercynian and Alleghenian orogenies.

Paleogeography and Paleoclimatology

In the Middle Devonian, collision of Laurentia and Baltica resulted in a reassembled equatorial landmass called Laurussia (Ziegler and others, 1979; Bambach and others, 1980). Terrestrial or continental portions of this landmass have been called the Old Red Sandstone (ORS) Continent (e.g., Goldring and Langenstrassen, 1979; Fig. 4). Southeastern portions of the ORS Continent (present-day Canadian Maritime provinces and New England; Fig. 4) were bounded by the Acadian Mountains which apparently formed the southwestern part of a peninsula which extended partially down what is today the New England and mid-Atlantic coastline of the United States. Farther northward, the Acadian Mountains joined the Caledonide Mountains in what are parts of present-day Ireland, Scotland, Greenland, and Norway. This belt of mountains continued westward around northern Greenland into parts of the Canadian Arctic Archipelago. On the western margin of the continental landmass, the Antler orogenic highlands began to rise during the Late Devonian, as older Devonian and underlying oceanic rocks were deformed and subsequently obducted eastward onto the western margin of the craton (Poole, 1974).

Lying between the Antler orogenic belt to the northwest and the Acadian orogenic belt to the southwest was a large expanse of low-lying craton partially covered by epicontinental seas during the Late Devonian. Immediately cratonward of each belt, subsiding foreland, peripheral, or exogeosynclinal basins developed in which great thicknesses of flyschlike mudstone, siltstone, and sandstone with minor amounts of impure limestone accumulated. The intervening parts of the craton were generally low-lying with essentially little or no relief. Epeirogenic uplift during the late Early Devonian and again near the Middle-Late Devonian transition resulted in brief periods of emergence and erosional planation causing the low relief (Ham and Wilson, 1967). Although local domes and arches like the Cincinnati Arch were probably periodically emergent during the Late Devonian, none of these structures was apparently high enough or of sufficient duration to affect circulation in the cratonic seas for long. The only major structure which had this kind of effect was the Transcontinental Arch which extended southwestward from the Canadian Shield to New Mexico as a large peninsula or series of large islands (Fig. 4). This arch stood high enough during the Late Devonian that it acted as an emergent barrier or shoal area that prevented large-scale exchange of sediments and waters so that different sedimentary regimes developed on each side of the arch. On the northwestern side of the arch, carbonate deposition dominated, whereas the southeastern side was dominated by the deposition of black, euxinic muds. The euxinic epicontinental sea southeast of the Transcontinental Arch, hereafter called the "Black-Shale Sea", opened to the southwest into deeper oceanic waters, but in the northward direction, the sea progressively tapered to a narrow arm projecting into the area presently known as Hudson Bay (Fig. 4). The "Black-Shale Sea" was not only enclosed on the western side by the Transcontinental Arch, but also on the north by the Old Red Sandstone Continent, on the east by the Acadian Mountains, and on the southeast and south (Conant and Swanson, 1961; Breger and Brown, 1962; Cook and Bally, 1975) by a low-lying peninsula, which at times may have been joined to the emergent Ozark Uplift (Fig. 4). Most of these bordering lands were probably vegetated at one time or another (Beck, 1964). Hence, except for a southwestern outlet to the open ocean and a shallow-water connection across the Transcontinental Arch, the "Black-Shale Sea" was a nearly enclosed epicontinental sea.

Most workers agree that Laurussia was an equatorial landmass, but there is some difference regarding placement of the Devonian paleoequator. Smith and others (1973) interpreted the paleoequator to have run north of Greenland and northwest of Alaska, whereas many other workers (McElhinny, 1973; Woodrow and others, 1973; Seyfert and Sirkin, 1973; Dott and Batten, 1971; Lowe, 1975; Zonenshayn and Gorodnitskiy, 1977; Habicht, 1979) indicated that the paleoequator passed through southern Greenland, Hudson Bay and the Pacific Coast. Others, however, suggested that the paleoequator essentially paralled the eastern Atlantic coastline of the United States (Bain, 1963) or ran through northern Greenland and north-central Canada (Greiner, 1978). More recently, two new interpretations for paleoequator placement have been developed by Heckel and Witzke (1970) and Ziegler and others (1979), Scotese and others (1979), and Bambach and others (1980). Heckel and Witzke (1979) placed the Late Devonian paleoequator east of Alaska and ran it through British Columbia, Washington, Oregon, and California; their interpretation is based largely on climatic and sedimentological criteria. Heckel and Witzke (1979) not only provided new and intriguing interpretations about the placement of the Devonian paleoequator and climatic belts, but also discussed the inconsistencies of earlier paleoequator reconstructions. Heckel and Witzke did not consider, however, the newer reconstruction of Ziegler and others (1979), Scotese and others (1979) and Bambach and others (1980) which indicates that the Devonian paleoequator continued from the Canadian Maritime provinces through the central United States and Baja California (Fig. 4). This reconstruction is based on the integration of paleomagnetic, faunal, tectonic, and climatic evidence and appears to be more consistent with currently available evidence than does the reconstruction by Heckel and Witzke (1979).

The patterns and dynamics of atmospheric circulation have remained much the same since the beginning of the Phanerozoic (Drewry and others, 1974). Because atmospheric circulation and its modification by continental physiography ultimately exert a major control over the distribution of marine carbonates, evaporites, clastics, and certain organo-sedimentary structures such as reefs, the distribution of these sediments and structures can provide valuable paleogeographic and paleoclimatic implications for the Late Devonian (Heckel and Witzke, 1979). Heckel and Witzke have summarized the most important sedimentological patterns and have developed a set of reasonable paleogeographic inferences from them for the Late Devonian. However, we do not believe that these inferences can adequately explain Late Devonian black-shale deposition, which must have some basis in paleogeography and paleoclimatology. Using the same data as Heckel and Witzke (1979) and the paleoequator of Ziegler, Scotese, Bambach and their co-workers, an alternate set of paleogeographic and paleoclimatic inferences for the Late Devonian can be made which are consistent with modern patterns of oceanographic and atmospheric circulation and aid considerably in understanding black-shale deposition. We will now examine the distribution of carbonates, evaporites, reefs and other features.

Upper Devonian shallow-water carbonates in our interpretation are restricted to a warm, tropical-subtropical belt which is free of major clastic influx and located within 30 degrees of the equator (Fig. 4). Upper Devonian reefs are restricted to a similar belt. Precipitation of carbonate by both biological and physical means is greatly enhanced in this belt due to increased temperature and salinity (Lees, 1975; Heckel and Witzke, 1979; Habicht, 1979).

Evaporites typically form in restricted environments characterized by excessive evaporation. According to Lisitzin (1972) and Heckel and Witzke (1979) such arid conditions characterize the dry, tropical trade-wind belts occurring on either side of the equator within the carbonate belt (approximately 10 to 30 degrees North and South); evaporites are absent in the humid, equatorial belt (doldrums) because of dilution by excess precipitation. In our reconstruction, thick, Upper Devonian evaporites are restricted to latitudes 10 to 20 degrees north of the paleoequator in the dry, trade-wind belt in the rain-shadow of Caledonide mountains.

Clastics are most abundant in the rainy, humid zones where vast amounts of detrital sediments are supplied by weathering and erosion of adjacent land masses. These rainy zones include the humid, equatorial belt (doldrums) within 5 to 10 degrees of and on either side of the equator, the temperate storm belts ranging from approximately 35 to 60 degrees north and south of the equator, and windward sides of mountain ranges in the trade-wind belt (Strahler and Strahler, 1973; Heckel and Witzke, 1979). This arrangement of humid, clastic-rich belts means that the tropical carbonate belt may be split along the equator by an equatorial clastic belt and bounded poleward by temperate clastic belts (Heckel and Witzke, 1979).

Heckel and Witzke (1979, Fig. 3c) suggested that the Late Devonian equatorial and temporate clastic belts nearly coincided with the Antler and Acadian mountain belts respectively. They argued that the immense detrital sequences associated with these belts required great amounts of rain which necessitate presence in one of the two humid, clastic belts. We do not question the necessity of rain nor the immensity of the clastic deposits associated with the Antler mountain belt, but we do question the paleoclimatic and paleogeographic origins of that rain and the relative immensity of the Catskill delta clastics in comparison.

In our interpretation (Fig. 4), the clastics associated with the Antler Mountains were deposited on the windward side of the mountains in a trade-wind belt. The dry trade winds would have picked up sufficient moisture while over the epicontinental seas east of the mountains. As the trade winds were forced to rise when crossing the Antler Mountains, a great deal of orographic precipitation would have resulted on the eastern flank, carrying much detrital material into adjacent parts of the epicontinental sea. Clastics in the extreme northwestern parts of Canada and south of the Arctic Archipelago Mountains occurred in the temperate, humid belt. Moreover, as the prevailing westerly winds impinged on the Arctic Archipelago Mountains, they would have been forced to rise, resulting in a great deal of orographic precipitation. This precipitation and the resulting alluvial and deltaic sedimentation, combined with the humid, subtropical climate, explains the presence of Late Devonian coal in the Arctic Archipelago islands.

The Catskill delta, on the other hand, was apparently located in the humid equatorial belt near the southern belt of easterly trade winds. The dominance of easterly winds in this area is indicated by the distribution and thickness patterns of the Tioga Bentonite (Dennison and Textoris, 1970, 1971, 1978). The delta, we believe, was very definitely located in the rainshadow of the Acadian Mountains and hence did not receive the maximum precipitation normally associated with the humid, equatorial belt. This is reflected in the sediment-starved nature of the adjacent, epicontinental (black-shale) seas and by indicators of restricted rainfall such as dipnoan trace fossils, carbonate paleosols, and redbeds in the Catskill-Old Red Sandstone facies (Woodrow and others, 1973; Allen, 1979). We will return to these arguments again in a later section.

Further westward, the humid equatorial belt coincided with parts of the Transcontinental Arch. However, because the arch had no significant relief and was developed on older carbonates, it did not supply sufficient detrital sediments to form the thick, coarse clastic sequences that often characterize the humid equatorial belt. Because of this, thin green-shales and shaly carbonates predominated in this part of the Late Devonian equatorial belt.

South America (western Gondwanaland, Fig. 4) at this time was largely situated between 5 and 30 degrees south latitude, an area where abundant carbonates might be expected, but few Devonian rocks are present in reality. Although doubt exists about whether many Upper Devonian rocks are present in the northern and western seaway, those rocks present are largely clastic. Conditions for carbonate deposition apparently were not favorable, for northern parts of the sea were on the windward side of a mountain range (Columbia and Venezuela) where clastic influx would have diluted any carbonates, and western sides of the seaway were probably subject to upwellings of cold, less saline waters from the subtropical gyre on the eastern side of the ocean (see Lees, 1975; Heckel and Witzke, 1979).

DEPOSITIONAL MODEL

Although the specific purpose of this study is to explain the deposition of the Upper Devonian-Lower Mississippian black-shale sequence in eastern Kentucky, this task cannot adequately be completed without examining the black shale throughout its entire distribution in North America, as well as the units contiguous with it. A number of models for the deposition of these black shales have already been proposed, and significant points regarding the origin of these shales have been brought out in many of them. Most of the models represent some variation on "shallow-water" or "deep-water" themes the most important of which are listed in the introductory section. We believe that neither of these basic models can adequately explain the entire black-shale sequence; whatever model is finally defined must be able to explain both shallow- and deep-water shales in the same sequence, for there is ample evidence of both types of shale.

The model we have developed emphasizes regional tectonic, climatic, and sedimentary patterns rather than the specifics of black-shale deposition. The specific conditions under which black shales accumulate are already fairly well known. What is not so well known, however, are the regional controls which permitted these conditions to form and operate. It is these regional controls that will be emphasized in this model. Nonetheless, few parts of the model are really totally new. At some time or other, most of our evidence has been discussed by earlier workers. We found particularly useful the recent work of Heckel (1977) and Heckel and Witzke (1979), although we disagree with their placement of the paleoequators. What is new about this model is our singular contention that these black shales owe their origin to an interplay of tectonic and paleoclimatic factors unique to the Laurussian continental mass (North America and northwestern Europe, Fig. 4) from the Middle Devonian through the earliest Mississippian. In many earlier studies, the influence of tectonic and climatic factors on the origin of these black shales was too often overlooked.

Origin of Black Muds

Sources of Organic Matter

Two problems are inherent in the origin of black muds: a source of abundant organic matter and a means of preserving that organic matter from the normal physical processes of oxidation that destroy it and biological processes that consume it. A source of organic matter is readily available in the plankton that inhabit the surface waters of seas and oceans almost everywhere. Trask (1939) estimated an annual production rate for organic matter in the ocean on the order of 1000 grams per square meter (approximately 3000 tons per square mile). This productivity may be further enhanced in smaller, largely enclosed seas where surface runoff from nearby land can continually replenish nutrients; or in seas along the eastern margins of oceans where nutrient-rich waters from oceanic depths upwell and mix with shallow waters resulting in great plankton blooms (Schopf, 1980, p. 102; Bougis, 1976). Paleogeographic reconstructions of North America during the Late Devonian indicate that the "Black-Shale Sea" was a largely enclosed sea or embayment (Fig. 4). Because this sea opened to the southwest and some of the shales deposited in it are highly phosphatic, it is also likely that deep, nutrient-rich, oceanic waters upwelled and mixed with the shallower waters of the "Black-Shale Sea." We will return to the role of oceanic upwelling in the deposition of the black shale in a later section.

Another important source of organic matter is that of terrestrial origin. Gripenberg (1934) estimated that up to 2 million metric tons of terrestrial organic material per year was being carried by rivers into the Baltic Sea, where black anoxic muds are currently accumulating locally, and the Baltic Sea is about half the size of the "Black-Shale Sea." Unless this material is destroyed by physical oxidation or consumed by organisms or transported beyond the depositional basin, it must be deposited with the other sediments. In the Devonian-Mississippian black-shale sequence of North America evidence of terrestrial organic matter is nearly everywhere abundant. The literature abounds with accounts of stems, logs, lepidostrobi, and other parts of terrestrial plants (e.g., Hoover, 1960; Conant and Swanson, 1961; Breger and Brown, 1962, 1963). Callixylon logs are perhaps the best known terrestrial constituents of the black shale. Most of this terrestrial organic material is assumed to have originated in the east, especially around the Catskill Delta area where coals are known to occur (Woodrow and others, 1973; Heckel and Witzke, 1979) and the in-place stumps of entire Callixylon forests have been exhumed (Goldring, 1924). The Ozark uplift and Cincinnati Arch may have also been sources of terrestrial plant debris. Breger and Brown (1962, 1963) suggested that the black shales are composed primarily of terrestrial (humic) organic debris, whereas more recent studies of the organic matter using carbon isotopes, suggest that the contribution of terrestrial organic matter increases in an easterly direction toward the major source areas Potter and others, 1980).

The principal point of the preceeding discussion is the fact that organic matter was relatively abundant in the large embayment that comprised the "Black-Shale Sea." Although the amount of organic matter in the form of plankton and other larger organisms living in upper parts of the water column is usually rather large, conditions in and near the "Black-Shale Sea" - basin configuration and size, nearby terrestrial sources of nutrients and organic debris, and the presence of upwellings during at least parts of black-shale deposition - would have served to enhance the production and accumulation of organic matter.

Preservation of Organic Matter

The effects of such a vast amount of organic matter can easily be reduced by physical oxidation, biologic consumption, or sediment dilution. When unusually large amounts of organic debris are sedimented, the oxygen demand of the physical system overrides that of the biological system, and free oxygen is depleted (Thiel, 1978). In a stratified water column where vertical replenishment of oxygen to the bottom can not take place, anoxic, reducing conditions develop, and more and more organic matter is preserved. The lack of free oxygen prevents metazoan life and only anaerobic and facultative anaerobic life can exist. A mechanism similar to this has been suggested by Byers (1977, 1979) and Heckel and Witzke (1979).

It is also possible, however, for organic matter to be preserved under oxidizing conditions. This can occur wherever organic matter accumulates in such abundance and so fast that organisms and oxidizing processes simply can not decompose all the mass. In these circumstances, it is possible to accumulate organic matter in an oxidizing realm. Although reducing conditions would rapidly set in below the sediment-water interface, environmental conditions on and above the substrate could be normal and support prolific benthic communities. The principal difference between this and the previous anaerobic situation is the fact that the abundant organic matter accumulates in water shallow enough to allow vertical mixing and replenishment of oxygen as it is destroyed by oxidation and biological processes. Conditions like these are probably represented by the upper Cretaceous Mancos Shales in

Colorado, the lower Pennsylvanian Belden Shale of Colorado, the Upper Mississippian, lower Pennington shales of eastern Kentucky and other fissile black shales which exhibit prolific benthic faunas. Similar conditions probably persisted locally during the early stages of Devonian-Mississippian black-shale deposition, for in many areas possible in-place benthic faunas occur on black-shale substrates in lower parts of the section (Linney, 1884; Foerste, 1906, Savage, 1930, 1931; Campbell, 1946; Hoover, 1960; Lineback, 1968).

Although evidence supports the presence of both reducing and oxidizing environmental conditions during the deposition of the black muds themselves, we believe, as have most previous workers, that the former predominated. The relative lateral and vertical distributions of these two environmental conditions are particularly instructive to the depositional model and will be discussed later.

Clastic Sources

Although production and preservation of organic matter are important aspects in understanding the formation of these black shales, we do not believe that they fully explain the abundance or predominance of organic matter in the black-shale sequence. As previously mentioned up to one-third of these shales may be composed of organic matter. There is a surprising lack of clay and coarser clastics in these shales, especially in view of the fact that the Acadian orogenic event was occurring to the east. One might expect a situation similar to the earlier Taconic orogenic event, where the vast amounts of clastic debris debouched into adjacent seas and was transported as far west as Indiana, Kentucky, and Tennessee. If vast amounts of clastic debris and the pulses of oxidizing waters that accompanied them had been debouched into the nearly enclosed "Black-Shale Sea" to the west, it is doubtful that the present black-shale sequence would have been formed. Clastic dilution, combined with oxidation and biologic consumption, would have reduced the relative abundance of organic debris, and its influence on the development of reducing conditions. Though not a new idea, we suggest that development of the present black-shale sequence is in large part related to the slow rate of clastic sedimentation, indicated by the relative paucity of clay in much of the sequence. Hence, the term "starved basin", which has been frequently applied to black-shale depositional conditions, is rather appropriate. The term "starved basin", however, must be used with some care, because even though slow sedimentation characterized large portions of the basin, thick sequences of deltaic and turbiditic sediments were accumulating in the Catskill Delta region of New York and Pennsylvania. The questions then arise, why was clastic sedimentation so slow, and why was the influence of the Catskill Delta so comparatively small in the enclosed, inland basin occupied by the "Black-Shale Sea"? We suggest that the answer lies in the relationship between regional tectonic and climatic factors.

That the Catskill Delta was the major source of clastic sediment in what is now eastern United States during the Middle and Late Devonian is unquestioned. Provenance studies (Towe, 1963; Potter and others, 1980), paleocurrent studies (Potter and others, 1979, 1980) and the large, regional facies relationships (e.g., Rich, 1951; Dunbar, 1960; Broughton and others, 1962) clearly indicate an eastern source. Even though this inland sea was bordered on nearly all sides by land, these land areas except for the Acadian Mountains, were relatively low-lying (Conant and Swanson, 1961) and probably covered by forests and other vegetative cover (Beck, 1964). This land, an extension of the flat surface over which black-shale seas transgressed (Conant and Swanson, 1961), had apparently been nearly peneplaned during the largely, emergent, erosive episode separating Middle and Upper Devonian rocks throughout most of the central United States. This event is marked by a prominent unconformity which Ham and Wilson (1967) suggested was probably the greatest unconformity of Devonian time. This surface which formed much of the land bordering the "Black-Shale Sea" was low in relief and largely developed on a carbonate terrain. Therefore, although bordering lands may have provided waters rich in dissolved substances, they apparently provided little in the way of substantial clastic input. Localized sandy facies within black shales far removed from the influence of the Catskill Delta (Conant and Swanson, 1961, p. 53) no doubt represent small streams debouching into the sea from adjacent borderlands, but their input was probably inconsequential compared to that of the Catskill Delta.

The Catskill Delta complex is an exogeosynclinal wedge of clastic sediment that spread cratonward through fluvial, deltaic, and turbiditic processes from an uplifted suture belt represented by the Acadian Mountains. These thick clastic wedges accumulated in the subsiding peripheral or foreland basin (also called an exogeosynclinal or pericratonic basin) just westward of the area of most intense deformation, the New York promontory previously mentioned. Although vast amounts of fine- and coarse-grained clastics from the delta accumulated in the subsiding peripheral basin, comparatively little of this material was transported farther westward to cratonic portions of the "Black-Shale Sea". Only fine-grained clastics in suspension and fine-grained clastics from the distalmost portions of the delta ever reached the "Black-Shale Sea".

Barriers to Clastic Sedimentation in the Black-Shale Sea

Paleomagnetic data (*e.g.*, Ziegler and others, 1979) and lithostratigraphic data used to compile the reconstruction of Late Devonian paleogeography in Figure 4 indicate that the Late Devonian paleoequator crossed parts of the "Black-Shale Sea" and crossed the Acadian Mountains obliquely in the Maritime provinces of Canada. The equatorial belt is typically a rather humid, rainy belt, because as the easterly, moisture-laden trade winds, particularly those blowing across the ocean, converge at the equator, they undergo convection, rise, and drop their moisture as rain due to cooling and condensation (Strahler and Strahler, 1973). However, because the Acadian Mountains, at least periodically, formed a high orographic barrier which crossed the equator at an angle (Fig. 4), the easterly trade winds could not everywhere (*e.g.*, west of the Acadian Mountains) converge at the equator and undergo normal convection. Instead, when the trade winds met the Acadian Mountains, they were forced to rise before reaching the equator. The cooling and condensation that resulted caused most of the precipitation to fall on the eastern side of the mountains. Most of the heavy precipitation was dropped on the east side of the mountains. After passing over the mountains, the then dry air descended and was heated, causing net evaporation rather than precipitation. To summarize, the Acadian Mountains periodically formed a high orographic barrier which would have caused heavy orographic precipitation (Strahler and Strahler, 1973) on the east side of the range, and a dry rainshadow on the western side of the range (Fig. 5). Unfortunately, the thick clastic sequences which would have formed on the east side of the mountains have been so altered or destroyed by episodes of orogenic activity in this area, that their former presence is difficult to prove. Periods of

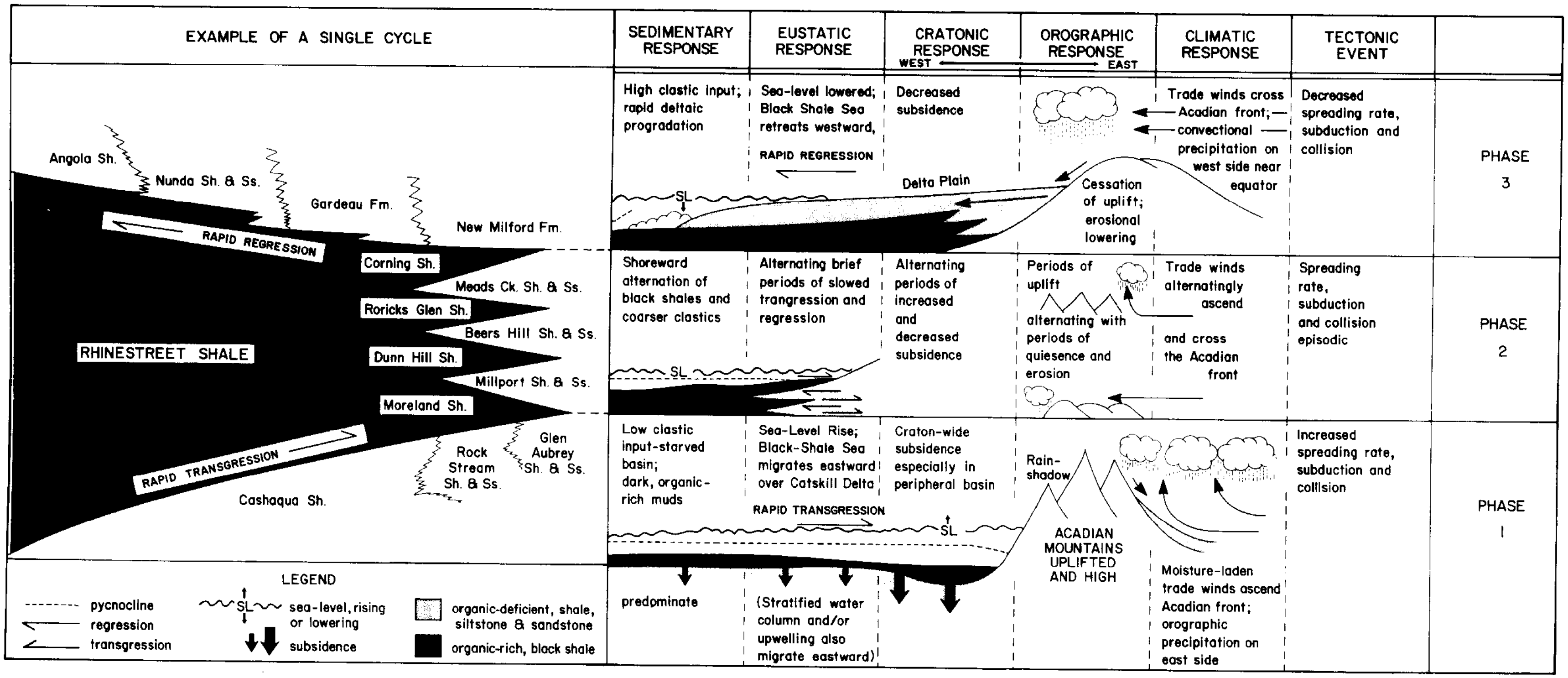


Figure 5. A model for the cyclicity of alternating black shales and coarser clastics in the Catskill Delta, illustrated with a sample stratigraphic interval from the Catskill Delta.

rainshadow conditions on the western side, however, would have resulted in low fluvial input and slow sedimentation throughout most parts of the adjacent "Black-Shale Sea." The small amount of clastic input would have permitted the abundant organic matter to become a major constituent of any sediment that accumulated in this sea. Interestingly, a model somewhat similar to this was presented by Grabau in 1913.

Besides the Acadian Mountains, no other major source of clastics for the inland "Black-Shale Sea" existed, and when that mountain range was fully elevated, precipitation necessary for eroding and transporting sediment into that sea was probably not available due to the rainshadow effect. Potential moisture-bearing trade winds coming from the northeast across the Old Red Sandstone Continent would have been equally dry after crossing the Caledonides (Fig. 4), and any convectional precipitation which did occur along the equator in this region would have fallen on the sea itself or on low-lying lands incapable of supplying much clastic debris. The situation would have been much the same for trade winds approaching from the south and southeast. Therefore, we suggest that the prominent black-shale units which intertongue with the thick clastics of the Catskill Delta, represent among other things, periods when the Acadian Mountains formed an effective rainshadow barrier (Fig. 5) to the moisture-laden trade winds converging at the equator.

On the other hand, when the mountainous barrier was lowered so that precipitation reached western parts of the mountains and provided the runoff and fluvial discharge necessary for eroding and transporting the vast amounts of clastic debris westward to the Catskill Delta, much of this material never reached western cratonic portions of the "Black-Shale Sea." So the nearly continuous black-shale sequences farther westward on the craton not only reflect periods of rainshadow development, but the general ineffectiveness of clastic-sediment transport mechanisms transverse to the mountain range and peripheral basin.

We suggest in the following section that this is related to the confining nature of the subsiding peripheral basin.

Middle and Late Devonian Transgression (and Regression)

The Middle Devonian-through-Lower Mississippian black-shale sequence in North America represents a period of dominant transgression (e.g., Conant and Swanson, 1961; Sloss, 1963; Gutschick and Moreman, 1967; Sutton and others, 1970; Byers, 1977, 1979) even though local areas like the Catskill Delta experienced dominant regression due to deltaic progradation. If the black-shale sequence is viewed as a single unit, it can be traced laterally from the Middle Devonian Marcellus Shale of central New York across the continent to the Lower Mississippian Exshaw Shale of western Canada. Viewed in this way, the transgression occurred during a period of time linking the Middle Devonian through Early Mississippian, resulting in widespread deposition of the diachronous black-shale sequence (Conybeare, 1979). The black-shale sequence is part of the larger Kaskaskia sedimentary sequence, encompassing the Middle Devonian through Early Carboniferous; it represents a time of maximum cratonic subsidence and transgression (Sloss, 1963; Sloss and Speed, 1974). More importantly, however, Johnson (1971) and Sloss and Speed (1974) have related this and other dominantly transgressive periods to episodes of increased sea-floor spreading, characterized by plate convergence at craton margins through obduction, subduction or collision. Moreover, this convergent mode seems to have dominated throughout the Middle and Late Devonian, and is evident in the subduction and collision forming the Acadian Mountains (*e.g.*, McKerrow and Ziegler, 1972), the obduction forming the Antler Mountains in the Cordilleran region (Poole, 1974), and in the various degrees of subduction and/or collision forming the ancestral Frankin Mountains in northern Canada, the Taimyr Mountains in eastern ancestral Siberia, and the Tabberabberan Mountains along the southern and eastern margins of Gondwanaland (Mintz, 1977, p. 363). Continental submergence and resulting transgression are not only related to eustatic changes brought on by the elevation of spreading centers and the accompanying displacement of ocean water, but also by progressive cratonic depression, particularly in craton-interior basins with a "primordial predilection" for subsidence (Sloss and Speed, 1974). Moreover, if subduction proceeds to the stage of imminent or ongoing continent-continent collision, as occurred in the Acadian Mountains during the Middle and Late Devonian, the edge of the consumed continental block would have been further depressed by partial subduction into a linear peripheral or foreland basin on the cratonic side of the suture zone (see Dickinson, 1974). The progressive subsidence characterizing such a basin, would have a definite confining effect on any clastics dumped into it, and may explain why coarser clastics were not transported beyond the peripheral basin into the cratonic "Black-Shale Sea", although longitudinal transport along the basin was effective as far south as Tennessee.

Nonetheless, coarse-clastic sedimentation in the Catskill Delta occurred as regressive, progradational pulses of light-colored shale, siltstone and sandstone separated by transgressive pulses of black, clastic-deficient, organic-rich shales (Fig. 3). We suggest that the cyclicity of black shale and coarser clastics in the Catskill Delta was related to a pulsatory spreading rate and a resultant pulsatory rate of subduction, and/or collision in the

Acadian Mountains (Fig. 5). Although it is difficult to prove specifically the occurrence of increased or decreased spreading and subduction rates, the cyclicity of the thick clastic wedges in the Catskill Delta certainly represents the alternation of times of high source areas and those of low source areas. In a collisional suture zone such as the Acadian Mountains, times of high, mountainous clastic sources would seem to best reflect times of increased subduction and/or collision. It is the interrelationship between times of increased spreading (and the resulting highlands) and climatic factors already discussed that apparently caused the cyclicity of black shales and clastics seen in the Catskill Delta. These interrelationships are shown schematically and illustrated with a sample stratigraphic interval from the Catskill Delta in Figure 5.

An episode in our model begins with a period of increased spreading, causing intensified subduction and/or collision in the Acadian Mountains (Fig. 5, Phase 1); the result was twofold. First, the Acadian Mountains were uplifted to form a high, orographic barrier. Secondly, the resulting eustatic sea-level rise and cratonic subsidence combined to cause rapid transgression. The high orographic barrier created by the uplifted mountains blocked moisture-laden, easterly trade winds, so that most of their precipitation fell on the eastern side of the mountains. This created a rainshadow on the western side of the mountains, and even though the mountains were high and could supply vast amounts of clastic debris, little or no precipitation was available here to erode and transport the debris to the adjacent seas. In fact, the presence of redbeds, calcareous crusts, and associated features in parts of the Catskill Delta suggest that areas west of the mountains may have been arid and dry (see Woodrow and others, 1973). The resulting low clastic input from these mountains, the only major clastic source in southeastern Larussia, produced "starved-basin" conditions in the adjacent "Black-Shale Sea." The sediments deposited in the sea at this time largely reflect sedimentation of the abundant organic debris produced in upper layers of the "Black-Shale Sea."

At the same time clastic sedimentation was effectively reduced, waters from the adjacent "Black-Shale Sea" rapidly transgressed over former basin and slope clastics and low-lying alluvial and delta plains (Sutton and others, 1970) to the east, as well as over older black muds and/or a relatively smooth erosion surface to the west. Such episodes of uplift and transgression apparently occurred rapidly, for the basal contact of the black shales with underlying clastics is usually sharp and any shallow-water deposits are usually condensed into the basal lag deposits already described, rarely is there any intertonguing.

Periodically, the spreading rate slowed and became episodic so that periods of active tectonism (subduction and collision) alternated with periods of tectonic quiesence (Fig. 5, Phase 2). As a result, short periods of uplift, accompanied by small and brief, but rapid, transgressions of sediment-starved seas, alternated with short periods of tectonic quiesence and regression, during which the rainshadow effect was reduced and sediment transport into the Black-Shale Sea resumed. The lithologic expression of this phase in the model is a series of black-shale intertongues that terminate most of the black-shale units in an eastward direction (Figs. 3, 5). In some thinner black-shale units like the Pipe Creek, this intertonguing is essentially absent or reflected as a stillstand stage between Phase 1 and Phase 3.

In Phase 3 of our model, spreading, and hence subduction, slowed to such a point that weathering and erosion gained ascendancy over uplift in the Acadian Mountains. As the mountains were slowly lowered, the orographic barrier to the moisture-laden trade winds disappeared, permitting the winds to cross the lower mountains relatively unimpeded and deliver precipitation to the west side because of convection near the equator (Figs. 4, 5). The runoff and discharge would have been sufficient to erode vast quantities of debris from the mountains and transport it westwardly to the "Black-Shale Sea" where one of the large Catskill Delta complexes would have formed. The prograding delta so formed would have introduced so much clastic material and accompanying pulses of oxidizing water that any organic matter would have been effectively diluted or destroyed in the area of clastic influx. At the same time, because of drastically reduced spreading, the amount of subsidence apparently declined and eustatic sea-level was lowered (see Sloss and Speed, 1974). This, combined with the actively prograding Catskill Delta, would have resulted in rapid regression in the area of the delta. This depositional scenario (Fig. 5) was repeated at least eight times resulting in the cyclic alternation of black shales and clastic wedges seen in the Catskill Delta (Fig. 3). Because some of the clastic wedges never prograded beyond the edge of the peripheral basin to the craton, and none ever prograded throughout all parts of the cratonic "Black-Shale Sea", large parts of the cratonic black-shale sequence contain nothing but homogeneous black shales.

Each of the thick prograding clastic wedges comprising the Catskill Delta complex emptied into parts of the peripheral basin created by successive episodes of subsidence. Based on regional cross sections (Wallace and others, 1978; Kepferle and others, 1978; Roen and others, 1978; Potter and others, 1978) and isopach maps in preparation, the western hinge line of this basin ran approximately through eastern Ohio, western West Virginia and west-central Virginia.

Apparently the cumulative effects of subsidence in the peripheral basin far exceeded the ability of the first three successive delta complexes in the Hamilton, Genesee, and Sonyea groups to fill it. And the intervening black-shale units (Marcellus, Geneseo-Burket, and Middlesex), at the most a few hundred meters thick each, contributed little to the infilling because of the sediment-starved conditions they represent and their great compactibility.

During the last three episodes of deltaic progradation on the Catskill Delta (Upper Olentangy-Angola-Hanover; Chagrin-Three Lick; Bedford-Berea) and during later lower Mississippian progradation (Borden-Grainger-Price-Maccrady-Pocono), subsidence in eastern parts of the peripheral basin apparently declined, and as the basin filled from the east, these progradations migrated westward onto the craton. This also pushed the eastern limit of each successive, intervening, black-shale transgression farther westward (Fig. 3). As the locus of subsidence and sedimentation shifted to western parts of the peripheral basin and adjacent parts of the craton, cratonic portions of the "Black-Shale Sea" appear to have deepened. The Huron, Cleveland and Sunbury black shales are thicker in this area than elsewhere, and contain paleontological and sedimentological evidence of deepening discussed in the following section. The successive westward shift of subsidence and the locus of clastic sedimentation, may have been related to the development of additional source areas to the north and northwest of the Catskill Delta as Africa and the southern European microcontinents began to collide with east-central parts of Laurussia during the Late Devonian and Early Mississippian (Badham and Halls, 1975).

Nonetheless, sediments from no one of these progradational events were effectively deposited throughout the entire "Black-Shale Sea." As these wedges thinned and pinched out westwardly with increasing distance from the source area, the black muds, that were deposited during successive, intervening transgressive events (manifest largely as progressive deepening on the craton), were progressively superposed on each other, forming the nearly homogeneous black-shale sequences seen in central and western parts of the craton. Hence, the failure of these major clastic influxes to reach most parts of the cratonic "Black-Shale Sea" had the same effect as the imposition of a "perpetual" Late Devonian rainshadown.

Development of Anaerobic Conditions in the "Black-Shale Sea"

Formation of a Stratified Water Column

Development of stagnant, anaerobic conditions is typically related to restrictions in mixing of surficial and deeper waters; in most moder instances this is related to a density stratification of the water column. Density stratification may be related to differences in temperature and/or salinity between warmer and/or less saline surface waters and colder, more saline bottoms waters (see Heckel, 1977; Byers, 1977). Because oxygen will not rapidly diffuse downward through the water column to the bottom, active oxygenation only occurs in a shallow surface zone, where oxygen can be mixed in from the atmosphere by local wind-driven circulation cells (see Heckell, 1977; Byers, 1977). Oxygen is also provided through photosynthesis by the abundant phytoplankton that live in this well-lighted portion of the water column. Oxygenation of deeper waters is typically dependent on strong vertical currents to carry oxygenated surface waters downward (Byers, 1977). Although dense, sediment-laden gravity-flow (turbidity) currents and storms can accomplish this on a local scale (Hülsemann and Emery, 1961), the most significant, large-scale vertical circulation is accomplished by thermal currents, generated where colled surface water sinks to the bottom (Byers, 1977). Such currents are usually initiated in polar regions and are best developed during times of glaciation (Berry and Wilde, 1978). In warm, temperate climates like that suggested for the Black-Shale Sea (Fig. 4), the water rarely cools enough to sink to deeper levels and displace colder bottom waters, so that a layer of warmer, lighter oxygenated water is formed near the surface (Byers, 1977). The zone between surficial and bottom layers where this temperature change occurs is called the thermocline. Even though the surficial layer of water may be oxygenated from the surface, if no large-scale vertical circulation exists, mixing will not occur, and the bottom waters will be relatively depleted of oxygen below the thermocline. Moreover, depletion not only occurs due to the absence of mixing, but also due to the decay of organic matter that settles below the level of net-oxygen replenishment by photosynthesis and surficial circulation. The top of the oxygen-minimum zone generally coincides with the thermocline and may occur at depths no greater than 50 meters (Sverdrup and others, 1942; Brongersma-Sanders, 1971; Heckel, 1977).

Vertical stratification of the type necessary to prevent mixing may also result from or be enhanced by the creation of a salinity gradient. In enclosed seas with a large fresh-water influx, the lighter, fresh or brackish water floats above the heavier, saltier, normal sea water. This situation can also prevent normal vertical circulation and lead to the loss of bottom oxygenation and the accumulation of black, organic-rich muds. Similar conditions are observed at present in the Baltic Sea and Black Sea where black, organic-rich muds are accumulating in the deeper parts (Segerstrale, 1957; Caspers, 1957). This density stratification leads to the formation of a halocline, or a zone of abrupt transition between fresh to brackish, surface waters and more salty, deeper waters. In the eastern Pacific, the halocline is approximately 100 meters thick and begins at about 85 to 100 meters below the surface (Tully and Barber, 1961). Not surprisingly, the depths and thicknesses of modern-day thermoclines and haloclines approximately correspond to each other, and Byers (1977) refers to this zone of rapid change of salinity and density as a pycnocline. In the pycnocline, no vertical mixing occurs and the amount of oxygen decreases from normal surface values to nearly zero (Byers, 1977). Using present-day depths and oxygen values from the Black Sea (Caspers, 1957), Byers (1977) established a idealized pattern of vertical water stratification for enclosed basins, which in at least a general way can serve as a comparative model for examples from the geologic record. Byers also compared this depth stratification with the biofacies of Rhoads and Morse (1971) that result where the different water layers intersect the bottom (Fig. 6).

The surface zone is characterized by well-oxygenated, warmer, and often less-dense water; it is nearly uniform in salinity and density and extends to a depth of at least 50 meters. This zone supports an aerobic biofacies characterized by a diverse calcified epifauna. A deep zone, greater than 150 meters in depth, is also uniform in salinity and density, and characterized by colder, saltier waters. More importantly, because of no vertical circulation and rapid use of available oxygen by organisms and decay, the zone has almost no oxygen and supports an anerobic biofacies. Because of the near absence of oxygen and any major circulation, this biofacies is characterized by fine, organic-rich muds which are nearly azoic except for certain bacteria, protozoans and small metazoans especially adapted to oxygen-deficient, reducing conditions. All normal, benthic fauna and bioturbation are absent in this zone, therefore all stratification (usually laminae) are undisturbed.

Between the surface and the deep, bottom zones is a zone approximately 100 meters thick (between 50 and 150 meters, Fig. 6) wherein salinity and density change rapidly; this is the pycnocline. Because vertical mixing does not occur and oxygen values decline rapidly, the fauna is reduced to a few

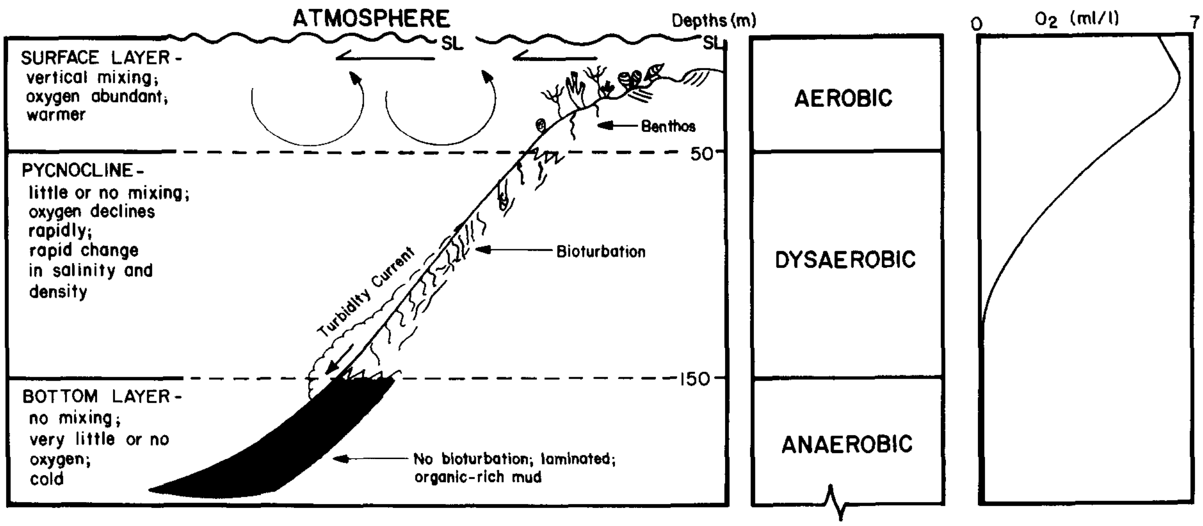


Figure 6. Schematic diagram showing characteristics of a stratified water column and the sediments accumulating within each water layer. Depths and oxygen content are general estimates based on the Black Sea (adapted from Rhoads and Morse, 1971, and Byers, 1977).

specialized infauna adapted to lower levels of oxygen. These typically include various soft-bodied worms, phosphatic brachiopods and weakly calcified crustaceans, pelecypods and articulate brachiopods. Because of the dominantly infaunal nature of the fauna, the facies is typically bioturbated. Because some oxygen is always present in this zone, a limited infauna is usually present and the sediments exhibit green to gray colors.

Finally, it should be noted that the depths and thickness of these three layers are variable depending on various seasonal and oceanographic parameters (Tully and Barber, 1961; Heckel, 1977; Byers, 1977).

Development of such a stratified water column requires in most cases, that there be no lateral exchange between deep waters in the enclosed sea and open ocean waters. Although horizontal mixing of some degree will always occur in the upper aerobic zone, horizontal mixing at depth would introduce oxygen to deep bottom waters and halt stagnation. Preventing lateral exchange or horizontal mixing at depth usually requires a sill or bar near the entrance to the sea, as in the Black Sea (Caspers, 1957), or the sea may be divided into a series of deeper basins separated by broad, higher rises or thresholds as in the Baltic Sea (Segerstrale, 1957). In the latter case, even though waters of the upper zone, and perhaps some from the pycnocline, are widely distributed throughout upper parts of the sea, anaerobic bottom waters of the deep zone are restricted to the individual basins if the basins are not connected. This can give rise to "different" anaerobic, bottom facies in each basin.

Heckel (1977), however, has suggested that a sill or other barrier to lateral bottom exchange is not necessary when the only water available to circulate at depth is already depleted in oxygen. He indicated that if depth in an enclosed epicontinental sea became great enough, anaerobic conditions would be established normally in the bottom waters below the pycnocline. Moreover, in this deep setting, any lateral bottom circulation from the open ocean would supply oceanic water from below the pycnocline already depleted in oxygen (Fig. 7). In a further ramification of this model, he suggested that the oxygen-minimum level and pycnocline might be elevated in the water column on the eastern sides of tropical oceans due to quasi-estuarine circulation and the resulting upwelling. In these circumstances, the persistent easterly trade winds drive enough of the lighter, oxygenated surface water offshore to allow the colder, poorly oxygenated bottom waters to rise and take their place on the east side of the ocean basin by upwelling (Brongersma-Sanders, 1971; Heckel, 1977, 1980). Not only is the deeper, upwelling water depleted in oxygen, but it is rich in phosphate, which is released at depth by oxidation of settling organic matter during sulphate reduction (Heckel, 1977; Burnett, 1977). The upwelling of waters rich in phosphate furnishes this critical nutrient in great abundance to the oxygenated surfical waters causing plankton blooms. The upwelling waters may also be rich in dissolved silica so that the tests of silica-secreting phytoplankton like radiolarians may accumulate on the bottoms in such abundance in the area of upwelling that extensive chert deposits can develope (Diester-Haass, 1978). The plankton concentrate the phosphate and other substances, notably certain heavy metals (Orren, 1973; Heckel, 1977), are transported by wind-driven currents throughout the sea where they settle below the pycnocline, decay, and further deplete the oxygen. The result is not only a tremendous rain of organic debris, which accumulates as an organic-rich mud on anaerobic bottoms below the pycnocline, but also the release of the concentrated phosphate and heavy metals for precipitation or recycling through the upwelling (Brongersma-Sanders, 1971; Heckel, 1977). New phosphate is also continually added to the system from deep,

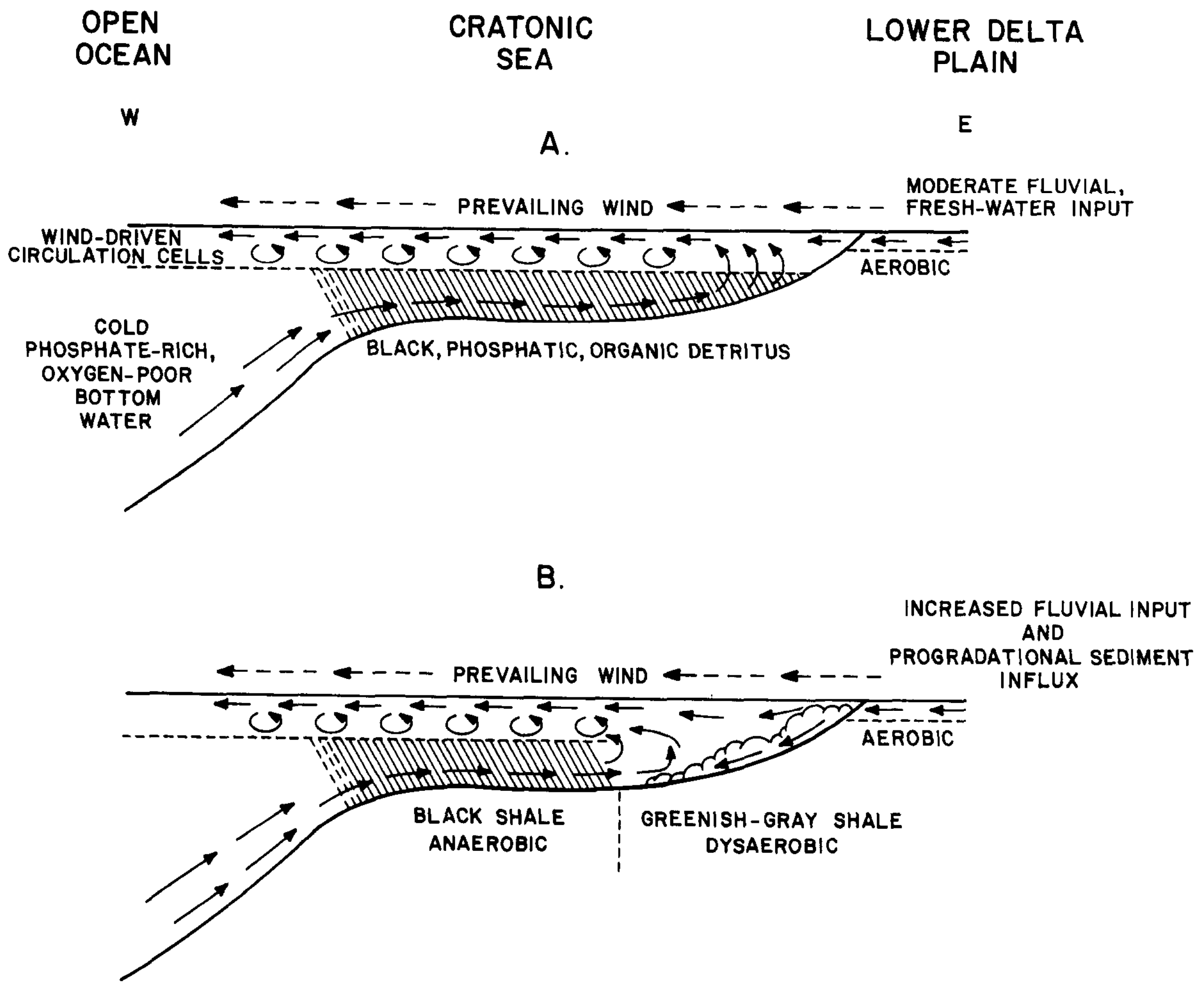


Figure 7. A.) Development of quasi-esturine circulation and upwelling in an epicontinental sea;
B.) Disruption of upwelling through progradation sediment influx.

upwelling oceanic waters. If the phosphate becomes sufficiently concentrated in the interstitial waters of bottom sediments, it will precipitate or replace available carbonate material. This process is facilitated by a constant supply of organic matter, a low rate of detrital sedimentation (which prevents dilution), a decrease in pressure, and an increase in temperature and pH (Manheim and others, 1975; Heckel, 1977); all are conditions that could have been fulfilled if an upwelling entered an enclosed, sediment-starved epicontinental sea like that proposed already for the "Black-Shale Sea" (Fig. 4).

Conditions in the "Black-Shale Sea"

The "Black-Shale Sea" was an island, equatorial, epicontinental sea enclosed on nearly all sides by land or shallow, submerged barriers (possibly, at times, the Transcontinental Arch, Fig. 4). The only major contact with the open ocean was along the continental margin to the south between the Marathon region of Texas and the Ouachita region of Oklahoma and Arkansas, and the presence of thicker deposits of radiolarian chert interbedded with phosphatic black shales in these areas throughout the Devonian and Early Mississippian (Park and Croneis, 1969; Morris, 1974; Lowe, 1975) suggests a divergence of oceanic currents marked by an upwelling (see Heckel and Witzke, 1979; Schopf, 1980). Shallow connections across the Transcontinental Arch with epicontinental seas to the west existed in Kansas and Colorado and possibly at times in Iowa and South Dakota (Fig. 4), but deeper oceanic waters would not have passed through these connections.

Because the Middle and Late Devonian were not times of glaciation, large-scale turbulent mixing of the oceans and epicontinental seas was probably absent (Berry and Wilde, 1978).

Vertical mixing on a smaller scale was also probably restricted in the

"Black-Shale Sea." Because the sea was equatorial, at least periodically, the large amounts of rain and runoff would have formed a lighter, fresh or brackish water layer throughout the sea leading to the formation of a halocline. The presence of supposed brackish to marine, pelagic algae such as Tasmanites (Brooks, 1971) and Foerstia (Schopf and Schwietering, 1970; Schopf, 1978) in abundance throughout all or parts of the black shale support this idea. In addition, the warm, tropical nature of the equatorial area, would have permitted very little cooling of surface waters to occur. This in turn would have resulted in a temperature stratification or thermocline, which is also effective in preventing vertical circulation. In equatorial areas, moreover, the thermocline is likely to be permanent (Degens and Stoffers, 1976). Finally, the enclosed nature of the sea, the uniformity of the equatorial climate, the position of the sea in a rainshadow for long periods of time, and the low-lying nearly peneplained surface over which the sea developed are all factors which would have mitigated or prevented vertical circulation. All of the above factors, combined with inferences from the presence of the shale itself, strongly indicate that a salinity and density stratification, or pycnocline, existed in the "Black-Shale Sea." The pycnocline would have prevented vertical circulation and oxygenation of the bottom and created suitable conditions for the accumulation of abundant organic material in an anaerobic, reducing environment.

It is also likely that an upwelling current moved into the "Black-Shale Sea" sometime during the late stages of black-shale deposition. Phosphate, both in finely disseminated and large concretional forms, is largely concentrated in upper parts of the black-shale sequence. In Kentucky, phosphate concentration shows a marked increase from the level of the upper Huron Shale upward (Markowitz, 1978; Fig. 1). Moreover, the "Black-Shale Sea" was on the eastern side of a tropical ocean in the trade wind belt (Fig. 4) and an area of oceanic current divergence and upwelling had been established on the southern continental margins since at least the beginning of the Devonian (Morris, 1974; Lowe, 1975). These conditions are all favorable for the development of an upwelling current, but water depth in the "Black-Shale Sea" must have increased to the point where deep, cold, oxygen-poor, and phosphate-rich oceanic waters could have flowed unimpeded into the enclosed sea. Although the "Black-Shale Sea" probably was not initially deep enough to permit this, as we have discussed previously, four lines of evidence suggest that the sea progressively deepened with time to the point where this exchange could have occurred: 1.) The Late Devonian was a time of world-wide transgression which continued into the Early Mississippian due to increased spreading rates (Sloss, 1963; Sloss and Speed, 1974); subsidence and eustatic sea-level rise can be correlated with the active collision and subduction occurring along the margins of Laurussia; 2.) the progressive onlapping of black-shale units from the Appalachian Basin onto the Cincinnati Arch (Fig. 3) suggests net transgression and deepening; 3.) the predominance of Palmatolepis and other wide-platform conodonts which are considered to be indicators of deeper water (Seddon and Sweet, 1971; Druce, 1973; Griffith, 1977) in the Late Devonian black shales; and 4.) the upward succession of trace-fossil communities from green-shale intervals within the black-shale sequence of Ohio and Kentucky also suggest increasing depth with time (Potter and others, 1980; Jordan, 1980).

Finally, in order for the deeper ocean waters to upwell in the "Black-Shale Sea", surficial waters must have been displaced westward by surface currents. Surface currents generated by the tradewinds and deflected to the right by the Coriolis effect (see Anikouchine and Sternberg, 1973) would have transported surface waters westward and enabled upwelling to occur almost anywhere in central parts of the "Black-Shale Sea." Hence, the presence of abundant phosphate in the upper black shales as well as evidence for deepening and the presence of appropriate climatic and oceanographic conditions suggest that upwelling occurred at least periodically in central portions of the "Black-Shale Sea."

One further line of evidence supporting the presence of an upwelling is the increased concentration of certain heavy metals in black shales from upper parts of the section. Geochemical analysis of black-shale sequences in eastern Kentucky by Markowitz (1979) indicate increased concentrations of heavy metals like barium, copper, zinc, molybdenum, strontium, vanadium, thorium and uranium (Fig. 1) in upper parts of the sequence. Although uranium is relatively concentrated throughout the entire black-shale sequence because it is adsorbed by certain organic materials (Breger, 1955; Swanson, 1961; Breger and Brown, 1962), its increased concentration, as well as that of the other metals, suggests abundant organic enrichment like that accompanying an upwelling (Diester-Haass, 1978). In an area of oceanic upwelling, the high nutrient contents introduced into the shallow waters result in high biologic productivity. Many of these organisms will selectively concentrate heavy metals both in life and after death (Siebold, 1970; Bostrom and others, 1974), so that the resulting sediments are enriched in these metals. In areas of upwelling, where the production of organic matter is very high, the enrichment of these metals in the resulting sediment can be significant (Brongersma-Sanders, 1965). Therefore, the increased concentration of such metals in upper parts of the black shale provides additional evidence of upwelling.

To summarize, we suggest that conditions in the "Black-Shale Sea" were appropriate for the development of a stratified water column and pycnocline. Once these conditions were established, the abundant organic debris produced and deposited in the sediment-starved sea could accumulate undisturbed in anaerobic conditions below the pycnocline. It is likely that this stage of black-shale formation was confined to the deeper, subsiding cratonic basins and that intervening cratonic highs like the Cincinnati Arch acted as barriers or thresholds to deep circulation and intersected the pycnocline, similar to the present situation in the Baltic Sea. As transgression and deepening continued throughout the Late Devonian, it is likely that water in the cratonic sea deepened sufficiently that a pycnocline was established throughout the sea and black, organic-rich muds accumulated even on the cratonic highs. With further deepening in the latest Devonian, oxygen-poor, phosphate-rich, deep oceanic waters upwelled into the "Black-Shale Sea" from the continental margin to the south, enhancing organic production and promoting deposition of phosphate in the black shales.

Depth

The depth of the "Black-Shale Sea" has been the subject of continued controversy. Certainly, the regional facies relationships suggest that the black shales represent a basinal or distal facies of the westwardly prograding Catskill Delta. This interpretation is consistent with the progressive subsidence of the craton which must have accompanied ongoing subduction and collision in both the Antler and Acadian mountains at this time. Using the method of Klein (1974) to calculate the depth of the "Black-Shale Sea" during Sunbury time in eastern Kentucky, a minimum depth of 230 meters (700 ft) is obtained. This is consistent with depths obtained by Rich (1951) and Potter and others (1980). However, we believe that depths may have been considerably greater in parts of the Appalachian peripheral basin where subsidence apparently was much greater.

It is also important to realize that during the initial phases of transgression onto the craton, the "Black-Shale Sea" was relatively shallow. These shallow water deposits, however, are usually poorly developed or condensed into a basal lag zone due to the rapidity of transgression and the low-lying nature of the surface over which transgression occurred. Generally, the cratonic black-shale sequence represents deposition in a progressively deepening inland sea.

Sequential History of Black-Shale Deposition

The history of Devonian-Mississippian black-shale must begin in the Middle Devonian with the deposition of the Onondaga Limestone and equivalent carbonate units as a rather broad blanket of shallow-water, platform deposits extending through east-central and midwestern United States (see Heckel and Witzke, 1979, Fig. 3B; Fig. 8A). Although probably submergent, the Cincinnati Arch was present because limestones equivalent to the Onondaga thin on its flanks. The Ozark Uplift was uplifted and emergent, and to the south and southwest in the Ouachita and Marathon region, divergence of oceanic currents, upwelling and high organic productivity is indicated by the presence of radiolarian chert, that intertongues with cherty limestones to the north.

The first indication of an uplifted clastic source in the east and the beginning of the Acadian Orogeny occurs at this time. In parts of Virginia, West Virginia, Maryland and southern Pennsylvania, the Onondaga grades eastward into the dark, calcareous Needmore Shale. This shale marks the first appearance of the Catskill Delta facies and is interpreted to represent basinal, prodeltaic deposition (Dennison, 1971). The Needmore grades westward into the Huntersville Chert and Onondaga Limestone and contains fissile, phosphatic black shale, as well as dark, fossiliferous, calcareous shales

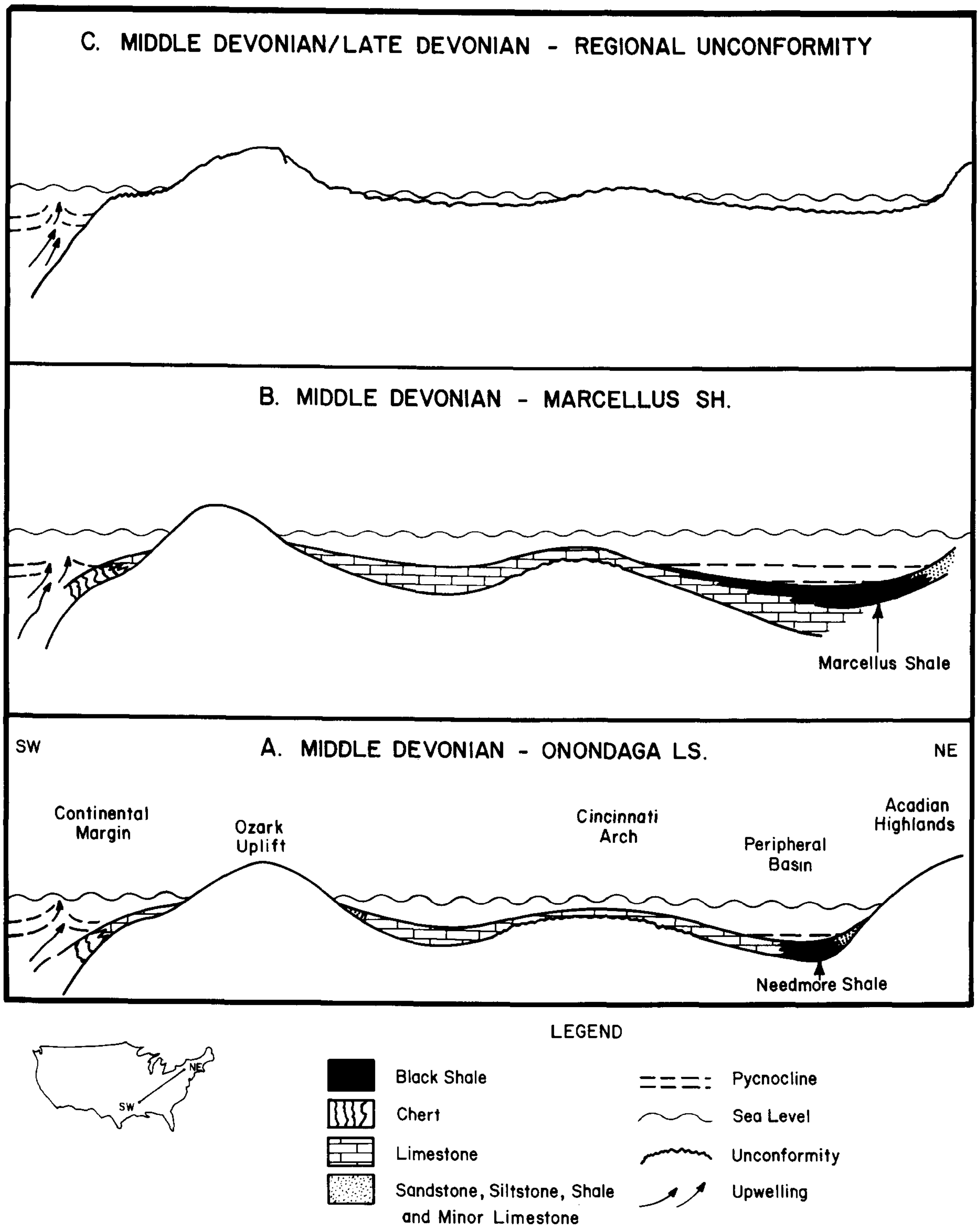
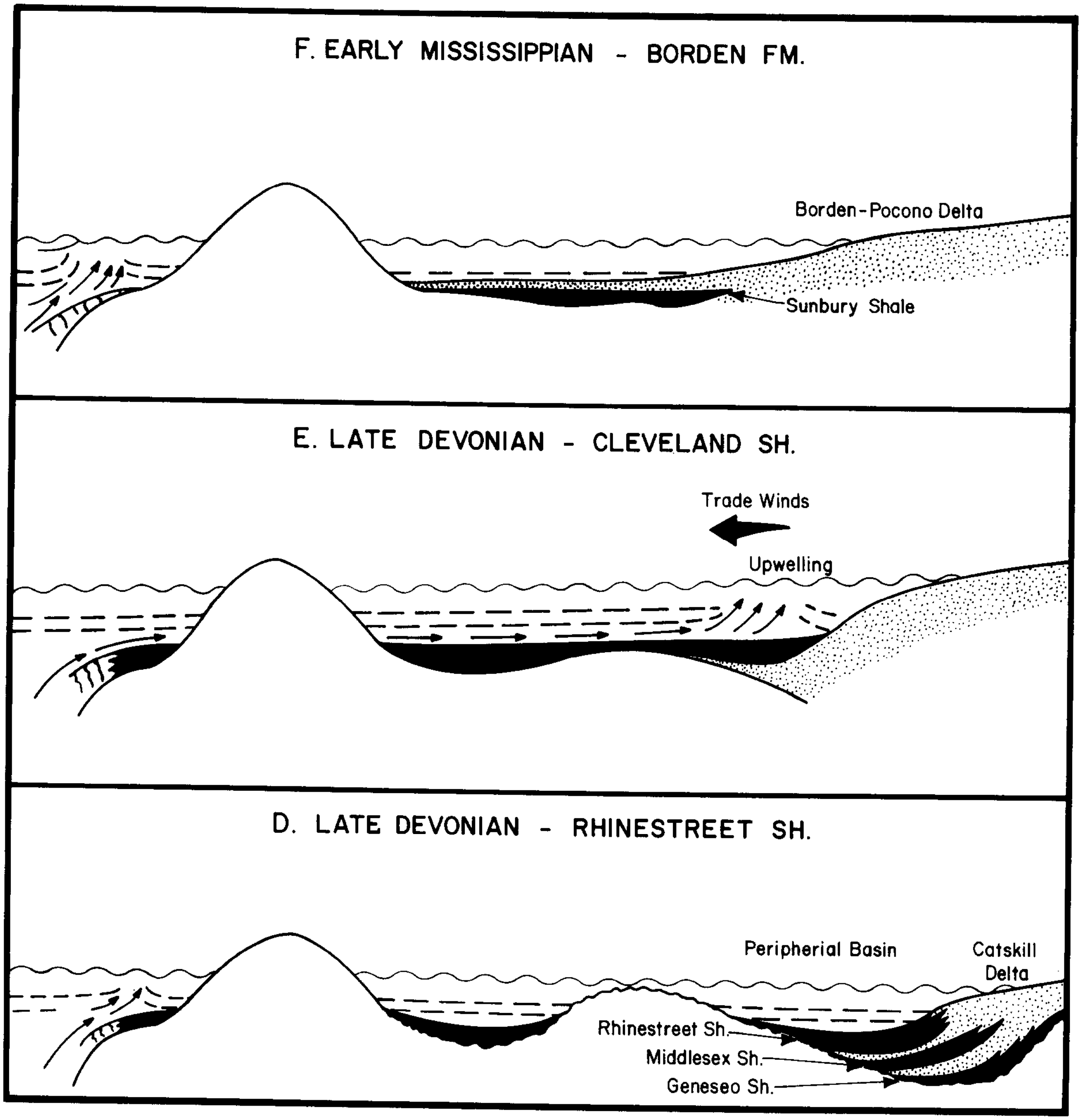


Figure 8. A series of schematic sections from New York to the Ouachita area showing the inferred sequential development of black-shale depositional environments from the Middle Devonian through the Early Mississippian. Even though the Ozark Uplift appears to have been a barrier to circulation in these sections, currents could have moved around the uplift (see Fig. 4). Not drawn to scale.


F. EARLY MISSISSIPPIAN - BORDEN FM.
Borden-Pocono Delta
Sunbury Shale
E. LATE DEVONIAN - CLEVELAND SH.
Trade Winds
Upwelling
D. LATE DEVONIAN - RHINESTREET SH.
Peripherial Basin
Catskill Delta
Rhinestreet Sh.
Middlesex Sh.
Geneseo Sh.

interbedded with limestone (Inners, 1979). Although containing anaerobic, dysaerobic, and aerobic facies (Newton, 1979), the Needmore appears to largely represent deposition near the base of the aerobic zone or top of the pycnocline. The presence of phosphate and chert may represent the short-lived incursion of an upwelling current into southwestern parts of the Appalachian peripheral basin (Inners, 1979) before the bordering Acadian landmass to the east and south (Fig. 4) developed in the late Middle Devonian and Late Devonian. The importance of the Needmore Shale lies in the fact that it reflects the beginning of the Acadian Orogeny and the resulting development of a peripheral basin deep enough to restrict vertical circulation and permit at least local development of a pycnocline.

By the late Middle Devonian, collision between the Avalon Prong and the east-central margin of Laurussia (New England Maritime region) was imminent or in progress. Collision resulted in the formation of a high Acadian mountain front cross the equator, and perhaps more importantly, subsidence and warping of the craton. Although subsidence was apparently greatest in the peripheral basin, just west of the mountains, other cratonic basins (Illinois and Michigan basins) also subsided. This subsidence, combined with the eustatic rise in sea level accompanying periods of increased spreading and subduction, resulted in transgression and deepening of the cratonic sea. Moreover, formation of the Acadian highlands to the south and east effectively enclosed the cratonic sea except for oceanic connections in the Arkansas and Oklahoma region (Fig. 4). The net effect of the subsidence, transgression, and the uplifted Acadian front was to create isolated, subsiding basins (Fig. 8B) in the rainshadow of the Acadian Mountains.

Even though subsidence occurred in all of the major cratonic basins as indicated by the thickened carbonate sequence in the Illinois and Michigan basins, only in the Appalachian peripheral basin did subsidence exceed sedimentation. This is indicated by the presence of the black Marcellus Shale, which we suggest developed in the rainshadow of the Acadian Mountains (Fig. 8B). The dominantly organic input to the sediment in this starved basin during a time of net transgression was apparently not sufficient to keep pace with increased subsidence in the peripheral basin. The fact that so much of the organic matter was preserved as black shale indicates that as the basin deepened, a stratified water column developed which prevented vertical mixing; this is the most likely origin for black, organic-rich muds in nearly-enclosed seas. In the cratonic basins more distant from the rising Acadian Mountains, subsidence apparently was slower or the carbonate sedimentation was better able to keep pace with sedimentation, for the presence of thick fossiliferous carbonates in these basins indicates that these basin bottoms never subsided below the surficial, oxygenated layer (Fig. 8B).

Deepening in the Appalachian peripheral basin at this time was apparently progressive and somewhat slower than that occurring during the Late Devonian, for this is one of the few instances where the basal contact of a black-shale unit with the underlying unit is one of intertonguing. The Marcellus intertongues with parts of the Onondaga and laterally equivalent carbonate units in western parts of the peripheral basin (east flank of the Cincinnati Arch; see Dennison, 1971). With transgression and deepening, the Marcellus black shales progressively displaced carbonate facies on the flank of the Cincinnati Arch in an onlapping facies relationship (see Schwietering, 1979). Certainly, with this kind of relationship, between carbonates and black shales, the initial Marcellus black shales probably did not represent extremely deep-water deposits. In fact, the presence of locally abundant, low-diversity benthic faunas, the absence of a uniform black, coloration, and the presence of local fossiliferous carbonate units wholly within the Marcellus, indicates that some of the Marcellus deposition occurred within or slightly above the dysaerobic layer (Fig. 8B); at other times the organic-rich sediments accumulated in the bottom anaerobic layer.

Seemingly, Marcellus deposition is related to the fact that subsidence in the Appalachian peripheral basin exceeded the ability of carbonate sedimentation to keep pace with it. As subsidence and transgression continued, in the absence of clastic input (rainshadow effect), the sea bottom progressively subsided into or below the pycnocline, where only black, organic-rich muds accumulated.

Near the end of the Middle Devonian, these conditions changed drastically as erosional lowering of the Acadian Mountains allowed the trade winds to cross the mountains and deliver their precipitation to the western side of the range near the equator. This caused a large influx of clastics to be debouched into the adjacent sea resulting in the first major progradation of the Catskill Delta, which is represented by the Ludlowville and Moscow formations in New York and the Mahantango Formation elsewhere. These formations are represented primarily by grayish-green fossiliferous shales and siltstones which were products of prodeltaic and delta-front depositon. Some parts of these units, however, are represented by very dark brown to nearly black shales, suggesting deposition in deeper, possibly dysaerobic prodelta or basinal conditions. Prominent limestones occur in the two New York formations and apparently reflect periods of decreased clastic input on the delta platforms. Even though distal parts of this clastic progradation overlapped the underlying Marcellus on the Cincinnati Arch, these clastics never prograded beyond the peripheral basin.

This like all of the clastic intervals between the black shales represents a rapid regression in the area of the delta accompanying a period of tectonic quiesence, decreased subsidence, and a drop in eustatic sea level. Most of these deltaic clastics accumulated in the upper oxygenated layer or in upper parts of the dysaerobic layer.

The Middle Devonian-Late Devonian boundary is marked by a prominent unconformity throughout most parts of central United States. The uncomformity represents a time of rapid uplift, warping and local emergence all over the craton (Fig. 8C) and may reflect a time when subduction was effectively halted by collision. This kind of event typically results in a period of regional uplift, when even the peripheral basin is largely drained (Dickinson, 1974). Parts of the craton like the Cincinnati Arch were certainly emergent and were deeply eroded. Even though other parts of the craton may have been slightly submerged beneath very shallow waters, the waters were so shallow that erosion predominated over deposition.

During this interval of uplift in the Catskill Delta, structures created to the east formed temporary, local barriers to clastic sedimentation on western parts of the uplifted delta platform which permitted a brief episode of carbonate sedimentation, represented by the Tully, to develope in the shallow, aerobic,clastic-deficient waters (Heckel, 1973). With renewed uplift in the Acadian Mountains to the east during the early Late Devonian, renewed subsidence, transgression, and sediment-starved conditions resumed on the craton, particularly in the Appalachian peripheral basin, where the Tully carbonate platform subsided below the pycnocline, giving rise to the black, fissile Geneseo or Burket shales (Fig. 8D).

In the Late Devonian and Early Mississippian, six major cyclic alternations of black, fissile shale and intervening fossiliferous clastics are represented in the record of the Catskill Delta (Fig. 3). Each cyclic alternation of black shale and fossiliferous clastics represents the alternation of tectonically active, elevated conditions with tectonically quiesent, low conditions in the Acadian Mountains as described in Figure 5. In contrast with the circumstances of Marcellus deposition, subsidence and transgression apparently were more rapid; for the black shales that were deposited during these sediment-starved, transgressive periods definitely accumulated below the pycnocline (Fig. 8D). Although nektic, planktic, and epiplanktic fossils are locally common in these black shales, there is little evidence of a benthic fauna or conditions which would have supported one.

Like the Marcellus, the lower three Late Devonian black-shale units (Geneseo-Burket, Middlesex, and Rhinestreet) and their intervening clastic deposits do not occur beyond the peripheral Appalachian Basin. Eustatic sea-level rise and subsidence across the craton apparently were not yet great enough to establish a pycnocline and an anaerobic bottom layer beyond the cratonic basins. Hence, cratonic highs like the Cincinnati Arch intersected the pycnocline (Fig. 8D). Nonetheless, biostratigraphic evidence indicates that black-shale deposition was occurring independently in the separate cratonic basins (e.g., Hass, 1947a; Hass, 1956; Scott and Collinson, 1961; Oliver and others, 1967; Klapper and others, 1971; Fig. 8D). Because none of the clastic intervals present in the Appalachian peripheral basin prograded beyond eastern parts of the Cincinnati Arch, the stratigraphic sequences in all three basins are largely different. While black shales were accumulating separately in the three cratonic basins, the intervening high areas like the Cincinnati Arch were subjected to periods of subaerial and/or subaequeous erosion in the very shallow waters that covered them (Fig. 8D). Very little deposition occurred in these areas, because carbonate sedimentation was not favored in the less saline, equatorial waters (Lees, 1975; Heckel and Witzke, 1979) and little clastic input reached these areas from source areas to the east due to the rainshadow effect and the confining nature of the peripheral basin. Also, the very shallow waters favored erosion and reworking rather than deposition. Therefore, the only deposits that formed in these shallow waters are lag or condensation deposits, composed of grains reworked from underlying units or transported from adjacent exposed lowlands, conodonts, fish fragments and plant materials derived from the water column, as well as phosphate reworked from underlying units and deposited authigenically. Some of these deposits may have been accumulating under conditions of low sedimentation since the Middle Devonian. Phosphate may be deposited authigenically in shallow waters with low clastic input, near low-lying land masses, which supply phosphate-rich surface waters to the adjacent seas (Bromley, 1967). This kind of phosphate occurrence is distinctly different from that accompanying an upwelling; such a shallow-water mechanism may account for the abundance of phosphate seen in the basal parts of the cratonic black-shale sequences (Fig. 1). Most important about this, however, is the fact that this and adjacent portions of the basal black-shale sequences on the craton accumulated in shallow waters and represent aerobic and dysaerobic conditons. As transgression and deepening progressed during the late Devonian, shallow waters would have initially covered high parts of the craton. However, because these parts of the craton were low in relief, transgression would have been rapid. The rapidity of transgression combined with the low rate of sediment input would have resulted in very little sedimentary expression of these shallow-water conditions. What sedimentary expression does occur is restricted to the basal sandstone layers (lags) and the rare occurrences of fossiliferous carbonates and shales at the base of the sequence (*e.g.*, Duffin/Harg/Ravenna facies of eastern Kentucky). As shown by evidence from the progressive onlapping of black-shale units on the Cincinnati Arch and other lines of evidence already mentioned, the "Black-Shale Sea" progressively deepened on the craton. Eventually, deepening was great enough that a pycnocline was established throughout the cratonic "Black-Shale Sea", and black, organic-rich muds accumulated in the bottom layer throughout the sea. In Kentucky, this occurred during the deposition of the middle Huron Shale Member, for this is the first unit to completely overlap the Cincinnati Arch (Swager, 1978; Ettensohn and others, 1979). This is approximately coincident with the first major occurrence of phosphate nodules in the upper Huron Shale Member, suggesting that the "Black-Shale Sea" had deepened sufficiently to allow upwelling (Fig. 8E).

During the same period, eastern parts of the peripheral basin were essentially filled by the Catskill Delta, and the locus of subsidence and sedimentation moved westward, pushing the effective eastward limit of successive black-shale transgressions progressively westward also (Fig. 8E). As the locus of sedimentation moved westward, the two last intervening progradational episodes (Three Lick-Chagrin, and Bedford-Berea) migrated onto portions of the Cincinnati Arch, thereby pushing the upwelling waters westward and establishing short-lived periods, of dysaerobic conditions (Barron and Ettensohn, 1980; Fig. 7).

In the Early Mississippian, the "Black-Shale Sea" attained its greatest extent, extending from eastern Ohio westward to southern Alberta. Large-scale collisional movements at this time in the Antler Belt (Poole, 1974) and in the present North Atlanta area where parts of Africa pushed the southern European microcontinents against east-central portions of Laurussia (Badham and Halls, 1975; see Fig. 4) resulted in depression of the entire central portion of the craton and eustatic rise in sea-level, causing the "Black-Shale

Sea" to transgress westwardly across the Transcontinental Arch (Fig.). Even though the transgression was relatively brief, the presence of relatively unfossiliferous fissile, black shales as far westward as Alberta indicate that the sea was sufficiently deep to establish a pycnocline and an anaerobic bottom layer. Although upwelling, as indicated by the presence of phosphate, continued in central portions of the Mississippian "Black-Shale Sea", it is uncertain whether upwelling occurred in the newer, western extension of the sea.

The Lower and Middle Mississippian clastic wedge (Borden-Grainger-Pocono) that overlies the Mississippian black shale actually marks the end of the last black shale-clastic cycle (Figs. 5, 8F) and the beginning of a period of regional tectonic quiesence. As the newly elevated mountains to the east were eroded, vast amounts of deltaic clastics prograded westward and southwestward in the "Black-Shale Sea" of the central craton (Fig. 8F). A similar progradation from the Antler Belt may have migrated eastward into western extensions of the sea (see Gutschick and Moreman, 1967). As subsidence and transgression declined in this period of tectonic quiesence, the deltaic clastics and associated deposits (e.g., Fort Payne) essentially filled the "Black-Shale Sea", establishing first, dysaerobic conditions (e.g., Nancy Shale of eastern Kentucky), and later aerobic conditions. The shallow-water platform built out into the former "Black-Shale Sea" basin during this progradation became the site of extensive, shallow-water carbonate deposition during the Middle and Late Mississippian.

CONCLUSIONS

1.) The Devonian-Mississippian black-shale sequence was deposited in an equatorial, inland, epicontinental sea. The sea was bounded on the west by the Transcontinental Arch, on the north by the Old Red Sandstone Continent, and on the south and east by the Acadian highlands. The only opening to the open ocean was to the southwest in the Ouachita region of Arkansas and in the Marathon region of Texas.

2.) Devonian-Mississippian black-shale deposition reflects a low rate of clastic influx, high organic productivity, and development of anaerobic conditions in a stratified water column within a restricted inland sea.

3.) The organic productivity in the "Black-Shale Sea" apparently was rather high. Although organic productivity in upper parts of the water column is usually high, organic productivity in upper parts of the "Black-Shale Sea" apparently was extraordinarily high. This was related to the equatorial nature of the sea, continual replenishment of nutrients by surface runoff from surrounding land, and the presence of an oceanic upwelling during later parts of black-shale deposition. Considerable organic input was also derived from terrestrial sources to the east, but much of the terrestrial organic matter is concentrated in eastern parts of the black-shale sequence.

4.) The black shales were deposited during a dominantly transgressive period, which can be related to a time of increased spreading rates on a world-wide basis. The increased spreading rates were reflected in increased subduction, obduction, and collision at continental margins.

5.) Deposition of the North American black shales was concurrent with and related to the Acadian Orogeny. The resulting Acadian Mountains developed across the paleoequator and just east of the "Black-Shale Sea."

6.) Collision and uplift in the Acadian Mountains not only caused cratonic subsidence and transgression to the west, but created a barrier to the moisture-laden trade winds. This caused rainshadow conditions west of the mountains and reduced clastic influx into the "Black-Shale Sea." In the absence of clastics, the indigenous organic debris forming in the upper part of the water column was the major constituent of accumulating sediments.

7.) During periods of tectonic quiesence, subsidence abated and erosion lowered the mountains to the point that the trade winds could cross the equator and deliver precipitation to western parts of the mountains. This resulted in vast influxes of clastics and rapid westward progradations of the Catskill Delta into the "Black-Shale Sea."

8.) Seven such major cycles of alternating black shales and coarse clastics are represented in the Catskill Delta complex. The black-shale units from these cycles are: Marcellus, Geneseo-Burket, Middlesex, Rhinestreet, Huron-Dunkirk, Cleveland, and Sunbury. The Pipe Creek Shale represents yet another black-shale unit occurring between the Rhinestreet and Huron-Dunkirk; because of its comparatively thin nature, it is not included with the others. Of the major black-shale units, only the latter three units (Hyron-Dunkirk, Cleveland, and Sunbury) were effectively deposited beyond the Appalachian peripheral basin.

9.) Cratonic subsidence was greatest in the Appalachian peripheral or foreland basin west of the mountains. The increased subsidence in this basin apparently had a confining effect on the progradational wedges, for most of the clastic wedges did not migrate beyond the peripheral basin. Hence, even during rainy periods to the east, starved-sediment conditions persisted in cratonic portions of the "Black-Shale Sea."

10.) Because the "Black-Shale Sea" received at least periodic influxes of fresh water, the surface waters were probably somewhat brackish. Moreover, due to the equatorial nature of the sea, the surface waters were probably warmer and less dense than the bottom waters. These conditions apparently resulted in the formation of a stratified water column or pycnocline which prevented vertical circulation and oxygenation of the cold, dense bottom waters. Under these conditions, organic-rich sediments were preserved in anaerobic, azoic conditions below the pycnocline.

11.) During the initial stages of transgression, each cratonic basin (Appalachian, Illinois, Michigan) developed its own pycnocline, and black muds accumulated spearately in each basin. As depth increased progressively with transgression, a pycnocline developed throughout the entire "Black-Shale Sea", so that black muds were deposited uniformly throughout the basin of deposition. In Kentucky this occurred during deposition of the upper Huron Shale, which was the first part of the shale sequence to completely overlap the Cincinnati Arch in Kentucky. Eventually, depth increased to the point that upwelling oceanic waters entered from the continental margin. This is indicated by the presence of phosphates in the upper part of the black-shale sequence.

12.) If the black-shale sequence is viewed as a single unit, it can be traced laterally from the Middle Devonian Marcellus Shale of New York across the continent to the Lower Mississippian Exshaw Shale of western Canada. Viewed in this way, the black-shale sequence represents a transgression during a period of time linking the Middle Devonian through Early Mississippian.

13.) The cratonic black-shale sequence represents deposition in a progressively deepening sea. Basal parts of the shale represent shallow-water conditions which are poorly preserved or condensed due to the rapidity of transgression and the low-lying surface over which the sea transgressed. Upper phosphatic portions of the shale represent the deepest phases of the sea.

14.) The "Black-Shale Sea" attained its greatest extent during the Early Mississippian when it extended from eastern Ohio across the Transcontinental Arch into Alberta, Canada. This extensive transgression is related to widespread cratonic subsidence accompanying pulses of tectonism in the Acadian and Antler mountain belts.

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☆ U.S. GOVERNMENT PRINTING OFFICE: 1980-740-146/33