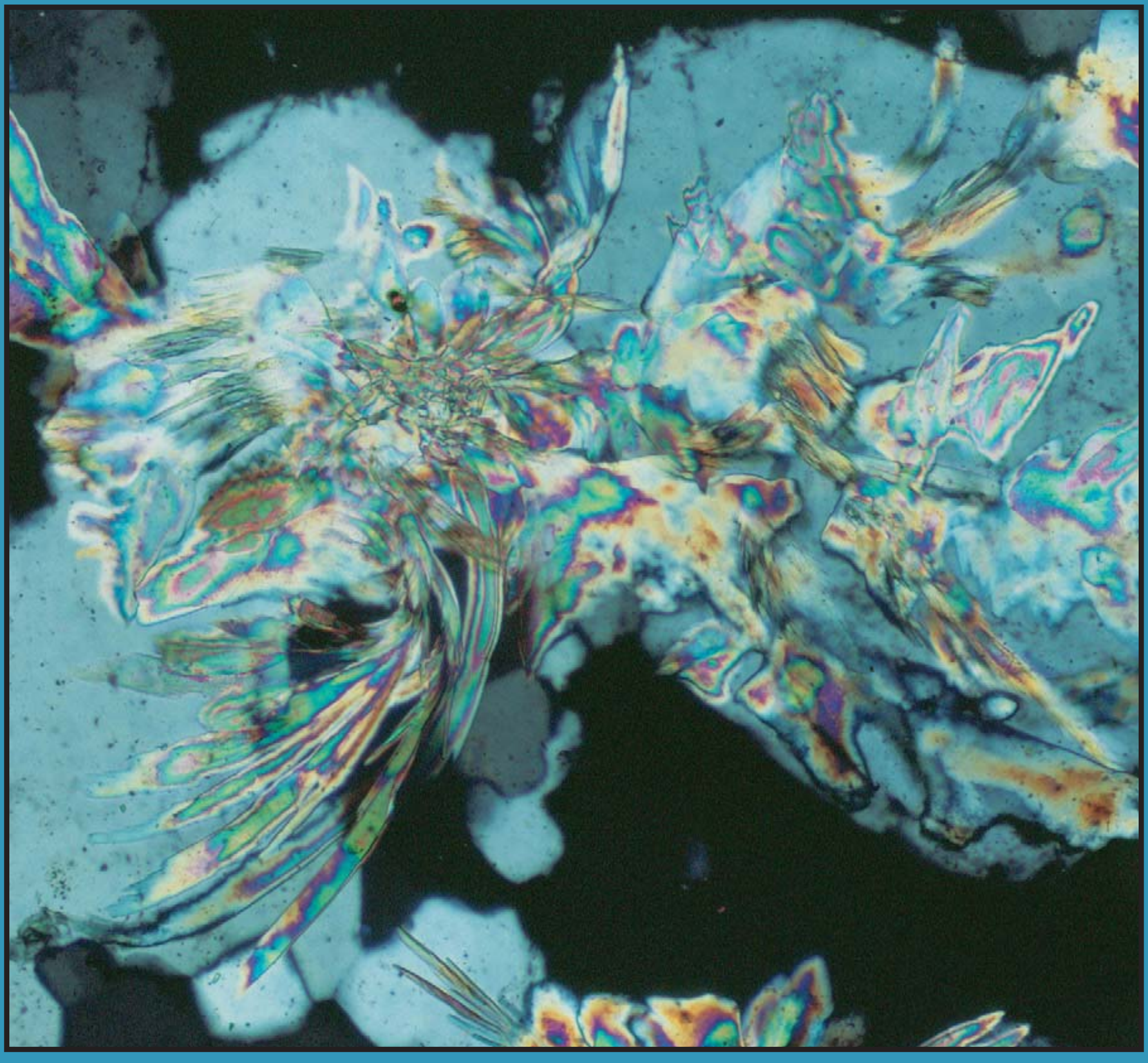
BULLETIN 73

GEOLOGY OF THE DUNKARD GROUP (UPPER PENNSYLVANIAN-LOWER PERMIAN) IN OHIO, WEST VIRGINIA, AND PENNSYLVANIA

by
Wayne D. Martin



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DIVISION OF GEOLOGICAL SURVEY
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Composition and layout by Lisa Van Doren

Cover illustration: Photomicrograph of authigenic illite, a clay mineral, replacing detrital quartz grains in the Hockingport Sandstone Lentil.

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ABSTRACT

In Late Pennsylvanian time and Early Permian time, streams flowed north and northwestward across the southeastern and central Appalachians. The streams originated in an orogenic belt of folded and faulted strata formed from recycled sediments and emptied into a shrinking epeiric sea of the Dunkard foreland basin. The outlet of this distal subbasin of the Appalachian Basin was to the west. A clastic wedge composed mainly of fine-grained sediments was developed north and northwestward across the region, for the most part in prograding fluvial-deltaic environmental complexes. Streams flowed southward from the Canadian Shield as well, bringing some detritus from the stable craton, where the surface rocks also were composed of recycled sediments.

A narrow marine embayment formed an extension of the epeiric sea of the Central Interior area in the region during Pottsville and Allegheny times and most of Conemaugh time of the Pennsylvanian Period. The last extensive marine incursion into the basin, the Ames sea, took place in mid-Conemaugh time, and overall regression of the sea followed. Fluvial-dominant deltas extended into the region during the regression of the sea. By late Conemaugh-Monongahela time, a river-influenced, low-salinity bay-lake having a western outlet was present; this bay-lake occasionally was freshened by minor marine incursions. By early Dunkard time, the bay-lake had become a fluvial-lacustrine-deltaic plain in the north. At the same time, to the south were lower and upper fluvial plains.

Owing to subsidence in the basin and uplift through time in the southeastern source terrane during the Alleghany orogeny, the lower and upper fluvial plains shifted northward over the more lacustrine-deltaic freshwater environments. Freshwater limestones, coals, carbonaceous shales, and sheet sandstones of the lower part of the 360-meter-thick Dunkard Group were replaced upward in the section by thicker, elongate sandstones and red mudstones characteristic of the southern fluvial plains. Many of the red beds of the upper Paleozoic rock sequence contain subaerial exposure features (gilgai structures) and carbonate nodules and represent paleosols formed in a tropical climate that alternated between heavy rainfall and drought.

Mudstones and lesser thicknesses of shales constitute nearly two-thirds of measured stratigraphic sections in the Dunkard Group, and sandstones nearly one-third. Coal and limestone make up approximately 5 percent of the sections; they constitute less than 10 percent of the rock sequence in the north and are virtually absent in the southern part of the basin. Mudstones and shales are composed mainly of quartz silt, kaolinite, illite, and mixed-layer clay minerals. The sandstones are lithic arenites (litharenites), rich in quartz, sedimentary and metamorphic rock fragments, and detrital mica and poor in feldspar.

The major paleoslope during Dunkard time was north to northwest, on the basis of cross-bed orientation in large sandstone bodies, trends of elongate sandstone bodies, grain-size and mineralogical differences, facies relationships, and the presence of the brackish-water brachiopod *Lingula*, suggesting proximity to a marine environment to the "west."

The generally freshwater to brackish-water environments of the northern part of the region provided a lush habitat for flora and vertebrate and invertebrate fauna. Leaves, stems, pollen and spores of lycopsids, sphenopsids, ferns, seed ferns, and conifers are represented in the fossil flora. Vertebrate fossils include sharks, reptiles, and amphibians. Shark remains are uncommon and consist primarily of teeth. Reptile remains are rare but significant and include the pelycosaur *Edaphosaurus*. Amphibian fossils are diverse and abundant at a few localities in Ohio and most commonly are represented by the tetrapod *Eryops*. Invertebrate fossils include conchostracan branchiopods, ostracodes, the inarticulate brachiopod *Lingula*, and nonmarine probably terrestrial gastropods. Fossil insects have been collected from the roof shales of coal beds.

Some paleobotanists believe that the seed fern *Callipteris conferta*, the early conifer *Walchia*, and the sphenopsid *Sphenophyllum thoni* may allow correlation of most of the Dunkard Group within the Autunian Stage (Lower Permian) of western Europe, supporting earlier observations that the thicker, upper part of the Dunkard sequence is Permian in age. Some invertebrate fossils, including the insects, also indicate an Early Permian age for the upper part of the Dunkard. The vertebrate fossils for the most part do not provide an age assignment more specific than Late Pennsylvanian or Early Permian.

The lack of extensive marine incursions and short-term tectonism and a gradual change from a seasonally dry tropical climate to drier climatic conditions resulted in a rock sequence transitional in nature and lacking regional unconformities. The age of the Dunkard Group has, therefore, been a controversial subject for well over a century.

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Chapter 1

INTRODUCTION

This bulletin relates the "Dunkard Story" as it can be told at this time. It is a compilation of knowledge of the Dunkard Group developed from many sources, some of which are not readily available. This compilation is not intended as a final analysis of the composition and origin of these upper Paleozoic rocks, but as a foundation on which to base future research.

The Dunkard Group is a coal-bearing, mixed clastic and carbonate unit, up to 360 meters[1] thick, that has been studied for approximately a century and a half. A large body of data exists on the mineralogy, facies, regional variation of facies, paleocurrents, and geometry of sandstone bodies of the sequence, owing to at least 28 graduate thesis studies conducted by students at several universities. As a result of these and other studies, the sedimentary environments, provenance terranes, and the location of the outlet of the Dunkard foreland basin are well defined. The age of the Dunkard Group, however, has been a controversial subject since serious study of the unit commenced and has not yet been clearly established further than that it is Permian or probably Pennsylvanian-Permian.

LOCATION AND STRUCTURAL SETTING

The strata of the Dunkard Group generally crop out in Ohio, West Virginia, and Pennsylvania in an elliptical area of approximately 12,800 km^2 within the central Appalachians (fig. 1). An additional very small area of Dunkard strata crops out in the Georges Creek basin of western Allegany County, Maryland (Berryhill, 1967). These rocks probably represent only a remnant of a vast extent of upper Paleozoic sediments once deposited in the region.

Existing Dunkard rocks in the main outcrop belt were preserved from erosion within an elongate, folded basin structure, having a northeast-trending axis approximately parallel to the Appalachian fold belt, which lies 80 km (50 miles) to the east. Regional dips are 2° to 5° toward the axis, except in the southern third of the area, where the main structure is the north-south-trending Burning Springs Anticline (Branson, 1962). The nature of this complex anticline and other folds and their influence on sedimentation in the region during the late Paleozoic have been described by Arkle (1974).

STRATIGRAPHIC CLASSIFICATION AND NOMENCLATURE

The rocks in the Dunkard Group have been described by various stratigraphic names. Arkle (1959), Berryhill and others (1971), and Barlow (1975) provided very brief sketches of the classification, nomenclature, and correlation of the Monongahela (Upper Pennsylvanian) and Dunkard strata through time. Larsen (1991) described the historical development and problems with the nomenclature of the Pennsylvanian System of Ohio.

H. D. Rogers (1858, p. 20) used the name Newer Coal Shales, or Upper Barren Group, for outcrops in the southwestern corner of Pennsylvania. In Ohio, Newberry (1874, p. 158) termed these strata the Barren Measures and included them in the Upper Coal Measures. Stevenson (1876, p. 356) regarded these beds as the Upper Barren Series but considered the thickness so great that for convenience he divided the rock sequence into two groups. The lower portion he designated the Washington County Group and included the strata from the top of what was later named the Waynesburg sandstone to the top of the Upper Washington limestone. The upper portion Rogers named the Greene County Group and included the beds above the Upper Washington limestone (see fig. 2).

Andrews (1873, p. 247-313; 1874, p. 441-587) did not separate the Upper Barren Measures from the coal-bearing strata of the Pennsylvanian System in his description of the geology of southeastern Ohio. Orton (1884, p. 1) accepted the original classification of Rogers but in 1888 (p. 3) referred to the rock sequence as the Upper Barren Coal Measures. A few years later, Orton (1893, p. 37, 55, 63) wrote that these rocks might possibly be Permian in age.

The name Dunkard was introduced into the literature by I. C. White in 1891 (p. 100-123). White used "Dunkard Creek Series" to include the Upper Barren Measures, the Waynesburg sandstone, and the roof shales of the Waynesburg coal, which together he considered to be Carboniferous-Permian in age. In 1903, White (p. 88) shortened the name to Dunkard Series.

In 1907, Stevenson (p. 96-97) considered the Dunkard Series to include his two subdivisions, which he named the Washington and the Greene Formations, thus replacing his original names of Washington County Group and Greene County Group. Stevenson also included the Waynesburg sandstone and the shales above the Waynesburg coal in the Washington Formation, following the suggestion of I. C. White (1891) that these strata should be included in the sequence (fig. 2). Authors of several folios of the U.S. Geological Survey covering portions of southwestern Pennsylvania used the term Dunkard Group for White's Dunkard Series, considered the group to be Permian in age, and divided it into the Washington and Greene Formations (Stone, 1905; Clapp, 1907a, 1907b; Shaw and Munn, 1911; Munn, 1912).

Prosser (1905) considered the Dunkard to be a formation rather than a group. Stauffer and Schroyer (1920, p. 11) used the 1907 classification of Stevenson and considered the rocks to be a Permian series divisible into the Washington and Greene Formations. Norling (1958, p. 88) used the term "group" rather than "series" for the Dunkard, following the custom of the U.S. Geological Survey.

Stevenson (1876), working in Pennsylvania, had named many of the coals, limestones, and prominent sandstones of the Dunkard Group and the underlying Monongahela Group. Numbers were assigned to the limestones and letters to the coals in an ascending numerical or alphabetical system.

[1]Metric measurements are used throughout this bulletin except for map distances, which are given in miles and kilometers.

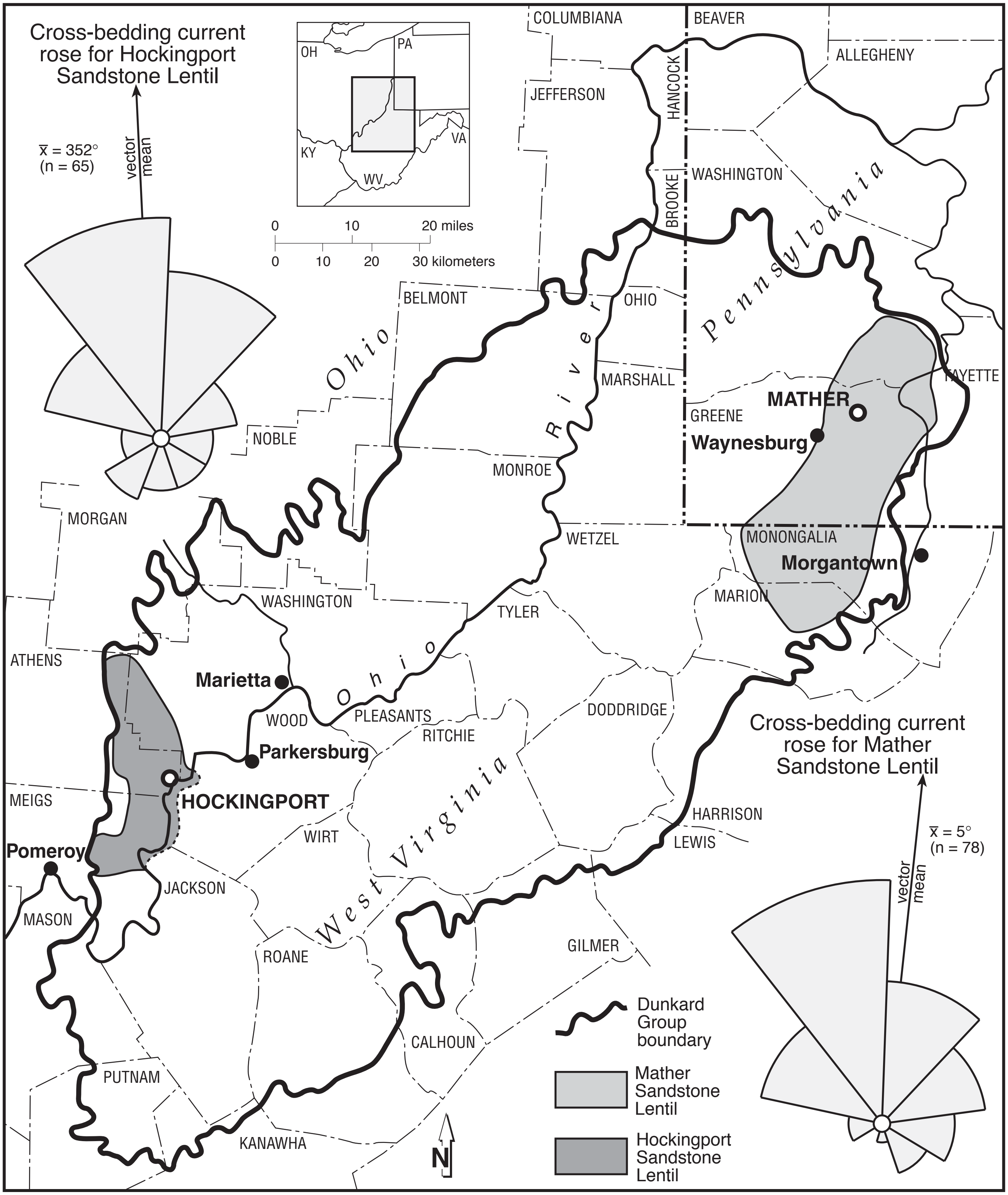

FIGURE 1.—Map showing the Dunkard Group boundary, approximate locations of the Mather and Hockingport Sandstone Lentils, and cross-bedding data for each sandstone body. Modified from Martin and Henniger (1969); reprinted by permission of the American Association of Petroleum Geologists. For rose diagrams, n = number of measurements, $\overline{x}$ = average dip direction.

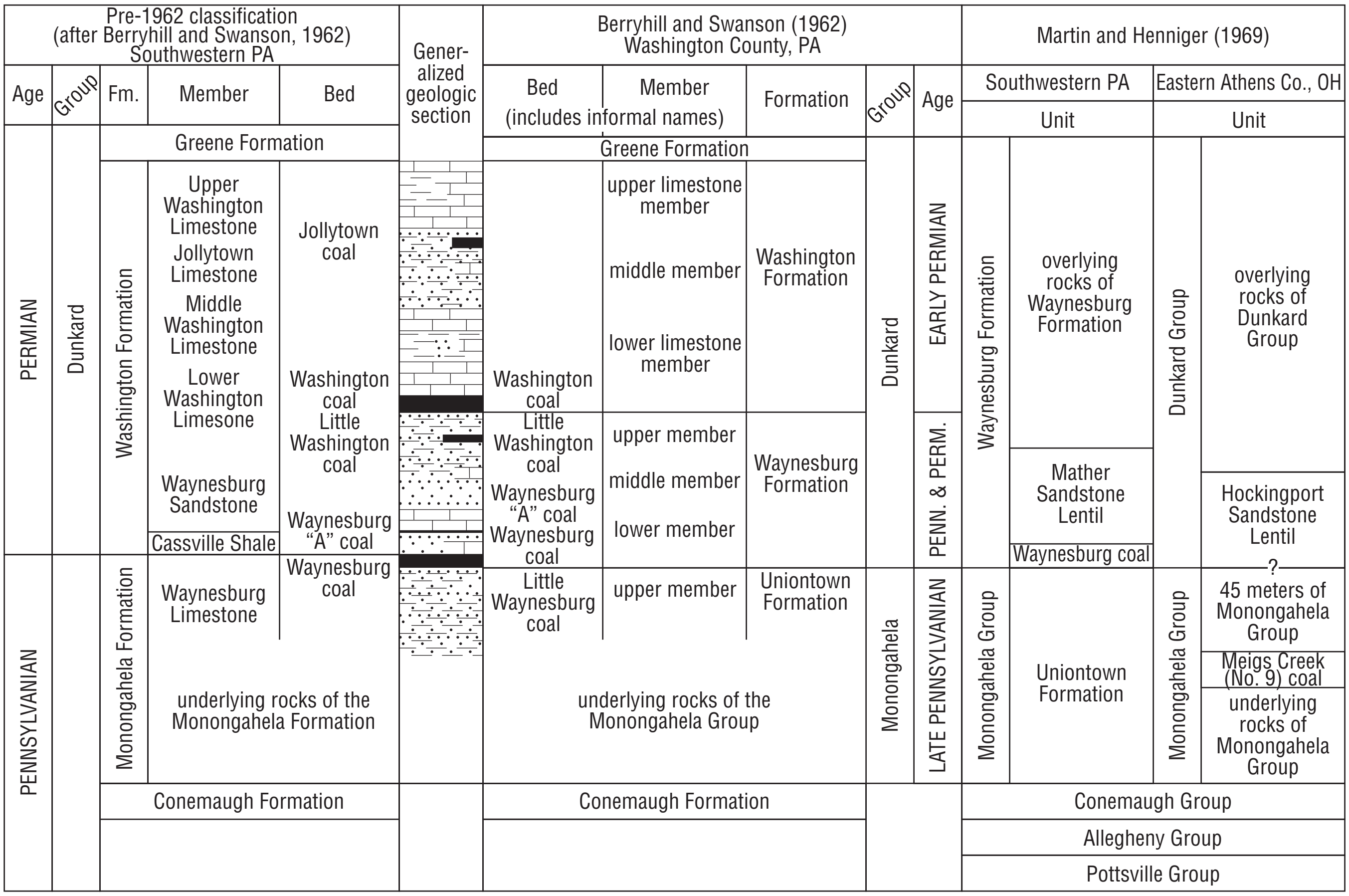

FIGURE 2.—Generalized stratigraphic nomenclature of the upper part of the Monongahela Group and the lower part of the Dunkard Group in southwestern Pennsylvania and eastern Athens County, Ohio. Not to scale.

I. C. White (1891) and other members of the Pennsylvania and West Virginia geological surveys assigned additional or alternate names.

Names were applied first to the mineable coal beds and to more persistent limestone units, then to a few sandstone units (Berryhill and Swanson, 1962). These rock units were considered members or beds and also were referred to as "horizons," especially where discontinuous (Stauffer and Schroyer, 1920). The same geographic name commonly was applied to more than one lithologic unit in the same area, for example, the Waynesburg coal and the Waynesburg sandstone. According to Berryhill and Swanson (1962), the name Waynesburg had been assigned to six different stratigraphic units, including rocks of three different lithologies, and more than 80 names were applied to the Pennsylvanian and Permian strata in Ohio, Pennsylvania, and West Virginia. The use of so many names added confusion, especially where the units could not be mapped or correlated. In addition, the continued use of the same geographic name for more than one lithologic unit in the same area violates article 7(b) of the Code of Stratigraphic Nomenclature (North American Commission on Stratigraphic Nomenclature, 1983), although, of course, the Code did not exist at the time the names were generated.

Columnar sections showing the more commonly used rock unit names are given in Barlow (1975) and Collins and Smith (1977). The following list of units of the Washington and Greene Formations, named for localities in Ohio, West Virginia, and Pennsylvania, is modified from the extensive section of Stout (1943):

Greene Formation:
- Gilmore sandstone, shale, limestone
- Nineveh sandstone, shale, coal, limestone
- Hostetter coal, shale
- Fish Creek coal, shale, sandstone
- Dunkard coal, shale
- Jollytown sandstone, shale
- Jollytown "A" coal

Washington Formation:
- Upper Washington shale, limestone
- Hundred sandstone, shale
- Upper Marietta sandstone, shale
- Washington "A" coal
- Middle Washington limestone-Creston Reds shale
- Lower Washington limestone, shale
- Lower Marietta sandstone, shale
- Washington (No. 12) coal
- Little Washington coal
- Mannington sandstone, shale
- Waynesburg "A" coal
- Waynesburg sandstone, shale
- Elm Grove limestone
- Cassville shale

I. C. White (1903) had extended the name Waynesburg sandstone from the sandstone body in southwestern Pennsylvania and northeastern West Virginia to include other sandstones across the Dunkard outcrop region. The extension of the name to include local sandstone units and other facies implies continuity of the sandstone. Stauffer and Schroyer (1920) referred to the Waynesburg sandstone in measured sections in southeastern Ohio and considered it a continuous sandstone in Washington, Athens, and Meigs Counties.

Sturgeon and associates (1958) suggested that the sandstone in the position of the Waynesburg in the Athens County area represents coalesced Gilboy and Waynesburg sandstones, and where the sandstone is extremely thick it may consist of these sandstones as well as the Mannington. The Gilboy and Mannington sandstones were named for localities in West Virginia. The Gilboy sandstone underlies the Waynesburg (No. 11) coal, which traditionally has been considered to be the uppermost unit of the Monongahela Group; the Mannington sandstone overlies the Waynesburg sandstone in the Dunkard Group (see list of units above).

In 1962, Berryhill and Swanson revised the stratigraphic nomenclature for the Upper Pennsylvanian and Lower Permian rock sequences in Washington County, Pennsylvania. The authors redefined the classical stratigraphic names and restricted these names to rock units in southwestern Pennsylvania. They elevated the name "Waynesburg" from member status to formation status, but also retained Waynesburg for informal application to coal beds. Their newly defined formation incorporated the lower part of the Washington Formation and included the Waynesburg coal, in contrast to its traditional position as the uppermost unit of the Monongahela Formation (fig. 2).

Prior to Berryhill and Swanson's 1962 revision, the Waynesburg sandstone had been considered a member in the lower part of the Washington Formation. In their revision, the sandstone was noted as a sandy facies and the main unit of the lower member of the Waynesburg Formation (fig. 2). The name Waynesburg sandstone had been applied to sandstones in West Virginia and Ohio. By restricting use of the new names to southwestern Pennsylvania, Berryhill and Swanson implied that the name Waynesburg sandstone became inappropriate for use in West Virginia and elsewhere.

Martin and Henniger (1969) proposed the name Mather Sandstone Lentil for the Waynesburg sandstone where it occurs as a continuous unit in southwestern Pennsylvania and northern West Virginia. They proposed the name Hockingport Sandstone Lentil, derived from Martin's (1955) Hockingport sandstone, for a similar sandstone body in a similar stratigraphic position present mainly in Washington, Athens, and Meigs Counties, Ohio (figs. 1 and 2).

The Waynesburg coal lies below the Waynesburg (Mather) sandstone in parts of southwestern Pennsylvania and northeastern West Virginia. Collins and Smith (1977) pointed out that nomenclatural problems arise from a lack of a definitely identifiable Waynesburg coal in Washington County, Ohio. They believed it unwise to correlate the Hockingport sandstone with the Waynesburg sandstone. Martin and Henniger (1969) identified the Mather and Hockingport Sandstone Lentils as separate, lenticular, sandstone bodies, separated by approximately 113 km (70 miles) (fig. 1).

On the Correlation of Stratigraphic Units of North America (COSUNA) chart for the Northern Appalachian region (Patchen and others, 1985), the Dunkard Group is divided into the Washington and Greene Formations in southeastern Ohio. The nomenclature of Berryhill and Swanson (1962) is indicated for West Virginia and also for southwestern Pennsylvania but with question marks placed at the boundaries of the Washington and Greene units for the Pennsylvania stratigraphic section. The chart shows the lower part of the Dunkard Group as Upper Carboniferous (Virgilian) and the thicker, upper part as Lower Permian (Wolfcampian and Leonardian).

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Chapter 2

LITHOFACIES CHARACTERISTICS

CYCLICITY IN UPPER PENNSYLVANIAN AND PERMIAN STRATA

Numerous workers have described the cyclicity of rock units in Upper Pennsylvanian and Permian strata. The cyclothem concept, introduced from studies of Pennsylvanian rocks in Illinois (Udden, 1912; Weller, 1930), was applied to these predominantly terrestrial cyclic rock sequences of the Appalachian Plateaus (Reger, 1931; Wanless, 1946; Cross and Schemel, 1956a). An 11-member cyclic rock sequence was described by Cross and others (1950) and by Cross and Schemel (1956a) for the upper part of the Monongahela Group and the lower part of the Dunkard Group; the upper part of the Dunkard was divided into eight cyclothems.

Beerbower (1961) described the cyclothems in the Dunkard Group as having been formed from an alternating sequence of alluvial-plain and lacustrine-deltaic-plain sediments. He pointed out that, although the Dunkard cyclothems show considerable similarity to those in Illinois, the Dunkard lacks marine units. Beerbower (1961, p. 1031) noted that, although some cyclothems can be traced throughout the Dunkard outcrop area, individual units are laterally discontinuous and show considerable variation in a few kilometers. Beerbower (1969) and Ghosh (1987) described the cyclic nature of rock units of the Monongahela and Dunkard Groups in central West Virginia and considered the accumulation of sediments as being entirely alluvial.

The cyclic repetition of Dunkard rock units in southwestern Pennsylvania has been described in several reports (Berryhill and Swanson, 1962; Berryhill, 1967; Berryhill and others, 1971). The cyclic pattern in the Dunkard Group of the Washington County, Pennsylvania, area is modified by an overall upward increase in quartz sandstone, siltstone, and mudstone relative to limestone. In addition, there are lateral differences in the vertical sequence owing to intertonguing of different rock types (Berryhill and others, 1971). Klein and Willard (1989) compared the types of cyclothems developed in the Kansas, Illinois, and Appalachian regions.

Larsen (1991) described the adoption, or lack of adoption, of cyclothemic terminology applied to the Pennsylvanian System during several decades of research by geologists of the Ohio Geological Survey. Placement of the stratigraphic boundaries between cyclothems was arbitrary and differed among Survey geologists. Boundaries were variously placed at the base or top of coal beds, the base of underclays, or the base of sandstones. The practice of applying the name of the primary key bed to unnamed strata between key beds led to the development and duplication of many stratigraphic terms. In 1956, the Ohio Geological Survey ceased to use the cylothem as a lithostratigraphic unit, but the concept of cyclic sedimentation was used for correlation and accumulation of lithostratigraphic data.

The cyclothems that were recognized in the coal measures on the basis of Udden's (1912) description of cyclic sedimentation were later believed to have developed as a result of regressive-transgressive couplets that were caused by tectonic and/or eustatic controls, especially glacio-eustatic controls (Donaldson and Eble, 1991).

Several authors have described cycles in the Appalachian and Illinois Basins in relation to deltaic environments and resulting from autocyclic or allocyclic controls (Williams and Ferm, 1964; Ferm and Williams, 1965; Wanless and others, 1970; Ferm, 1970, 1975). Autocylic deposition, originally defined by Beerbower (1964, p. 32), results from shifting supplies of sediments within a sedimentary system. Allocyclic deposition (Beerbower, 1964 p. 32) results from changes in the supply of energy or sediments, such as tectonic or eustatic controls. Donaldson and Eble (1991) referred to many studies in which emphasis on depositional environments and their determining processes resulted in the development of depositional models. Donaldson and Eble also described both autocycles and allocycles in the Upper Pennsylvanian rock sequences of the Appalachian basins, including the Dunkard basin.

CHRONOSTRATIGRAPHY OF DUNKARD GROUP ROCKS

Lateral lithic variability and a paucity of identifiable marker beds are both characteristic of the Dunkard Group. Other than three or four persistent limestone and coal beds in the northern third of the outcrop area, stratigraphic units traceable over more than a few tens of square kilometers are generally lacking. In the southern part of the area, well-defined units suitable for regional correlations simply do not exist. The added problems in regard to nomenclature introduced by previous attempts to extrapolate locally restricted units over thousands of square kilometers, the so-called "layer-cake" concept, have been dealt with elsewhere (Martin, 1955; Berryhill and Swanson, 1962; Martin and Henniger, 1969). According to Ferm (1974b), environmental modeling of Carboniferous sedimentary rocks has helped in clarifying problems that have existed in understanding the stratigraphic sequences. Some solutions have been provided, but serious questions also have been raised. Ferm (1974b, p. 94) stated that environmental modeling "has provided a greater possibility for predictive stratigraphy than the simple 'layer-cake' models of the past, but it also demands more detailed information and greater precision in mapping and stratigraphic work."

One current approach to the study of rock-unit relationships is sequence stratigraphy, the study of genetically related facies within a framework of chronostratigraphically significant surfaces (Van Wagoner and others, 1990). The eroded upper part of the Dunkard Group lacks a significant chronostratigraphic boundary. The Waynesburg coal best serves as a chronostratigraphic unit at the base of the group, but this coal is most extensive in the northern part of the basin, where it lies below the Mather (Waynesburg) Sandstone Lentil (figs. 1, 2, and 3). However, until Berryhill and Swanson (1962) reclassified the Waynesburg coal as the basal unit of the Dunkard Group (fig. 2), the Waynesburg coal was considered the upper unit of the Monongahela Formation. In a 1967 publication Berryhill still referred to the Waynesburg coal as the upper unit of the Monongahela rock sequence, but Berryhill and others (1971) considered this coal to be the basal unit of the Dunkard Group. The Ohio Geological Survey (Larsen, 1998) still considers the Waynesburg coal to be the uppermost unit of the Monongahela Group. Thus, the chronostratigraphically significant surface in the Monongahela-Dunkard rock package is either the base or the top of the Waynesburg coal.

LITHOFACIES TYPES

A large body of lithofacies and paleocurrent data on the Dunkard rocks has been developed in thesis studies at Miami University, including the description and measurement of 134 selected stratigraphic sections, each greater than 90 meters in thickness, spaced throughout the Dunkard basin (Liston, 1962; Baker, 1964; O'Brien, 1964; Camp, 1968; Lorenz, 1971). Fine clastic rocks—shale and mudstone—predominate in the Dunkard Group, forming 65 percent of the thickness of measured stratigraphic sections. Sandstone constitutes 30 percent of measured-section thickness, and minor amounts of coal and limestone constitute the remaining 5 percent. Thin, freshwater limestones and coals constitute less than 10 percent of the rock sequence in the north but are virtually absent in the southern part of the outcrop area (Martin and Lorenz, 1972).

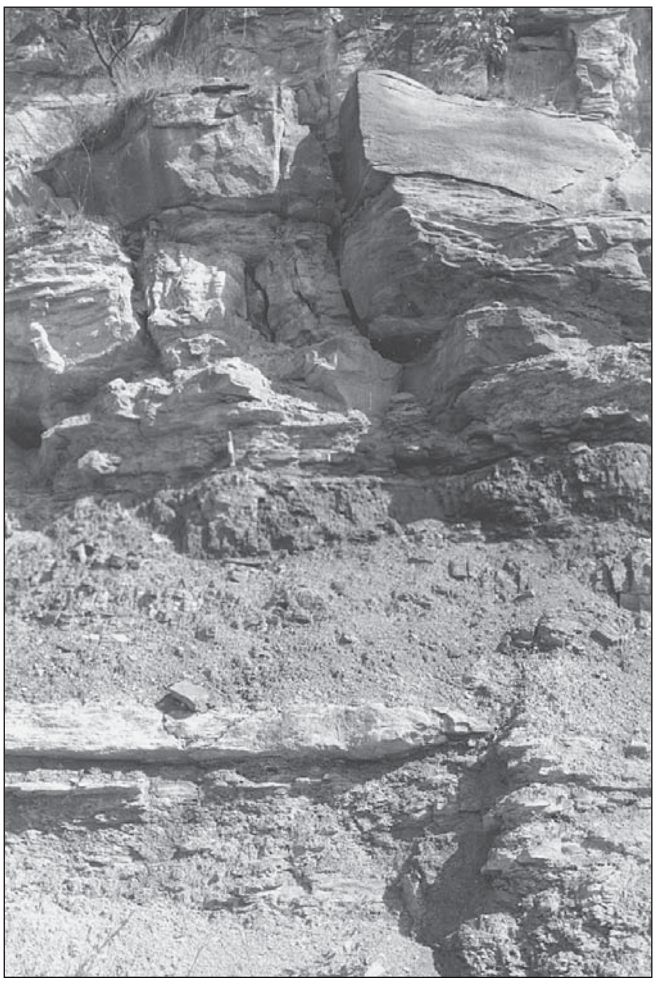

FIGURE 3.—Outcrop of the Waynesburg coal below the blocky to massive Mather (Waynesburg) Sandstone Lentil in a railroad cut 3.2 km (2.0 miles) east of Waynesburg, Greene County, Pennsylvania. Photo taken in 1950. The coal is approximately 0.6 meter thick. The hammer resting on the coal is 30 cm long. From Martin and Henniger (1969); reprinted by permission of the American Association of Petroleum Geologists.

The term "mudstone" is used in this bulletin as a general term for fine-grained clastic rocks, regardless of relative amounts of terrigenous clay, silt, and sand and presence or lack of lamination and fissility. Potter and others (1980, p. 14) classified mudstone as a fine-grained rock having more than 50 percent grains less than 0.062 mm and bedding thickness greater than 10 mm. This classification is appropriate for most of the fine-grained, clastic rocks of the Dunkard Group.

Color of the Dunkard mudstones ranges from red, ocher, purple, maroon, and buff in the southern part of the outcrop area to predominantly gray, green, and black in the north, reflecting oxidation potentials in the respective sedimentary environments and at the surface. Arkle (1959, 1969, 1974) described the Dunkard facies as gray, transitional, and red from north to south in the basin. To simplify reference to the mudstones according to color, the terms "red" and "nonred" terms are used herein. Buff is included in the red group. Gray, green, and black units are considered as "nonred."

A. C. Donaldson (West Virginia University, personal commun., 1994) has determined that, on the basis of mineralogy, texture, and structure, the red rocks of the region can be differentiated into red shales, red claystones, and red mudstones. The laminated red shales appear to have developed from undisturbed, water-deposited sediments, and the nonlaminated red mudstones represent paleosols (disturbed and weathered zones). According to Donaldson and others (1985), the red claystones that have both pseudoanticlinal structures and carbonate nodules oriented orthogonal to bedding indicate soil formation in a paleoclimate that alternated between heavy rainfall and drought.

The black, thinly laminated, carbonaceous shales of the Dunkard Group commonly are associated with the coals. The shale units are, in general, only several centimeters thick and rarely more than 30 cm. Where the coal beds split into "benches" the shales invariably separate them (Arkle, 1959, p. 122).

DISTRIBUTION OF LITHOFACIES

Values for nine facies variables in Dunkard rocks were computed by Lorenz (1971), together with a small set of summary statistics, which are listed in table 1 of this bulletin. These variables reflect the regional distribution of clastic particle size, bedding thicknesses, abundance of coals and limestones, and the relative proportions of red and nonred mudstones. Lorenz (1971) also developed lithofacies maps based on the facies variables; six of these maps are reproduced in figure 4.

Except for the clastic/total thickness ratio, which can range only between 0 and 1, the facies variables are defined for all positive, real numbers. Table 1 conveys an idea of the sample distributions of these variables. The coefficients of variation indicate that the red/nonred mudstone ratio,

TABLE 1.—*Summary of Dunkard Group lithofacies statistics*[1]

Variable	Range	Mean	Standard deviation	Coefficient of variation
Average sandstone thickness	3.07 - 67.50	13.17	10.10	0.77
Sandstone/mudstone ratio	0.11 - 2.55	0.84	0.44	0.52
Number of nonred mudstones per 60 m	0.87 - 38.50	11.21	8.11	0.72
Clastics/total thickness ratio	0.66 - 1.00	0.97	0.05	0.05
Number of limestones per 60 m	0.00 - 22.30	2.05	3.58	1.75
Number of coals per 60 m	0.00 - 8.76	1.19	1.71	1.44
Number of sandstones per 60 m	2.10 - 19.30	8.39	3.99	0.48
Number of red mudstones per 60 m	0.66 - 21.50	6.52	3.98	0.61
Red/nonred mudstone ratio	0.01 - 15.00	1.51	2.20	1.45

[1]Lithofacies data calculated from 134 measured sections. Base data from Liston (1962), Baker (1964), O'Brien (1964), Camp (1968), and Lorenz (1971). Compilation and calculations from Lorenz (1971).

number of coals per 60 meters of section, and number of limestones per 60 meters of section are all highly positively skewed; the clastic/total thickness ratio is negatively skewed. Most of the other distributions are more nearly symmetrical, although their large positive ranges reflect at least mild asymmetry.

Clastic lithofacies

In figure 4A, contours having a value of 1.0 on the red/nonred mudstone ratio map connect all stratigraphic sections in which red mudstone equals nonred mudstone. In general, red (or buff) mudstones are uncommon in Dunkard sections in the northeastern third of the outcrop area. However, red mudstones are three to ten times more abundant than nonred mudstones in the southern portion of the region. Red and nonred mudstone thicknesses are approximately equal in the central portion of the outcrop area.

The number of red mudstone units per 60 meters of section (fig. 4B) doubles across the outcrop area, from five units in the northeast portion to 10 units toward the southern margin. A closed contour of 10 units per 60 meters is mapped north and east of Marietta, Ohio, in the north-central part of the area.

Contours showing a value of 1.0 on the sandstone/mudstone ratio map (fig. 4C) connect localities where sandstone (including minor conglomerate) and mudstone are equal in the rock sequence. Values less than 1.0 indicate increased thicknesses of mudstone relative to sandstone, as in the area northwest of the outcrop axis, where mudstones are twice as abundant as sandstone and conglomerate. Contour values of 1.0 or greater in the southern loop of the Ohio River in the vicinity of Meigs County in the western part of the region reflect the presence of a large sandstone body. Another large sandstone body is apparent in the northeastern portion of the West Virginia outcrop area and in adjacent Pennsylvania.

A clastic-to-total-thickness ratio map (fig. 4D) was prepared rather than the more commonly used clastic/nonclastic ratio as devised by Sloss and others (1950) because the paucity of limestone and coal (nonclastics) in the Dunkard Group results in very small clastic/nonclastic ratios. Where the entire section is composed of clastics, the clastic thickness and total thickness are equal and the clastic/total thickness ratio is 1.0. The 1.0 contour thus defines the southern limit of nonclastics. The 0.90 contour indicates that 3 meters of each 30 meters of section, or 10 percent of the rocks, are nonclastics. The lacustrine-deltaic environments in which Dunkard nonclastics accumulated were largely confined to the northeastern third of the outcrop area, and these environments persisted over a longer time in the northern end of the basin.

Limestone lithofacies

In the northwestern portion of the outcrop area, there are 10 or more limestone units per 60 meters of section in the Dunkard Group (fig. 4E). Thin- to medium-bedded, generally light gray, dense limestones interbedded with calcareous mudstones were described by Arkle (1959, 1969) in his gray facies. He observed that these rock units are thinner, more nodular, and argillaceous where they are present in the southern half of the outcrop area.

Dunkard Group limestones are mainly micrites and intraclastic dismicrites, commonly containing ostracodes. Many beds contain impurities of clay and silt, and some have carbonaceous matter. Five limestone units appear to be the most distinctive and extensive carbonate rocks in the northern part of the outcrop area—the Elm Grove limestone and the lower limestone member, the middle member, and the upper limestone member of the Washington Formation and the Nineveh limestone of the Greene Formation (fig. 2).

The oldest limestone unit of the Washington Formation is the Elm Grove, named for outcrops at Elm Grove, West Virginia (Grimsley, 1906, p. 68-69). The Elm Grove limestone lies just above the Waynesburg coal and was described by Stauffer and Schroyer (1920) as a dark-bluish to black, slaty, argillaceous limestone. The Elm Grove limestone, or its correlative, can be traced over the eastern third of Belmont County, Ohio, where the combined thickness of beds is up to 2 meters (Berryhill, 1963, p. 50). Stauffer and Schroyer (1920, p. 141) reported that the Elm Grove limestone contains fish scales and teeth, worm tubes, pelecypods, and ostracodes. Berryhill (1963, p. 51) also reported ostracodes and fish remains from the Elm Grove.

The Lower, Middle, and Upper Washington limestones were named by Stevenson (1876) for exposures in Washington County, Pennsylvania, where they are best developed and attain a thickness of several meters. These units were later reassigned as the lower limestone member, middle member, and upper limestone member of the Washington Formation (Berryhill and Swanson, 1962; Berryhill and others 1971). Berryhill (1963) described all three limestones

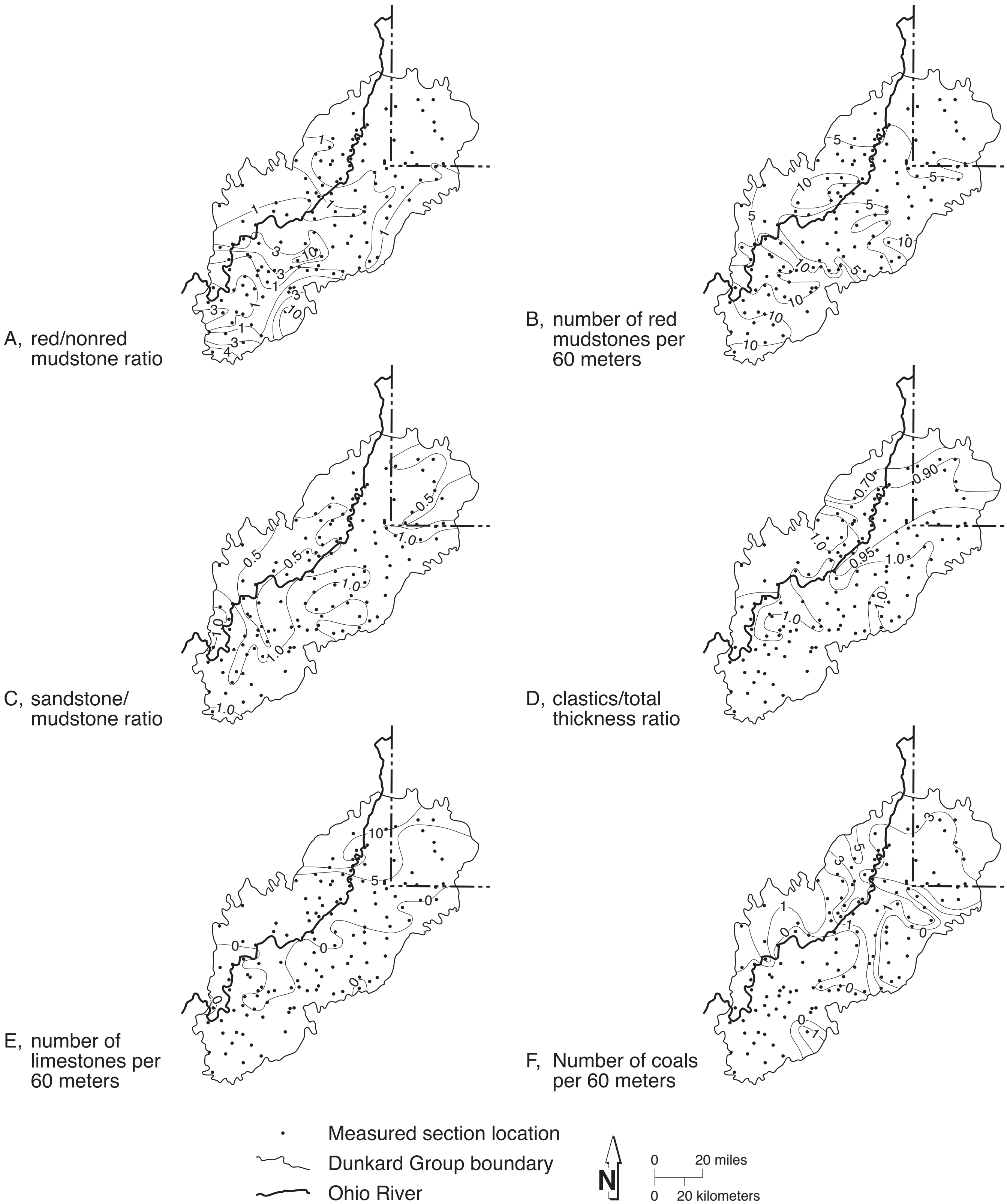

FIGURE 4.—Contoured lithofacies-distribution maps on six variables from the Dunkard Group. Modified from Martin and Lorenz (1972).

in Belmont County, Ohio, and traced the units across the northern panhandle of West Virginia into Washington and Greene Counties, Pennsylvania. Stauffer and Schroyer (1920) identified all three limestones in the northern part of the Dunkard outcrop area in Ohio and noted that the middle limestone (middle member) is best developed in Belmont County, Ohio. The upper limestone member is most prominent in the Washington County, Pennsylvania, area (Berryhill and others, 1971), where it is approximately 6 meters thick near the town of Vance (fig. 5). The uppermost Washington limestone (upper limestone member) is locally fossiliferous, containing gastropods, ostracodes, and fish bones and teeth.

The Nineveh limestone, named by I. C. White (1891) for outcrops at Nineveh, Pennsylvania, is a prominent and persistent unit in the northern panhandle area of West Virginia (Cross and Schemel, 1956a). The Nineveh occurs in several evenly bedded layers, interbedded with calcareous mudstone, and has a total thickness of nearly 4 meters in the extensive Clark Hill Road section in Monroe County, Ohio (Cross and others, 1950, p. 55).

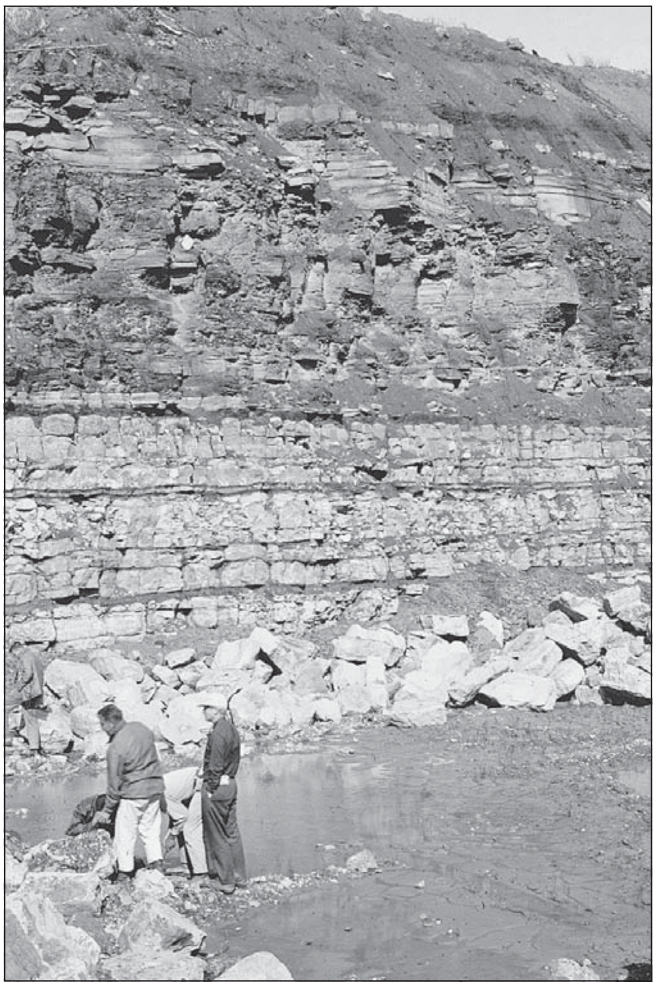

FIGURE 5.—Excellent exposure of the upper limestone member of the Washington Formation in a quarry highwall at Vance, near Washington, Pennsylvania. Photo taken in 1965. The limestone beds in the lower part of the wall are 6 meters in total thickness. Kent and others (1965) identified the carbonaceous mudstones and thin-bedded sandstones above the upper limestone member at this locality as the lower part of the Greene Formation. (Note: U.S. Geological Survey geologist Stanley E. Norris is standing at right.)

Coal lithofacies

The regional distribution of coal is generally similar to that of limestone, except in the western part of the Dunkard outcrop area (fig. 4F). South of Monroe County, Ohio, and in adjacent West Virginia, many of the coal units are not present, and limestones are thin and nodular. Although a few coal beds (for example, the Waynesburg and Washington coals) are continuous over hundreds of square kilometers in the northernmost part of the outcrop area, most appear to represent accumulation and preservation of organic matter within relatively limited areas. Arkle (1959, p. 122) noted that in the Dunkard both the limestones and the coals reach maximum thickness toward the center of the gray facies development, and then thin slightly northwestward, as does the entire rock sequence.

Where they are present, coal units commonly are thin, impure, and discontinuous, and locally may split into two or more benches. Arkle (1959, p. 122) reported that Dunkard coals commonly contain one or more thin shale and clay partings and rest on an underclay. The best development of coal is confined to the lower 60 to 90 meters of the Dunkard section.

The Waynesburg (No. 11) coal, at the Monongahela-Dunkard boundary, is quite variable in thickness, ranging from 30 cm to 12 meters in the northern part of the basin (Berryhill, 1967). In Belmont County, Ohio, the maximum thickness of the Waynesburg coal is 1.5 meters (Berryhill, 1963, p. 45). The Washington (No. 12) coal lies approximately 30 meters above the Waynesburg coal in Belmont County, where it attains a thickness of 2 meters (Stauffer and Schroyer, 1920, p. 19). Berryhill (1963, p. 48) reported that the Washington coal is persistent throughout the county and locally is more than a meter thick. This coal is stratigraphically the highest persistent, thick coal in the Dunkard Group (Berryhill and Swanson, 1962, p. C46). Cross and Schemel (1956b, p. 19) noted that the coal is of marginal quality but is mineable in 11 counties in West Virginia.

SANDSTONE BODY GEOMETRY

The sandstones of the Dunkard Group are mainly borderline between lithic arenites and lithic graywackes (see Chapter 4) and range from thin, and thin-bedded, fine-grained units to very thick bedded, medium- to coarse-grained, locally conglomeratic, cliff-forming bodies up to 30 meters thick (fig. 6). They are uniformly blue gray in fresh exposures and weather to buff. The sandstones occur in belt, dendroid, ribbon, pod-shaped, elongate, lenticular, and sheet bodies as defined by Potter (1962) and by Pettijohn and others (1987, p. 345).

The belt sandstone bodies described by Potter (1962) from the Illinois Basin had weakly meandering outlines and were 40 to 75 km wide. They were formed by the coalescing of dendroid sand bodies. Dendroid sandstone bodies have patterns similar to belts and range in width from 7.5 meters to nearly 5 km and grade into belts. Ribbons are long, narrow sandstone bodies, and pods are small, isolated bodies that vary in shape. Sheet sandstones, which commonly are finer grained than elongate bodies, may be patchy or may be present over a wide area (Pettijohn and others, 1987, p. 345). Ribbon and pod sandstone bodies are very common in

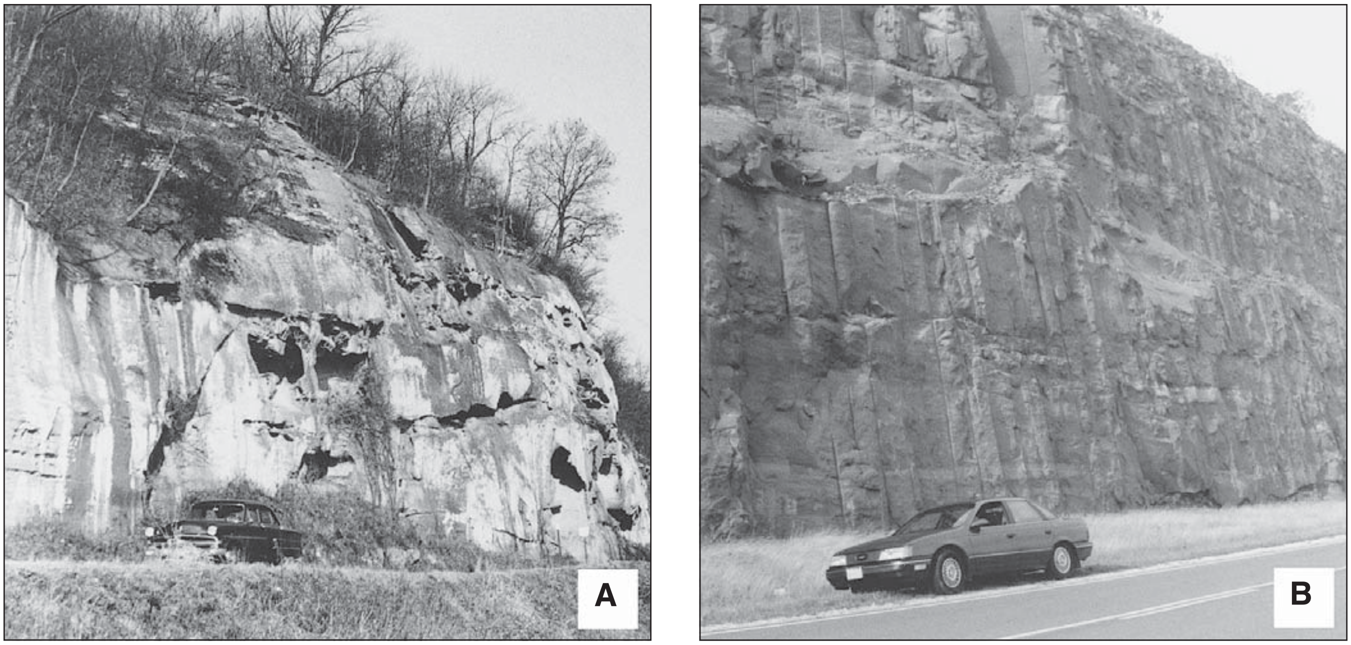

FIGURE 6.—**A**, Hockingport Sandstone Lentil in 1954 at the type locality 1 km (0.7 mile) northeast of Hickingport, Athens County, Ohio. From Martin and Henniger (1969); reprinted by permission of the American Association of Petroleum Geologists. **B**, photo of the same area taken in 1993 following reconstruction of the highway in the early 1990's.

the Dunkard Group, especially in the southern two-thirds of the outcrop area (fig. 7).

The thick-bedded and very thick bedded belt sandstones of the Dunkard Group are mappable units ranging from several hundred square kilometers to over 2,000 km^2 in areal extent. Three of these belt sandstone bodies have been studied in detail: (1) the Hockingport Sandstone Lentil in the southwestern part of the outcrop area, (2) the Mather (Waynesburg) Sandstone Lentil in the northeastern part (Martin, 1955; Henniger, 1964; Martin and Henniger, 1969) (see figs. 1, 3, 6, and 8), and (3) the Leith sandstone in northeastern Washington County, Ohio, and adjacent West Virginia (Swinehart, 1969). The Leith sandstone occupies the stratigraphic position of the Mannington sandstone (H. R. Collins and B. E. Smith, personal commun. to T. W. Swinehart, 1969).

Several smaller, mostly dendroid sandstone bodies have been studied in detail, including the Lower and Upper Marietta sandstones in the Marietta area of Washington County, Ohio (Martin, 1949; Thoms, 1956; Healy, 1959). These two sandstones in the type area are separated by at least 12 meters of predominantly red mudstone and thin sandstones termed the Creston Reds (figs. 9 and 10). Sandstone bodies in Meigs County, Ohio, and adjacent West Virginia were studied by Mushake (1956) and Healy (1959).

The thin, thinly bedded sheet sandstones of the Dunkard

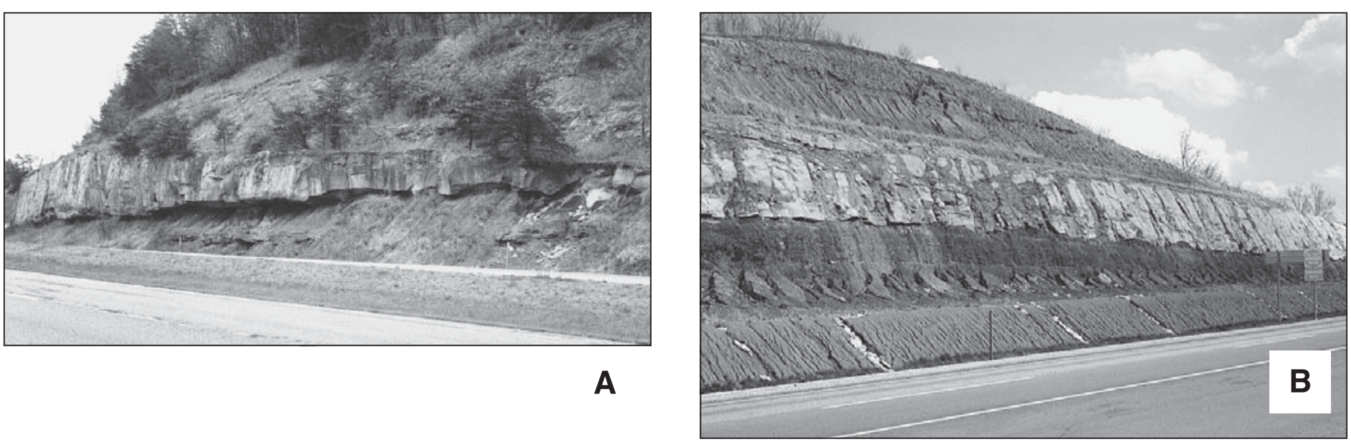

FIGURE 7.—**A**, outcrop of the margin of a ribbon sandstone body on U.S. Route 50, approximately 35.8 km (22.4 miles) east of the junction with I-77, Wood County, West Virginia. Photo taken in 1998. Mudstones and thin sandstones lie above and below the tapered eastern (right) edge of the unit. Stakes on highway are approximately 1.2 meters high. **B**, outcrop of a ribbon or dendroid sandstone body on U.S. Route 50, approximately 0.8 km (0.5 mile) east of the junction with I-77. Photo taken in 1971. The even profile of the top and bottom of the sandstone body indicates a longitudinal section. Red mudstones lie above and below the sandstone.

FIGURE 8.—Blocky to massive Mather Sandstone Lentil (Waynesburg sandstone) in railroad cut 3.2 km (2.0 miles) east of Waynesburg, Greene County, Pennsylvania. Photo taken in 1950. Hammer at lower right is 30 cm long.

tend to be more areally equidimensional than the belt or dendroid sandstone bodies. Thicknesses of these sheets range from several tens of centimeters to a few meters. Many outcrop sections contain sequences of sheet sandstones interbedded with siltstones and mudstones. Field relations indicate that Dunkard sheet sandstones generally are not as extensive as the belt and dendroid deposits. In contrast to the thicker, elongate sandstone bodies, the thinner sheet sandstones commonly are better sorted, erosional scour seems to have been minimal, and cross-bedding is almost exclusively planar rather than of the trough variety. Sheet sandstones typically are associated with the coals and limestones of the northern and northwestern parts of the basin rather than the thicker and blocky to massive sandstones and red mudstones to the south and east.

Prior to the publication of the classification by Pettijohn and others (1987), Berryhill and others (1971) recognized three prominent shapes of sandstone bodies (sheetlike, elongate, and lobate) in the Washington County, Pennsylvania, area. Their sheetlike bodies range from 7.2 to 13.6 km wide, the elongate bodies are from 0.3 to 6.4 km wide and over 9.6 km long, and the lobate sandstones are typically less than 1.5 km wide and 5 km long. The width of the lower part of

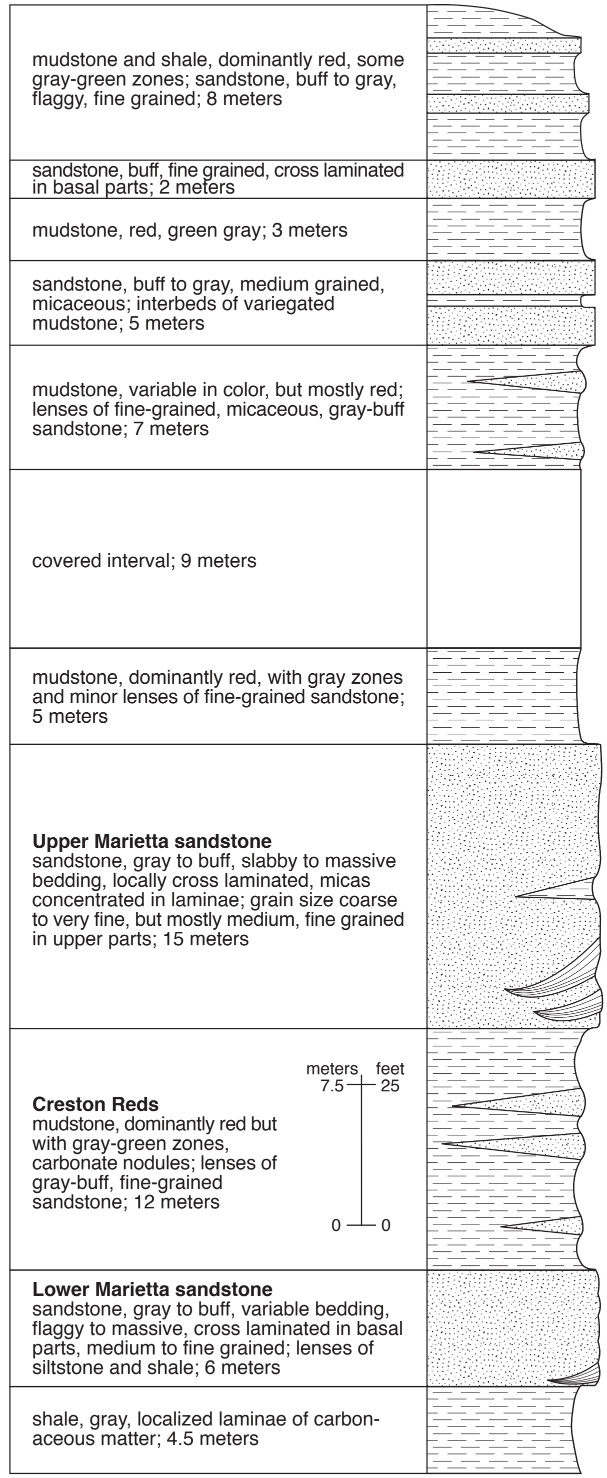

FIGURE 9.—Profile columnar section of part of the Washington Formation, showing the Lower Marietta sandstone, the overlying dominantly mudstone Creston Reds, the Upper Marietta sandstone, and overlying rocks. Modified from Healy (1959). The outcrops represented are 2.5 km (1.6 miles) southwest of Marietta, Washington County, Ohio, along Ohio Route 7. The Creston Reds here occupies the stratigraphic position which, in other localities, includes the lower and middle limestone members of the Washington Formation. According to Stauffer and Schroyer (1920, p. 19), the Creston Reds was a source of clay for brick kilns at plants in Marietta.

FIGURE 10.—Outcrop of the Upper Marietta sandstone at the type locality 2.5 km (1.6 miles) southwest of Marietta, Washington County, Ohio, along Ohio Route 7. Photo taken in 1998. The barrier on the highway is approximately 0.75 meter high.

the elongate bodies is greater than in most modern stream channels. Some elongate sandstone bodies flare outward in the lower parts into broad sheets that lack the characteristics of floodplain deposits. Berryhill and others (1971) believed that the sediments which formed these sandstone bodies were laid down in very shallow water, as elongate subdeltas basinward from the mouths of streams.

Both belt and dendroid bodies are better developed in the lower part of the Dunkard Group and are present mostly in the southern part of the outcrop area. Ribbon and pod sandstones also are common in the southern two-thirds of the region and probably result from the filling of channel segments of tributaries of larger streams.

SEDIMENTARY STRUCTURES AND TEXTURES

Dunkard sandstones have several characteristics of fluvial sandstones: (1) the elongate trends of the belt, dendroid, and ribbon sandstone bodies; (2) concave-downward cross section; (3) indistinct but flat upper boundaries and scoured basal contacts; (4) scour-and-fill structures; (5) unimodal cross-bed roses; and (6) vertically decreasing grain sizes. A typical scour-and-fill structure in the Hockingport Sandstone Lentil is depicted in figure 11. Most of the sedimentary structures and textures of the Dunkard sandstones are common to point bar, channel bar, and alluvial island deposits that accumulate for the most part by lateral accretion of streambed load during the sidewise migration of fluvial channels, as described by Allen (1965, p. 125). Vertical accretion also takes place on planar or massive-bedded bars, which are diamond or lozenge shaped in plan view, are elongate parallel to flow direction, are bounded by active channels, and have eroded margins (Miall, 1981, p. 21). The belt and dendroid sandstone bodies show large- and small-scale cross-stratification, both planar and trough types, including large-scale, low-angle cross-bedding termed epsilon by Allen (1963). Epsilon cross-bedding, according to Miall (1981, p. 33), develops on the lateral accretion surfaces and preserves them within the deposit (fig. 12).

Abundant poorly sorted mixtures of sand and gravel and local concentrations of pure gravel formed conglomerates in the Mather and Hockingport Sandstone Lentils (fig. 13). Thin sheets of pebbles, which were concentrated as channel-lag deposits (Happ and others, 1940; Allen, 1965, p. 129) by winnowing of sand and gravel mixtures, are present along bedding planes. Within the Dunkard Group sandstones there is an upward decrease in the proportion of conglomerate to sandstone. Locally, the sandstones

FIGURE 11.—Scour-and-fill structure in the Hockingport Sandstone Lentil 0.6 km (0.4 mile) south of Long Bottom, Meigs County, Ohio. Photo taken in 1952. Pick is 32 cm long.

FIGURE 12.—Epsilon cross-bedding showing profiles of surface of truncation in a former outcrop at the type locality of the Hockingport Sandstone Lentil 1 km (0.7 mile) northeast of Hockingport, Athens County, Ohio. Photo taken in 1952. Knife is 9 cm long.

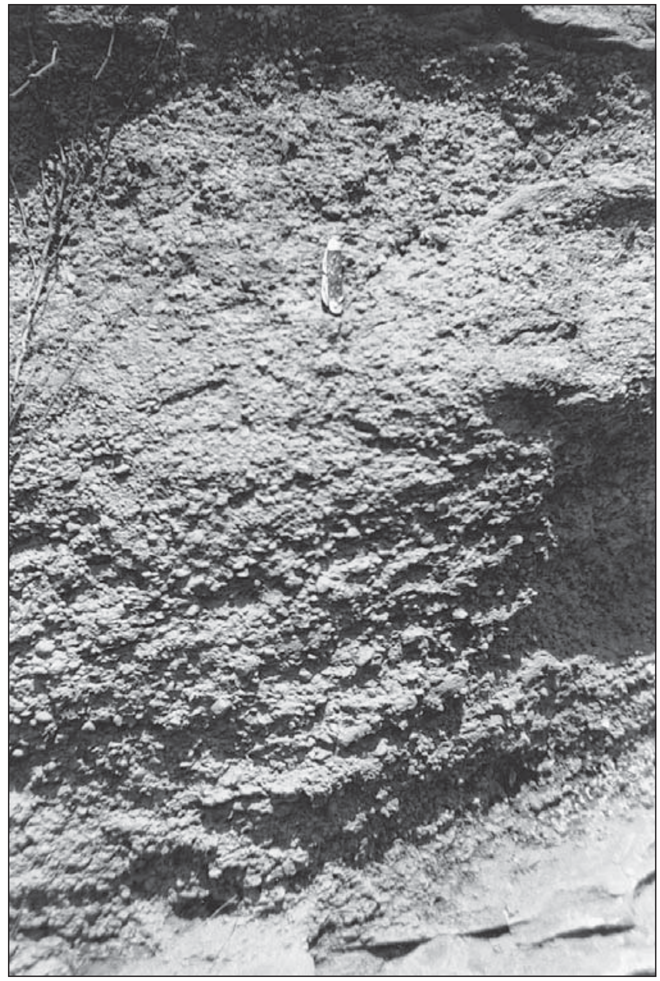

FIGURE 13.—Pebble conglomerate in the lower part of a former outcrop at the type locality of the Hockingport Sandstone Lentil 1 km (0.7 mile) northeast of Hockingport, Athens County, Ohio. Photo taken in 1952. Knife is 9 cm long.

contain bodies of essentially nonpermeable siltstones and mudstones. The sediments that formed these rocks probably accumulated as channel-fill deposits in abandoned or decaying channels. Large clasts of sandy mudstone, probably derived from stream banks, are present in the Upper Marietta sandstone (fig. 14).

Ripple marks are present in the sandstones, and desiccation cracks are present in the more argillaceous beds of the sandstones or in the enclosing rocks. Stauffer and Schroyer (1920, pl. 7) illustrated mud cracks in the shaly partings of a sandstone near Marietta, Ohio. Fossil plants, including molds and casts of limbs and logs (fig. 15), and trace fossils characteristic of the nonmarine *Scoyenia* ichnofacies (see Ekdale and others, 1984, p. 313) are common in the Dunkard sandstones. The associated, mainly nonmarine coals and ostracode-bearing micrites lack unquestionable marine fossils.

FIGURE 14.—Intraformational breccia containing clasts of laminated, sandy mudstone in sandstone, shown here in a cull from a grindstone quarry. The clasts were probably torn from stream banks during a flood. Photo taken in 1949. Pick is 32 cm long. The sandstone is a dendroid body in the Washington Formation at Constitution, Ohio, 13 km (8.1 miles) southwest of Marietta, Washington County, Ohio. This dendroid sandstone body was referred to as the Upper Marietta sandstone by Stauffer and Schroyer (1920, p. 132) and Martin (1949, p. 12).

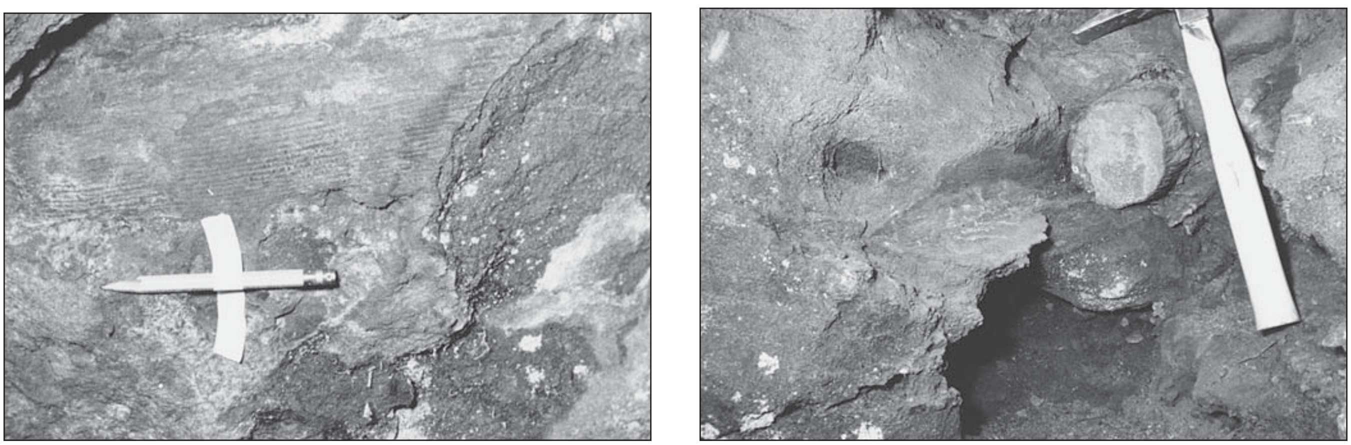

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FIGURE 15.—Plant fossils in the Hockingport Sandstone Lentil 2.4 km (1.5 miles) southeast of Cutler, Washington County, Ohio. Photos taken in 1952. **A**, impression of the stem of *Calamites*, a large Pennsylvanian rush. Pencil is 10 cm long. **B**, internal mold of a hollow log, probably of *Calamites* (originally published in Martin and Henniger, 1969; reprinted by permission of the American Association of Petroleum Geologists). Pick is 32 cm long. Scouring rushes, the largest represented by *Calamites*, exceeded 30 cm in diameter and were 9 meters or more high. Like the lycopsids, or scale trees, the trunks of rushes were not solid wood but rather were thin, woody cylinders filled with a core of pith and surrounded by thick bark. According to Hook and Miller (1996), after lycopsids died, the bark decayed more slowly than the spongy interior, leaving a hollow center. Following splitting of the bark, the hollow was filled with sediment transported by water. Upon induration of the sediments, an internal mold (pith cast) of the hollow log was formed. *Calamites* and the development of pith casts of this plant have been described by Cross, Gillespie, and Taggart (1996, p. 405-406).

Chapter 3

PALEOSLOPE AND DEPOSITIONAL ENVIRONMENTS

PALEOSLOPE INDICATORS

Many workers who integrated facies distributions with paleocurrent and petrographic data concluded that the paleoslope during the late Paleozoic Era in the central Appalachians dipped to the north or northwest, and the source-land was to the south or southeast (Martin, 1955; Arkle, 1959, 1969; Beerbower, 1961; Liston, 1962; Berryhill, 1963; Baker, 1964; O'Brien, 1964; Henniger, 1964; Camp, 1968; Martin and Henniger, 1969; Lorenz, 1971; Martin and Lorenz, 1972). Paleogeographic maps of the area by Donaldson (1969, 1972, 1974, 1979) depict a dominantly northward-dipping paleoslope. Donaldson and Eble (1991) represented the trend of the channel sandstones of the Upper Pennsylvanian Monongahela Group to be northwest-southeast across the Dunkard region.

General criteria that indicate a paleoslope direction are: (1) fluvial-sandstone body trends, (2) decrease in size and mineralogical differences in clastic particles in a downslope direction, (3) facies and their relationships to each other, (4) direction of thickening of sediment accumulation, (5) orientation of fossils, and (6) cross-bedding dip directions. Each of these facets to the question of paleoslope direction has been examined for the Dunkard Group.

Studies of several elongate sandstone bodies of fluvial origin in the southwestern and western parts of the Dunkard outcrop area show that the thickest parts of the units trend in a northerly direction (Martin, 1955; Mushake, 1956; Thoms, 1956; Healy, 1959; Swinehart, 1969). The largest of these sandstones, which is of belt proportions, is the Hockingport Sandstone Lentil (Martin, 1955; Martin and Henniger, 1969; see figs. 1, 2, and 6).

In the northeastern part of the Dunkard outcrop area is an even larger sandstone body, the Mather (Waynesburg) Sandstone Lentil (Martin, 1955; Henniger, 1964; Martin and Henniger, 1969; see figs. 1, 2, 3, and 8). The long axis of the Mather Sandstone Lentil is oriented slightly east of north (fig. 1). Malone (1969) developed isopach maps of three Dunkard Group sandstones in the northern part of the outcrop area. The trend of these sandstone bodies is northwest, except for the thickest portion of the Mather, which trends northward. Isopach mapping by Moyer (1978) showed that the trend of the thickest part of the Mather (Waynesburg) sandstone is north-northeast, and he reported a main northern trend for the sandstone. Henniger (1964) had noted the same trends for the Mather (Waynesburg) sandstone.

Henry and others (1979) reported that the very thick, coarser sandstone bodies in the I-77 corridor area of Jackson County, West Virginia, are elongated and oriented roughly north-northwestward. According to these authors, the "Waynesburg Sandstone" in this region, which Krebs (1911) had correlated with the Waynesburg Sandstone Member of the Washington Formation of southwestern Pennsylvania and northern West Virginia, averages over 18 meters in thickness and has a maximum thickness of nearly 25 meters.

Mudstones make up the greater part of the Dunkard Group compared to sandstones and increase in relative abundance to the northwest across the Dunkard outcrop area. In the northeastern part of the Dunkard outcrop area, Thomsen (1980) noted a general decrease in the weight percentages of sand and silt fractions, along with an increase in the clay-size fractions, of mudstones to the north-northwest. Sand fractions of samples decrease from 3 to 2 percent, silt fractions from 60 to 45 percent, and clay fractions increase from 37.5 to 54 percent, a difference of approximately 17 percent (Thomsen, 1980). Benton (1983) found similar northwesterly trends in the grain-size fractions of mudstones in the central portion of the area. Weimer (1980) determined that in the western part of the outcrop area the sand fractions of samples decreased from 11 percent to 6 percent from south to north, but significant changes in the silt and clay fractions were not apparent.

Thompson (1963) and Lambert (1969) noted an increase in matrix components and large, detrital mica grains and a corresponding decrease in feldspar and rock fragments (especially low-rank sand-size metamorphic fragments) from south to north in Dunkard sandstones. Although the percentage differences in the abundance of these components from the two areas range from 1.5 to 2+ percent, the differences are significant because of the relatively short distances involved, approximately 50 to 100 km (31-62 miles). The differences in sandstone composition in the downslope direction are presumed to be the result of selective sorting of grains by currents, of chemical weathering leading to disaggregation, and of the mechanical breakdown and abrasion of grains in transit.

In general, facies contour values of the sandstone/mudstone ratio map (fig. 4C) indicate a decrease in grain size to the northwest of the basin axis, and contour trend directions are mainly northeast-southwest. The trends of the contours are mostly perpendicular to the presumed generally northwest paleoslope.

The contours of other facies maps, including red/nonred mudstone (fig. 4A), clastics/total thickness (fig. 4D), and number of limestones per 60 meters (fig. 4E), also have a northeasterly trend. Red and buff mudstones are more common in the southern and southeastern part of the outcrop area (figs. 4A, 4B), reflecting high oxidation-reduction potential; these mudstones probably represent paleosols. Coals and limestones are present for the most part in the northern and northwestern parts of the outcrop region, an indication that swamp and lacustrine environments were present down-gradient of well-drained upper paleoslope areas (figs. 4D, E, F).

Cross and Schemel (1956a, p. 48) pointed out that the Pennsylvanian- and Permian-age sediments generally thicken to the east and south in the Appalachian region. On the basis of orientation measurements of 1,400 ostracode carapaces in limestone samples and supplementary stratigraphic data, Jones and Clendening (1969) concluded that paleocurrent flow was in a generally northward direction in the northern part of the outcrop area in Monongahela and Dunkard times.

Abundant cross-bedding orientation data, another indicator of paleoslope, were acquired in numerous regional studies of Dunkard sandstones (Liston, 1962; Baker, 1964; O'Brien, 1964; Camp, 1968; Martin and Henniger, 1969; Lorenz, 1971). Lorenz (1971) analyzed these accumulated data and developed maps showing paleocurrent trends across the Dunkard outcrop area.

The attitudes of nearly 1,500 cross-beds at 389 localities were measured to determine the regional depositional slope (fig. 16). The number of readings per outcrop ranged from 1 to 17; the average was somewhat less than 4. Outcrop selection could not be randomized, but an attempt was made to ensure an even distribution over the entire outcrop area. Almost all measurements were made on well-exposed, planar cross-beds in sheet, dendroid, or belt sandstone units. Dip inclinations ranged from less than 10° to more than 35°; readings that had dips of less than 10° were not included in the paleocurrent analysis because cross-beds that have extremely low dips generally are not reliable indicators of the paleoslope (Pettijohn, 1962; Allen, 1966). Although this exclusion of low-dip cross-beds tends to reduce the sample variance, it should not significantly affect the vector means or modal-class frequencies. The computation of the vector mean of dip azimuths for each locality is described in some detail by Lorenz (1971).

A prevailing northwesterly current pattern for the entire central portion of the Dunkard outcrop area is readily noted in the cross-bed moving-averages map (fig. 16). It is evident from this map, as well as from the current-rose map (fig. 17) and paleocurrent map (fig. 18), that the paleocurrent pattern varies across the region. The cross-bedding measurements recorded in the north-trending Hockingport Sandstone Lentil and other sandstone units in the southwestern part of the Dunkard outcrop area are reflected in the subregional current rose having a vector mean of N 23° W (**HSL** in fig. 17), depicting the paleoslope in that area. The measurements of cross-bedding in the north-trending Mather Sandstone Lentil and other sandstone units in the northeastern part of the outcrop area are reflected in the vector mean of N 17° W (**MSL** in fig. 17).

Although cross-bedding is variable locally, the main directional current transport of sediments appears to have been northwestward. The current rose map shows a grand mean for the entire outcrop area of N 38° W (fig. 17). More than 50 percent of the cross-bed readings for the sandstones of the Dunkard Group are oriented between N 80° W and true north.

The unimodal current-rose patterns common over most of the Dunkard outcrop area are in general characteristic of fluviatile sands. Although unimodal patterns also may be developed in eolian and turbidite sands (Pettijohn and others, 1987, p. 327), evidence for eolian and turbidite sedimentation is lacking in Dunkard rocks. The current-rose pattern for sandstones in the northernmost part of the region is markedly polymodal (fig. 17). This polymodal pattern may reflect greater variances in cross-bed direction resulting from increased stream meandering on a lower-angle paleoslope (Pelletier, 1958, p. 1046) or currents bringing sediments from a secondary source. Both possibilities are likely in this northernmost part of the region; however, the following evidence indicates that a secondary northern source probably is mainly responsible for the variability.

Rendina (1985) compared the composition of sandstone and mudstone samples collected in the northwestern part of the Dunkard outcrop area with samples collected from elsewhere in the Dunkard. He noted the distinct discrimination of rock samples into two groups based on composition: a rather geographically restricted "northern" group, and a more extensive "southern" group. This discrimination (described in detail in Chapter 5) is consistent with paleocurrent and facies distribution data and supports the belief of Berryhill (1963) and Donaldson and Eble (1991) in a northern, subordinate sediment source.

Berryhill (1963, p. 1) suggested that during Conemaugh and Monongahela times, clastic sediments probably came from several source areas, but that the principal source was to the north of Belmont County, Ohio. He reported (p. 88) that the pattern of sedimentation during early Dunkard time was similar, if not identical to that of late Monongahela time. He stated that "thin, deltaic sheets of sand were spread southeastward periodically to the easternmost part of Belmont County, Ohio, where they interfingered with limy mud . . . . " Berryhill noted (1963, p. 1) that during early Permian time, the pattern of sedimentation changed and most of the rocks above the Washington coal are composed of sediments that came from the southeast. The northern source, therefore, according to Berryhill, supplied sediments which make up the lower part of the Dunkard rock section in the Belmont County area ("south-trending" double arrows of fig. 18). A high dispersion of cross-bed vectors reflects the influence of several current systems and is consistent with Berryhill's hypothesis of an early, second source for sediments in the northern part of the region for at least some of the Dunkard strata (figs. 16, 17, 18).

Donaldson and Eble (1991, p. 529 and fig. 6) postulated that a river system drained into the Dunkard basin region from the northeast during Conemaugh and Monongahela times; however, the principal flow direction for fluvial-deltaic systems into the basin was to the northwest. Although there are no preserved rocks of Dunkard age north of the present outcrop area, deltaic sedimentation of the Monongahela-age northern systems could reasonably be presumed to have continued into Dunkard time.

In summation, data on cross-bedding-dip direction indicate drainage in a dominantly northwesterly direction during deposition of the sediments that formed the sandstones of the preserved Dunkard rock sequence in the western part of the outcrop area. The cross-bed dip directions in the northeastern part of the region show a paleoslope inclined to the north. Variability in cross-bed data in the northernmost part of the region and differing composition of sandstones and mudstones in the northern and southern areas (probably of greater significance) indicate a subordinate northern sediment source. From the evidence provided by the paleoslope indicators and analysis of depositional environments and clastic-rock composition of Dunkard rocks, described in the following chapters, it appears that the sedimentary framework during Dunkard time consisted of a topographically high source area to the southeast, a topographically lower shield area to the north, and the principal outlet of the basin to the west (figs. 17 and 18).

In a contrary opinion, not generally accepted by subsequent workers, Berryhill (1967, p. 4) suggested that the presence of thick limestone beds in the Dunkard Group north of the thick sandstone and red mudstone facies indicated that drainage was northeastward rather than southwestward. As pointed out in the following section, it seems more likely that the sedimentary environments in which the calcare-

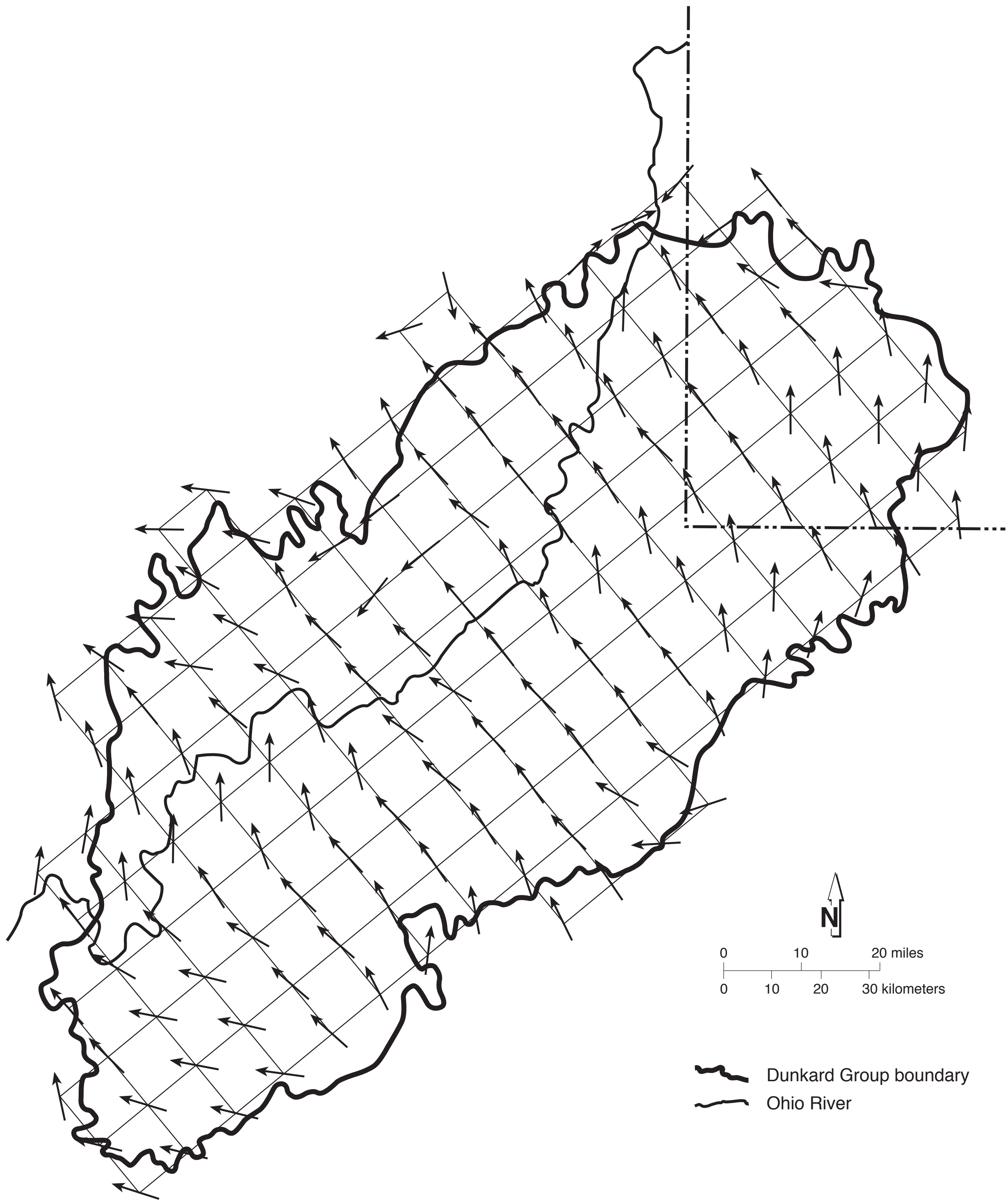


FIGURE 16.—Vector map of cross-bed moving averages of the Dunkard Group. From Lorenz (1971) and Martin and Lorenz (1972). Grid spacing is 12.8 km. Measurements were taken at three to four locations per grid square on average. The vector mean of all readings in the four adjacent quadrants was plotted at each grid intersection.

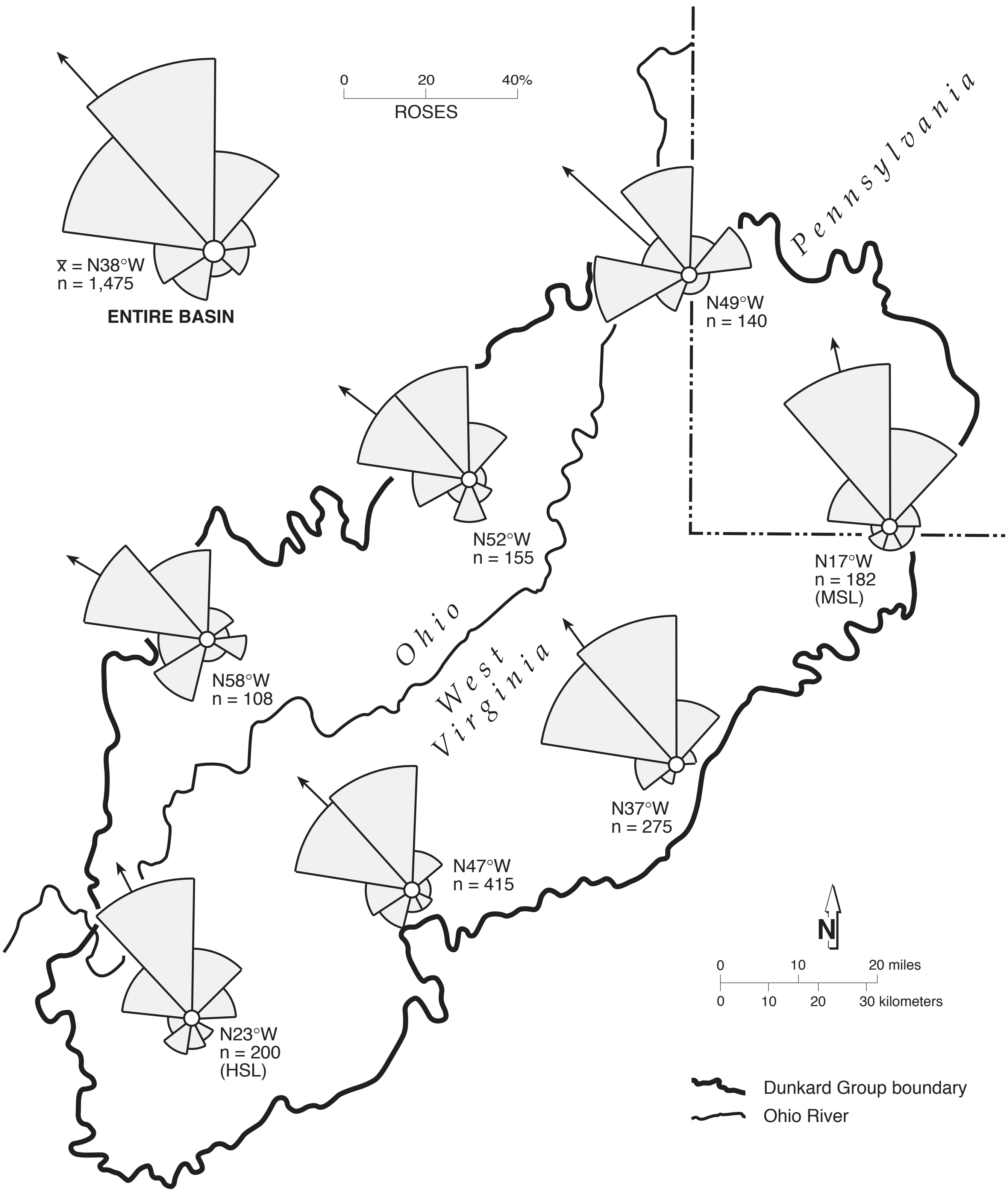


FIGURE 17.—Current-rose map of the Dunkard Group showing regional cross-bedding distributions and distributions in the entire basin. Modified from Lorenz (1971) and Martin and Lorenz (1972). Current rose labeled (MSL) in the northeastern area includes data from the Mather Sandstone Lentil; current rose labeled (HSL) in the southwestern area includes data from the Hockingport Sandstone Lentil. n = number of individual readings on which each azimuth mean is based.

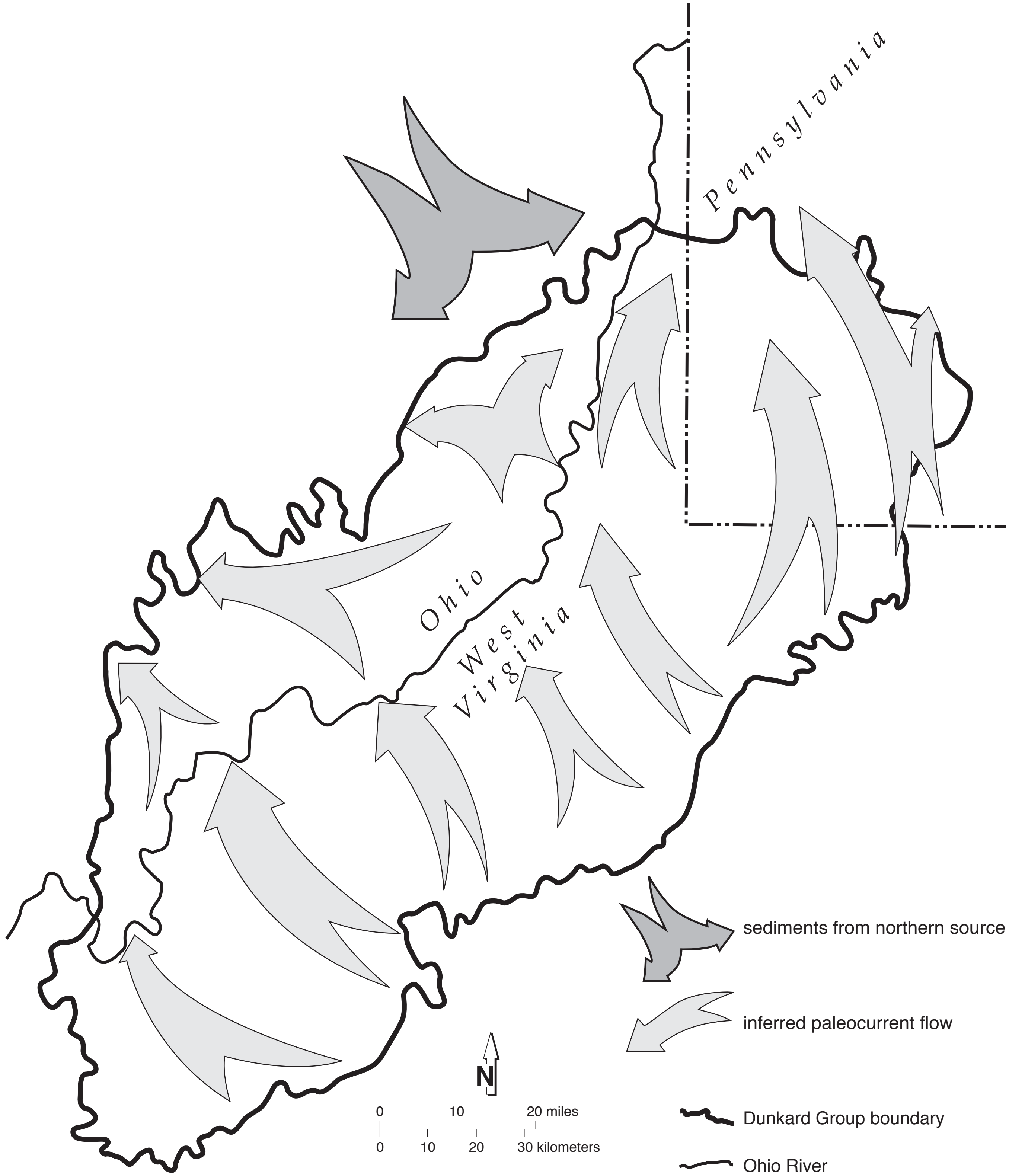


FIGURE 18.—Map showing paleocurrent sediment-dispersal patterns in the Dunkard Group. Modified from Lorenz (1971) and Martin and Lorenz (1972).

ous sediments were deposited were merely remnants of the inland sea, which originally extended northeastward from the midcontinent region.

DEPOSITIONAL ENVIRONMENTS

Donaldson (1974, 1979) noted that the Pennsylvanian-Permian rocks in the central Appalachian region show a progressive change in paleogeography. He outlined the principal environments in existence during the late Paleozoic Era from Pottsville time through Dunkard time and illustrated the paleogeography of the region. Donaldson and Shumaker (1981) provided a detailed account of the tectonics and sedimentary framework of the region during the late Paleozoic. The tectonic setting and deposystems for Pennsylvanian sedimentation in the central Appalachians also were described by Donaldson and others (1985) and by Donaldson and Eble (1991).

According to Donaldson (1979, p. 123) a narrow marine embayment extended from the southwest into the region during Pottsville time and early Allegheny time. Maximum submergence took place in early Conemaugh time, and overall regression of the sea followed. The embayment was periodically flooded as far eastward as the present Dunkard outcrop region during early Late Pennsylvanian time (Donaldson and Eble, 1991). The sediments that formed the Ames limestone of mid-Conemaugh time were deposited during the last extensive marine incursion, the Ames sea (Darrah, 1969; Merrill, 1988, 1993; Merrill and Kivett, 1995). Fluvial-dominant deltas extended into the region during the regression of the sea, and by late Conemaugh-Monongahela time, an entirely river-influenced, low-salinity bay-lake existed. During Dunkard time this bay-lake was further reduced to a fluvial plain containing relatively small lakes (Donaldson, 1974, p. 47).

Many workers have concluded that most of the sediments which formed the rocks of the Dunkard Group were deposited in a series of north- and northwestward-shifting fluvial, fluvial-swamp, and fluvial-lacustrine-deltaic environmental complexes of a broad, low-lying, coastal plain (Cross and Schemel, 1956a; Cross, 1972, 1975, 1976; Arkle, 1959, 1969; Beerbower, 1961; Berryhill, 1963, 1967; Lorenz, 1971; Martin and Lorenz, 1972; Donaldson, 1972, 1974, 1979; Moore, 1981; Greenlee, 1985; Donaldson and others, 1985; Donaldson and Eble, 1991).

The upper fluvial plain and the source area to the south and southeast prograded through time over a lower fluvial plain containing local swamps, as this environmental complex was shifted over a fluvial-lacustrine-deltaic plain (fig. 19). The nature of the lithofacies, cross-bedding, and the environments of sedimentation are summarized in table 2.

Stream gradients on the upper fluvial plain were generally higher than those in the remainder of the basin, resulting in streamflow conditions competent to transport mainly medium and coarse sand and some larger particles ranging up to and including uncommon cobbles. The channels of some systems may have been braided. The more northern parts of the region were drained by low-gradient, medium-sized streams having high sinuosity (fig. 19). Deposition was mainly by channel-lag and point-bar accretion. Paul E. Potter (University of Cincinnati, personal commun., 1993) suggested that the larger streams were probably comparable in size to the Great Miami and Scioto Rivers of Ohio. Major stream courses were relatively stable, and continuous channel deposition produced large, well-defined, mappable sand bodies.

Donaldson and Eble (1991, p. 534) used the term "fluvial-deltaic apron," introduced by Galloway (1981), for the Upper Pennsylvanian sedimentary deposits of the central Appalachians. The major belt sandstones such as the Hockingport and Mather Lentils represent preserved, upstream channel deposits of a fluvial-deltaic apron. The downstream deposits, as well as those developed farther upstream, have been removed by post-Permian erosion.

Dominic (1988) studied four sandstone bodies in northern West Virginia: three sandstones of the Monongahela Group and the Waynesburg (Mather) sandstone of the lower part of the Dunkard Group. He developed paleohydraulic reconstructions of the channels in which the sediments that formed the sandstones were deposited. Dominic determined that the sinuosity of the channels was moderate (ranging from 1.3 to 1.8) and the channels were not braided. He demonstrated that two distinct sizes of channels had existed in the development of the sandstone bodies, one with an average bankfull width of 78 meters, and the other with an average bankfull width of 250 meters. The discharge in successive smaller paleochannels decreased throughout the sandstone interval studied, and the larger channels existed only in the channel-filling by sediments that formed the Waynesburg (Mather) sandstone.

Gardner (1983) suggested, on the basis of study of a paleochannel and point bar of the Pennsylvanian-age Harold Sandstone in eastern Kentucky, that a river about 10 meters deep and only 140 meters wide may have had an upstream drainage basin area of 30,000 km^2 and a stream length of about 200 to 300 km (125-185 miles). Considering Dominic's (1988) estimated bankfull width of up to 250 meters for the streams transporting the sediments which formed the Waynesburg (Mather) sandstone, the stream length was probably in excess of 300 km (185 miles).

Cross (1975, p. 298) concluded that the sediments of the Dunkard rocks were mostly extensively recycled coastal-plain sediments from earlier, poorly consolidated deposits but also included some sediments derived from sourcelands 320 to 800 km (200 to 500 miles) to the southeast. The boundary of existing Dunkard outcrops near Sissonville, West Virginia, is approximately 320 km (200 miles) in a straight-line distance northwest of the coastal plain at Winston-Salem, North Carolina. Some fossiliferous chert pebbles in the Hockingport Sandstone Lentil and other Pennsylvanian sandstones of the Appalachian Plateaus, however, were probably derived from Lower Devonian units as close as 175 km (110 miles) to the southeast, which were unroofed during the Alleghany orogeny (Merrill and Dutro, in prep.).

Berryhill and others (1971, p. 30) believed that the bifurcating or distributary shape and sinuous patterns of thicker parts of sandstone bodies in the Washington County, Pennsylvania, area represented channels of meandering streams and indicated either fluvial or deltaic deposition. Thinner and finer grained, sheetlike sand accumulations were developed more commonly in the more northern part of the region.

The physiochemical properties of sediments deposited in the region depended primarily on the dip of the paleoslope and on the position of the water table relative to the depositional surface. Because of the higher elevation and good drainage in the upper fluvial plain, the ground-water table would have been well below the depositional surface, allowing oxidation of the floodplain deposits and preservation of ferric oxides of primary origin and preventing the formation

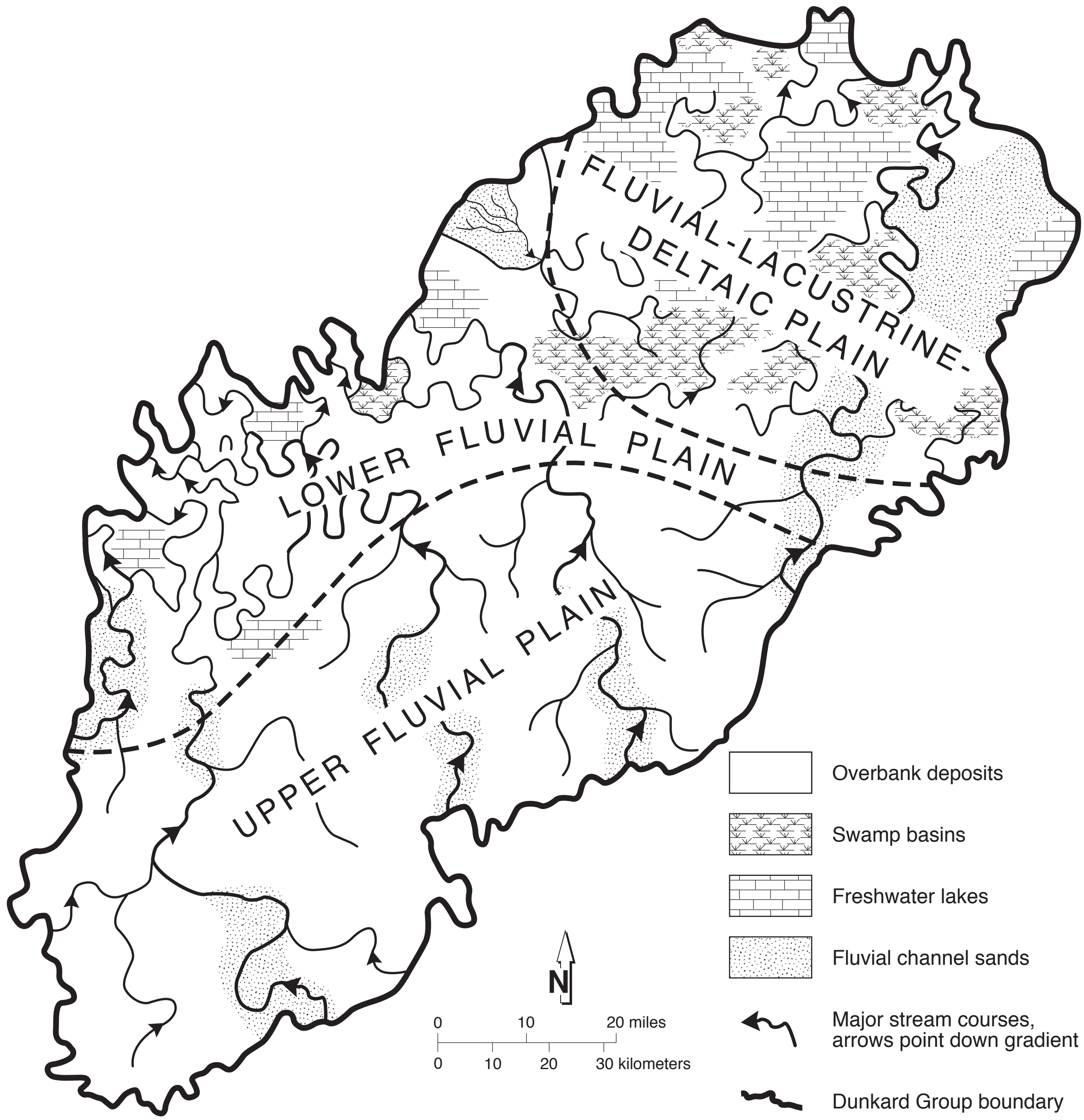


FIGURE 19.—Diagrammatic reconstruction of the sedimentary environments of the Dunkard Group outcrop. Modified from Lorenz (1971) and Martin and Lorenz (1972).

of swamps and lakes.

Dunbar and Waage (1969, p. 291) and Cross (1975, p. 298) believed that the red coloration of the mudstones of the Dunkard Group is almost entirely primary. Primary red beds (Krynine, 1949) are those in which the red color is derived from lateritic soils and is preserved in oxidizing depositional and diagenetic environments (Krumbein and Sloss, 1963, p. 564). However, Potter and others (1980, p. 54) concluded that "color in sediments, because it can be changed so easily, is almost always of depositional or diagenetic origin rather than detrital. In other words, red sediments are produced by oxidizing depositional environments, not by red soils (Berner, 1971, p. 197)." The voluminous literature on the origin of red beds was reviewed by Van Houten (1973).

Clark (1962, table 1) reported variegated red beds in parts of the Pennsylvanian-age section in the Pittsburgh, Pennsylvania, region where Monongahela Group rocks crop out. The variegated red beds, according to Clark, have a postdepositionally acquired red coloration, that is, they are the postdepositional red beds of Krynine (1949).

The greenish mudstones of the Dunkard Group, at least in part, have been reduced from former red beds by the leaching of ferric to ferrous iron owing to the percolation of organic acids from swamps (Cross, 1975, p. 298). Such leaching took

TABLE 2.—*Summary of major regional sediment depositional provinces in the Dunkard Group*[1]

Regional province	Lithofacies	Cross-bedding	Environment
Upper fluvial plain and southern source area	Thick belt sandstones and coarse-grained red and buff mudstones abundant; moderately high sandstone/mudstone and clastic ratios; almost no coal or limestone beds	Current directions generally north in extreme eastern and western sectors, northwest to nearly west elsewhere, dominantly northwest, $\bar{v}$ = N 37° W; low variance in central portion (see figs. 16-18)	Upper fluvial plain—surface generally above water table (high Eh); integrated radiating drainage with medium-sized competent streams; few undrained backswamps or lakes; paleoslope moderately high
Lower fluvial plain and drainage basin	Numerous thin (belt-dendroid) sandstones, medium to very fine grained; numerous thin to thick, red mudstones; some nonred and mixed mudstones; a few nodular limestones but very few, thin coals	$\bar{v}$ = N 52-58° W, high variance in current directions; current distribution locally polymodal; vectors oriented westward to west-northwestward (see figs. 16-18)	Lower fluvial plain—surface generally above water table, but fluctuating; rapidly shifting, anastomosing streams with low gradients; a few small transitory lakes and swamps; crevasse splays common, poorly drained
Fluvial-lacustrine-deltaic plain	Numerous thin, fine-grained to very fine grained sandstones, boundaries poorly defined; numerous gray-green to very dark, carbonaceous shales; numerous limestones and coals; very few red beds	$\bar{v}$ = N 17° W, moderate variance; cross-bed vectors trend northward to northwestward (see figs. 16-18)	Fluvial-lacustrine-deltaic plain—surface at or below water table (low Eh); moderate to low paleoslope; sluggish meandering distributaries separated by highly vegetated, poorly drained swamps and lakes

[1]Modified from Martin and Lorenz (1972).

place to the greatest extent in the fluvial-lacustrine-deltaic plain of the north and northwestern parts of the region, but also on the lower fluvial plain where swamps and lakes were extensive.

Donaldson and Eble (1991, p. 539) concluded that the lithologies in the Appalachian Basin indicate the existence of an everwet, tropical climate during the Early Pennsylvanian and that a seasonally dry, tropical climate prevailed in the Late Pennsylvanian (including early Dunkard time). The associated coal beds, freshwater limestones, and red-bed paleosols exhibiting subaerial exposure features (gilgai structures) and carbonate nodules support the interpretation of a climate with seasonal rainfall (Donaldson and others, 1985). In their study of the Lower Permian (Wolfcampian) paleosol-bearing cyclothems of Kansas, Miller and others (1996) reported some of the features listed by Donaldson and others (1985) such as pseudoanticlines, gilgai structures, and carbonate nodules, and interpreted the climate to have fluctuated from arid to semi-arid conditions to seasonally wet or dry conditions within a single cycle. The trend of the paleoequator in Late Pennsylvanian time was approximately N 45° E through the Appalachian Basin (Donaldson and Eble, 1991, fig. 3).

Numerous authors have suggested that the limestones of the Monongahela and Dunkard Groups resulted from deposition of calcareous sediments in lakes under freshwater, or at most, brackish-water environmental conditions rather than marine conditions (Arkle, 1959, 1969; Cross and others, 1950; Cross and Schemel, 1956a; Cross, 1975; Beerbower, 1961; Bain, 1979; Warshauer and others, 1980; Eggleston and Ferdinand, 1990). These fresh or brackish lakes ranged in size from several hundred to more than a thousand square kilometers in area (Cross, 1976, p. 831). The intraclastic limestones (dismicrites) probably formed by initial desiccation of mud flats developed by loss of water in the lakes, followed by an influx of water which reworked and redeposited the hardened carbonate clasts (fig. 20).

Progressive northwestward progradation of the fluvial plain eventually raised much of the depositional surface above the ground-water table. In the north, especially, the abundant nonclastics characteristic of the lower half of the rock section are gradually replaced upward by sandstones, siltstones, and buff to red shales (Berryhill, 1963, p. 90). These upper strata are analogous to the red facies of the western drainage system.

Although evidence of continued facies shifts is lacking owing to post-Permian erosion, it is probable that the preserved strata do not represent the final stages of basin filling. From existing evidence of facies shifts, it is also probable that the sedimentation rate was not decreasing but increasing in Late Pennsylvanian and Early Permian times during the Alleghany orogeny.

FOSSIL FAUNA AND FLORA

The generally freshwater to brackish-water environments of the northern part of the Dunkard outcrop region provided a lush habitat for flora and for vertebrate and invertebrate fauna, including insects. Lycopsids, sphenopsids, ferns, seed ferns, and early conifers were abundant on the warm, humid to mesic coastal plain (Cross, 1975, p. 298).

Vertebrate fossils, including freshwater sharks, several kinds of reptiles, fish, and aquatic amphibians, as well as rare pelecypods, gastropods, the worm tube *Spirorbis*, and abundant ostracodes occur in the limestones or associated limy mudstones along with carbonized plant fragments (Beerbower, 1961, p. 1036). Scott (1971) reported a eurypterid from the Dunkard Group. Stauffer and Schroyer (1920) illustrated *Lingula permiana* from the Dunkard Group, along with a few gastropods, pelecypods, and the ostracode *Cythere*. Cross and Schemel (1956a, p. 51) pointed out that the brackish-water brachiopod *Lingula* collected from a shale parting in the Washington coal in northern West Virginia indicates that marine conditions existed nearby.

FIGURE 20.—Fragment of a weathered Upper Pennsylvanian limestone, an intraclastic dismicrite, comparable to Dunkard Group dismicrites, from a few meters below the Hockingport Sandstone Lentil in Carthage Township, Athens County, Ohio. Photo taken in 1951. Bar equals 1 cm.

Arkle (1959, p. 121) reported that *Lingula* had been observed in Washington coal partings in southern Belmont County, Ohio, and in the Elm Grove limestone in northern West Virginia. Brackish-water or marine orbiculoid brachiopods and gastropods also have been identified in the Elm Grove limestone and the Washington coal zone (Cross, 1975, p. 298). Glen K. Merrill (University of Houston–Downtown, personal commun., 1998) found fragments of shells of *Lingula* in samples collected from a shale parting between two benches of the Washington coal. The samples lacked agglutinate foraminifera or other indicators of a nearshore environment. He concluded that "the *Lingula* specimens were ripped up by a storm and transported with a load of mud into the purely freshwater coal swamp. There they survived, flourished, and probably reproduced, filter feeding microcrustaceans and the like from the freshwater. Eventually the pond filled in and plant growth resumed." Viktoras Skema (Pennsylvania Geological Survey, personal commun., 1997) suggested that the final marine incursion into the region is indicated by the presence of *Lingula* in the shale partings of the Washington coal.

Egar (1975) described bivalve faunas from the Dunkard Group and underlying units. He considered the faunas to be nonmarine, including some genera which Stauffer and Schroyer (1920) had tentatively believed to be marine forms. Jones and Clendening (1969) analyzed 1,400 ostracode carapaces from fine-grained rocks of the Dunkard basin, including the smooth-shelled genera *Carbonita* and *Gutschickia*, in their shell-orientation study.

The fossil fauna and flora of Ohio have been thoroughly described in Ohio Division of Geological Survey Bulletin 70, *Fossils of Ohio* (Feldmann and Hackathorn, 1996). In this volume, Hansen (1996, p. 288-369) provides a detailed account of fossil vertebrates, and Cross, Taggart, and Gillespie (1996, p. 370-395) and Cross, Gillespie, and Taggart (1996, p. 396-479) describe the fossil plants of the state. *Fossils of Ohio* and other faunal and floral studies are described in Chapter 6.

Chapter 4

COMPOSITION OF DUNKARD CLASTIC ROCKS AND THEIR ECONOMIC USES

MUDSTONES

Studies of Dunkard Group mudstones in the southwestern portion of the outcrop area were made by Weimer (1980), in the central portion by Benton (1983), and in the northeastern portion by Thomsen (1980). The focus in these studies, which had a total of 218 samples, was on particle-size distribution and mineral content. Rendina (1985) compared the composition of the clay-size fractions of some Dunkard mudstones to those of sandstones collected from adjacent or nearby beds.

The principal nonclay minerals of the 218 mudstone samples, determined by X-ray diffraction, are quartz and potassium and plagioclase feldspars. Minor nonclay minerals commonly reported are muscovite, biotite, pyrite, and calcite. The principal clay minerals are kaolinite, illite, mixed-layer clays, and minor amounts of chlorite and vermiculite.

Quartz is the most abundant nonclay mineral in the mudstone samples and is present in the sand, silt, and coarse clay fractions. Many quartz grains observed by a scanning electron microscope and in thin sections show evidence of in situ dissolution (Benton, 1983). Potassium feldspar, plagioclase feldspar, or both are present in varying amounts in the sand and silt fractions of the majority of samples studied. Some feldspar grains have been partially replaced by authigenic kaolinite and illite.

Biotite and muscovite are more abundant in mudstone samples collected in the western and central parts of the region than in samples of the northeastern area. Minor amounts of pyrite are present, mostly in the sand fractions of the mudstones, and more commonly in samples collected in the northern parts of the region.

Calcite is present in the sand and silt fractions of the mudstones and, like pyrite, is more abundant in samples from the northern portions of the basin. Lambert (1969) and Orndorff (1980) reported calcite as very abundant in some sandstone samples from the northern part of the region, occurring as a late diagenetic mineral replacing other minerals. The greater abundance of pyrite and calcite in rocks of the northern part of the basin is believed to be related to the sedimentary environments. Under reducing conditions, organic materials were preserved to form black shales and coals; alkaline conditions resulted in the development of limestones.

Illite, interlayered with an expandable clay, and kaolinite are the major clay minerals and are present in virtually all of the clay fractions and in most silt fractions of the mudstones but vary in abundance. Chlorite and vermiculite are present in silt and clay fractions of many of the samples but generally in minor amounts. In thin sections of the coarse-grained mudstones, and in some sandstones, illite can be observed as a fringe along grain boundaries and internally in grains of quartz and feldspar as an authigenic replacement of the grains (fig. 21A). Illite also may develop by the diagenetic degradation of muscovite (Grim, 1968).

In mudstones from the southwestern portion of the outcrop area, Weimer (1980) noted concentrations of presumably detrital chlorite in samples collected in a zone along an inferred boundary between the upper and lower fluvial plain environments (see fig. 19); this inferred boundary parallels the axis of the outcrop area and also is parallel to the depositional strike. This trend of the chlorite concentration suggested to Weimer (1980) that sediment accumulation was rapid in this zone, and chlorite particles could therefore be buried and preserved before the mineral composition and structure were altered by weathering. Chlorite group minerals are common constituents of argillaceous sediments, occurring both as authigenic crystals and as detrital grains derived from the degradation of pre-existing ferromagnesian minerals. Hayes (1970) concluded that 80 percent of all chlorite he studied was of detrital origin.

In a sedimentary environment, vermiculite exists principally as a weathering product of muscovite, biotite, or chlorite alteration (Berner, 1971; Deer and others, 1975). Thomsen (1980) observed that vermiculite is present in the more weathered samples from the northeastern part of the basin and chlorite is present in the fresh samples; therefore, the vermiculite may be a weathering product of the chlorite.

Most of the minerals of the Dunkard mudstones are probably detrital in origin. Various workers have stated that the majority of minerals in fine-grained, terrigenous, clastic rocks are strongly representative of the source area and have been only slightly modified in transit, in the depositional environment, or diagenetically (Weaver, 1956; Keller, 1970; Blatt and others, 1972; Folk, 1974; Potter and others, 1975; Pettijohn, 1975; Karlin, 1980; Elliot, 1980; Pettijohn and others, 1987).

SANDSTONES

Some Dunkard sandstones, in particular the Hockingport and Mather Sandstone Lentils, contain lenses of conglomerate as well as pebbles scattered along bedding surfaces (see fig. 13). Most pebbles in Dunkard rocks are milky quartz, but tan, gray, and black chert, quartzite, sandstone, and siltstone pebbles also are present. A typical angular tan chert pebble measures approximately 1.5 and 2.0 cm in intermediate diameters and 3.5 cm in long diameter. Most pebbles other than chert are smaller and well rounded. Two cobbles, both measuring approximately 4 and 5 cm in intermediate diameters and 7.5 cm in long diameter, were discovered in the Hockingport Sandstone Lentil. They appeared to be highly weathered, micaceous, metamorphic rocks (gneiss?).

Thompson (1963) completed a petrographic study of thin sections of 74 samples of Dunkard sandstones from the southern part of the Dunkard outcrop area. Lambert (1969) completed a similar study of 67 samples of sandstones from the northern part of the basin. The east-west boundary between the areas runs through Marietta, Ohio. Sandstone compositional data acquired in these studies were averaged and reported by Martin and Lorenz (1972), and herein will

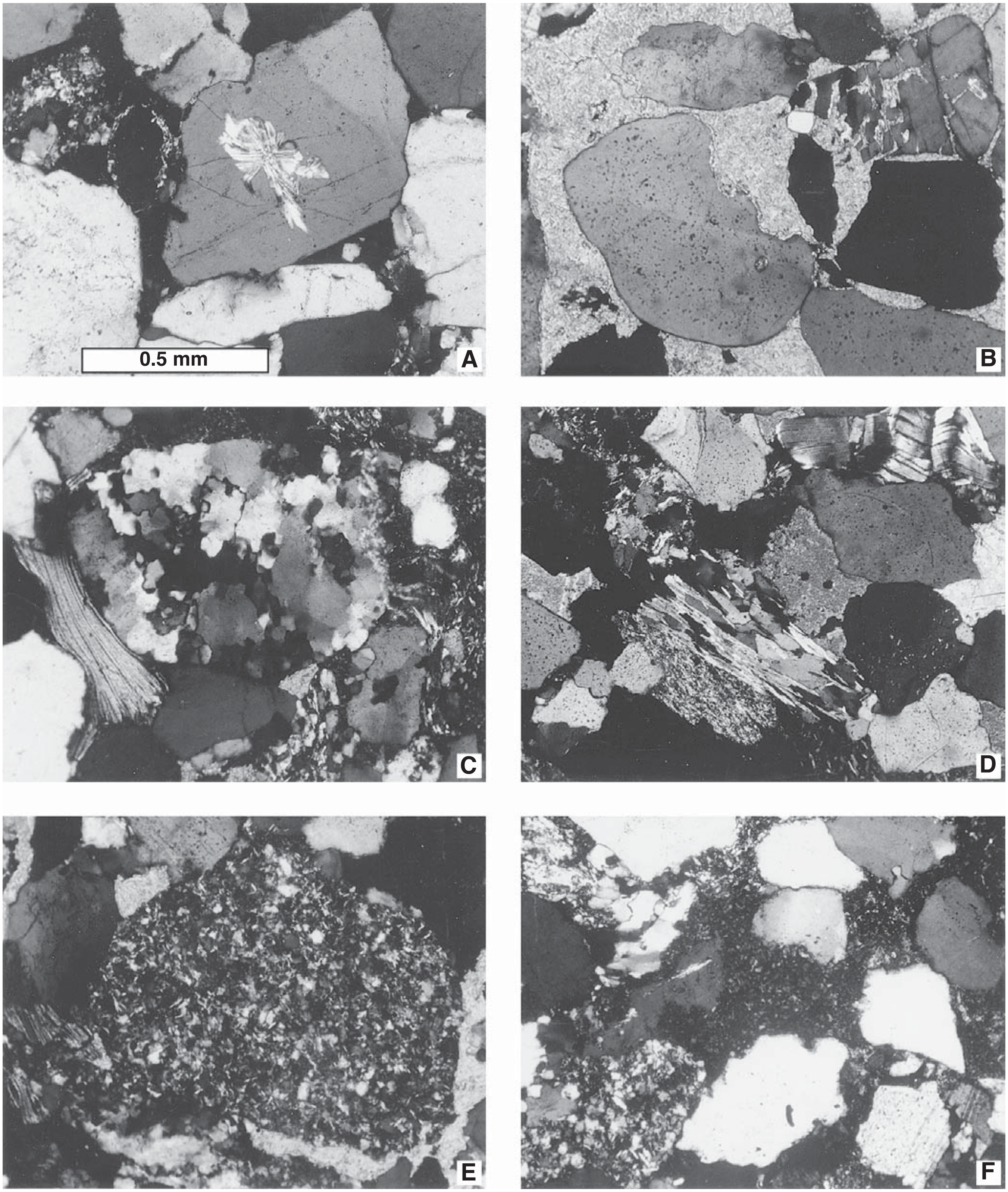


FIGURE 21.—Photomicrographs of Dunkard Group sandstones. Scale in **A** applies to all photos. **A**, mostly monocrystalline quartz, grain in center partly replaced by illite. **B**, calcite as cement and replacing quartz grains, center and upper right. **C**, pressure metaquartzite grain in center, detrital mica grain to left. **D**, schistose metaquartzite grain near center, phyllite grain below, mica grain in upper right. **E**, silty, sedimentary lithic fragment in center. **F**, pore-filling authigenic kaolinite in center, twinned feldspar grain in lower right.

be referred to as the average sandstone composition for the Dunkard Group. Martin and Henniger (1969) provided thin-section and heavy mineral composition data for the Hockingport and Mather Sandstone Lentils. Rendina (1985) compared the composition of sandstones and mudstones collected in the northern part of the outcrop area with samples obtained from around the margin but well within the border of the area. Several other studies of Dunkard sandstones included thin-section petrographic analyses (Mushake, 1956; Thoms, 1956; Healy, 1959; Swinehart, 1969; Orndorff, 1980; Gospodarec, 1983).

The major mineral composition of the Dunkard sandstone bodies as determined by point counts of 141 thin sections (Thompson, 1963; Lambert, 1969; Martin and Lorenz, 1972) is quartz, 63.5 percent; feldspar, 3.1 percent; detrital mica, 5.5 percent; pelitic (very fine grained) sedimentary and micaceous metamorphic rock fragments, 3.5 percent; calcite, 2.5 percent; and matrix approximately 21 percent. Minor components include detrital chert, which constitutes 1 percent of the framework grains. Calcite is present as cement and has replaced other components of the rocks, especially quartz and feldspar grains and some of the matrix (fig. 21B).

Quartz occurs mainly as monocrystalline grains that lack extreme undulose extinction as defined by Doty and Hubert (1962), that is, requiring more than 30° rotation of the microscope stage to produce complete extinction (fig. 21A). Three main types of polycrystalline quartz grains were observed: polycrystalline grains having two or three crystal units which lack high undulose extinction, possibly derived from plutonic sources, and two types of metaquartzite rock fragments, pressure and schistose.

Pressure metaquartzite grains (Doty and Hubert, 1962) are aggregate grains that have generally high undulose extinction and are characterized by crenulated, sutured, or granulated internal boundaries of small, lensoid crystals (fig. 21C). These fragments were recognized as quartzite grains by Krynine (1946), aggregate quartz by Graham and others (1976), and were figured by Young (1976). Schistose metaquartzite fragments (Doty and Hubert, 1962), also termed schistose quartz (Folk, 1974), injected metamorphic quartz (Krynine, 1946), or quartz-mica tectonite (Graham and others, 1976), are aggregate grains that have internal elongate units bounded by straight edges and laced with a minor amount of mica (fig. 21D). Mack (1981) referred to such grains as foliated quartz and mica grains and classified them as metamorphic rock fragments if mica composed greater than 10 percent of the grains. Metaquartzite grains make up about 7 percent of the framework quartz grains of the Mather and Hockingport Sandstone Lentils (Martin and Henniger, 1969). Rendina (1985) determined that the two types of metaquartzite rock fragments constitute greater than 95 percent of the polycrystalline quartz population in the sandstone samples which he studied. Authigenic overgrowths of quartz on detrital grains are common in the sandstones and coarse mudstones.

Although feldspar constitutes approximately 3 percent of the average Dunkard sandstone (Martin and Lorenz, 1972), it forms 4 percent of the Hockingport samples and 5 percent of the Mather samples (Martin and Henniger, 1969). Three main divisions of feldspar were made in the modal analyses: untwinned feldspar, microcline, and plagioclase. Much of the untwinned feldspar may be potassium feldspar—orthoclase or microcline. Grains showing a grid twin pattern or subparallel, tapering twin lamellae were classed as microcline. The plagioclase grains commonly display the twinning characteristic of albite. Perthite grains are present but uncommon.

Many of the feldspar grains show various degrees of alteration, notably replacement by illite (sericite), kaolinite, and calcite. Illite flakes occur along cleavage traces of detrital microcline, indicating incipient pseudomorphic replacement of the detrital grains. Kaolinite has replaced feldspar grains internally as well as in marginal areas. Morris and others (1979) noted that kaolinite minerals are the most common weathering products of plagioclase and microcline. Orndorff (1980) and Rendina (1985) reported that, in Dunkard sandstones, plagioclase grains generally show a higher degree of alteration to kaolinite than microcline grains do. Calcite replacement of some grains is very pervasive, to the extent that the original detrital minerals are nearly obliterated.

In addition to metaquartzite rock fragments from metamorphic rocks, phyllite and slate metamorphic rock fragments and pelitic sedimentary rock fragments constitute 3.5 percent of the average sandstone sample. Phyllite fragments (fig. 21D) differ from schistose metaquartzite fragments by their preponderant content of mica relative to quartz. Slate fragments are predominantly fine mica but also contain clay. Chert, siltstone (fig. 21E), and shale rock fragments are less commonly reported and volcanic rock fragments are rare.

Mica, both biotite and muscovite, occurs as large, detrital flakes (fig. 21C, D) and as fine, pore-filling aggregates mixed with silt and clay, together constituting approximately 5.5 percent of the average Dunkard sandstone. Much of the mica in pores may be authigenic, and pore-filling mica was counted as matrix. In outcrop, detrital mica may be observed in laminae a millimeter or two in thickness.

Matrix constituents—grains less than 0.03 mm in diameter—constitute approximately 21 percent of the average Dunkard sandstone sample. Matrix components observed in thin sections may be broadly divided into two categories: (1) fine-grained aggregates of birefringent mica and clay minerals (presumably mainly illite and chlorite) occurring with silt-size detrital grains (mainly quartz), and (2) pore-filling, pure kaolinite, mostly clear but also iron stained. Orndorff (1980) studied the Mather Sandstone Lentil and Gospodarec (1983) the Hockingport Sandstone Lentil, focusing on clay mineralogy and diagenesis of the sandstones. The results of X-ray diffraction show that kaolinite and illite are present in all silt- and clay-size fractions of the sandstone samples. Chlorite, montmorillonite, vermiculite, and mixed-layer clays also are present in these size fractions but are not evident in all samples. Kaolinite, free of admixtures of mica and detrital silt, is less abundant than other matrix constituents; books or aggregates of kaolinite are as large as 100 micrometers, but most are no larger than 50 micrometers and are probably authigenic (fig. 21F).

Rendina (1985) compared the composition of the clay-size fractions of 12 Dunkard sandstones and 12 Dunkard mudstones. Kaolinite constitutes nearly 67 percent and illite nearly 33 percent of the clay-size fraction of the sandstone samples. Kaolinite constitutes nearly 53 percent and illite nearly 47 percent of the clay-size fraction of the mudstone samples. Chlorite and vermiculite minerals are present in about half of all samples studied. The kaolinite occurs as loose, pore-filling booklets up to 100 micrometers in diameter, each composed of individual crystals that show pseudohexagonal outlines. The presence of kaolinite booklets in the Mather and Hockingport Sandstone Lentils was reported by Orndorff (1980) and Gospodarec (1983) in scanning electron microscopic studies of kaolinite and other minerals. Gospodarec (1983) determined that the book-crystal habit is formed by the interlocking, pseudohexagonal, platy crystals stacked face-to-face. Other occurrences of authigenic kaolinite in Dunkard sandstones include the vermicular habit of the mineral ("worms") as described by Scholle (1979, p. 67). These tightly packed books, up to 60+ micrometers in length, were illustrated by Orndorff (1980, p. 80) embedded in quartz cement and by Gospodarec (1983, p. 23) replacing a detrital quartz grain.

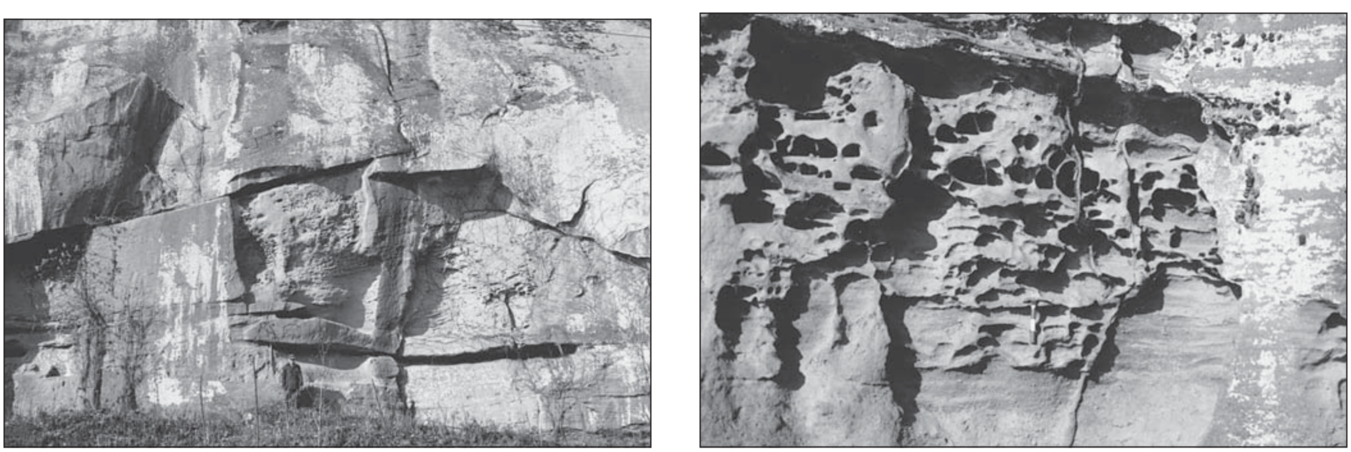
Orndorff (1980, p. 63) concluded that, in the Mather Sandstone Lentil, the paragenesis of minerals formed diagenetically is quartz overgrowths, illite, kaolinite, silica cement, and carbonates. Iron oxides also are present in samples collected from weathered outcrops, as a stain in matrix-filled pores except in some pores containing kaolinite. The iron oxides staining the matrix constituents in sandstones probably were formed by oxidation of ferrous iron compounds (Pettijohn, 1957, p. 139). Uneven distribution of diagenetic cements and case hardening in the sandstones probably cause the irregular weathering, development of pitting, and a honeycomb appearance on the faces of outcrops of Dunkard sandstones (figs. 22A, B). Parts of the surface may become case hardened as a result of interstitial water in the rock being drawn to the exposed surfaces and evaporated, leaving behind precipitated minerals such as calcite, silica, and iron oxides. This explanation was provided by Kiersch (1950, p. 936) for case hardening and development of desert varnish in outcrops of the Navajo Sandstone in Utah. The Hockingport Sandstone Lentil has surface pitting on both large and small scales. Some indentations have dimensions of 1 to 3 meters long (see fig. 6A), but most pits measure 5 to 15 cm (Martin, 1955). Healy (1959) described pitting in a dendroid-type Dunkard sandstone near Ravenswood, in Jackson County, West Virginia, and across the Ohio River in Meigs County, Ohio.

Considering the composition of framework grains (quartz, feldspar, and nonquartzose rock fragments) and total matrix (unadjusted for diagenetic clays), the average Dunkard sandstone sample plots as a lithic graywacke (fig. 23A). The figure of 21 percent matrix includes all pore-filling, argillaceous-micaceous constituents. However, the kaolinite, which occurs as clear or iron-stained aggregates filling some pores, is believed to be diagenetic in origin. Siever (1957, p. 242) and Potter and Glass (1958, p. 32) reached the same conclusion with regard to the origin of the kaolinite in some of the Pennsylvanian-age sandstones of the Eastern Interior coal basin.

An indication of the authigenic development of kaolinite in some pores of Dunkard sandstones is the lack of an admixture of other minerals. Also, Rendina (1985) noted the large size of the books (too large to pass through pore throats as detrital particles), the good crystal outlines, and the existence in pores with no apparent relationship to each other or to surrounding grains. These criteria and others supporting an authigenic origin of kaolinite in sandstones have been described by Keller (1970), Wilson and Pittman (1977), Almon and Davies (1979), and Scholle (1979). In a study of 67 sandstone samples from the northern part of the Dunkard outcrop area, Lambert (1969) determined that 7 percent of matrix constituents of a total of 22 percent matrix is pore-filling kaolinite.

In relating sandstone mineralogy to provenance and transport, components of diagenetic origin are set aside. Pettijohn and others (1987, p. 145) provided a classification of sandstones using ternary plots on triangular diagrams, where, in addition to plotting the framework components, a second criterion, the matrix content, is considered. Sandstones having less than 15 percent matrix are "clean" sandstones or arenites, and those with more than 15 percent matrix are "dirty" sandstones or wackes. Pettijohn and others (1987) recognized that matrix may be largely diagenetic, so diagenesis as well as transport and provenance are introduced in classifications of sandstones. The composition of the average Dunkard sandstone (Martin and Lorenz, 1972) is such that the rock does not fit neatly into some sandstone classifications.

The total matrix content of the average Dunkard sandstone is approximately 21 percent, and if none of the matrix is considered diagenetic, the average sandstone would plot on triangle diagram A of figure 23 in the lithic graywacke field. If a minimum of 6 to 7 percent (one-third) of the matrix is diagenetic, as it appears to be, then the average



A B

FIGURE 22.—**A**, outcrop of the Hockingport Sandstone Lentil at the type locality before highway relocation (see fig. 6), 1 km (0.7 mile) northeast of Hockingport, Athens County, Ohio. For scale, my father, Dudley Martin, is standing below the area of irregular, honeycomb weathering in lower center of photo. **B**, closer view of honeycomb weathering in former outcrop at the type locality. Hammer near lower center of photo is 32 cm long. Photos taken in 1954.

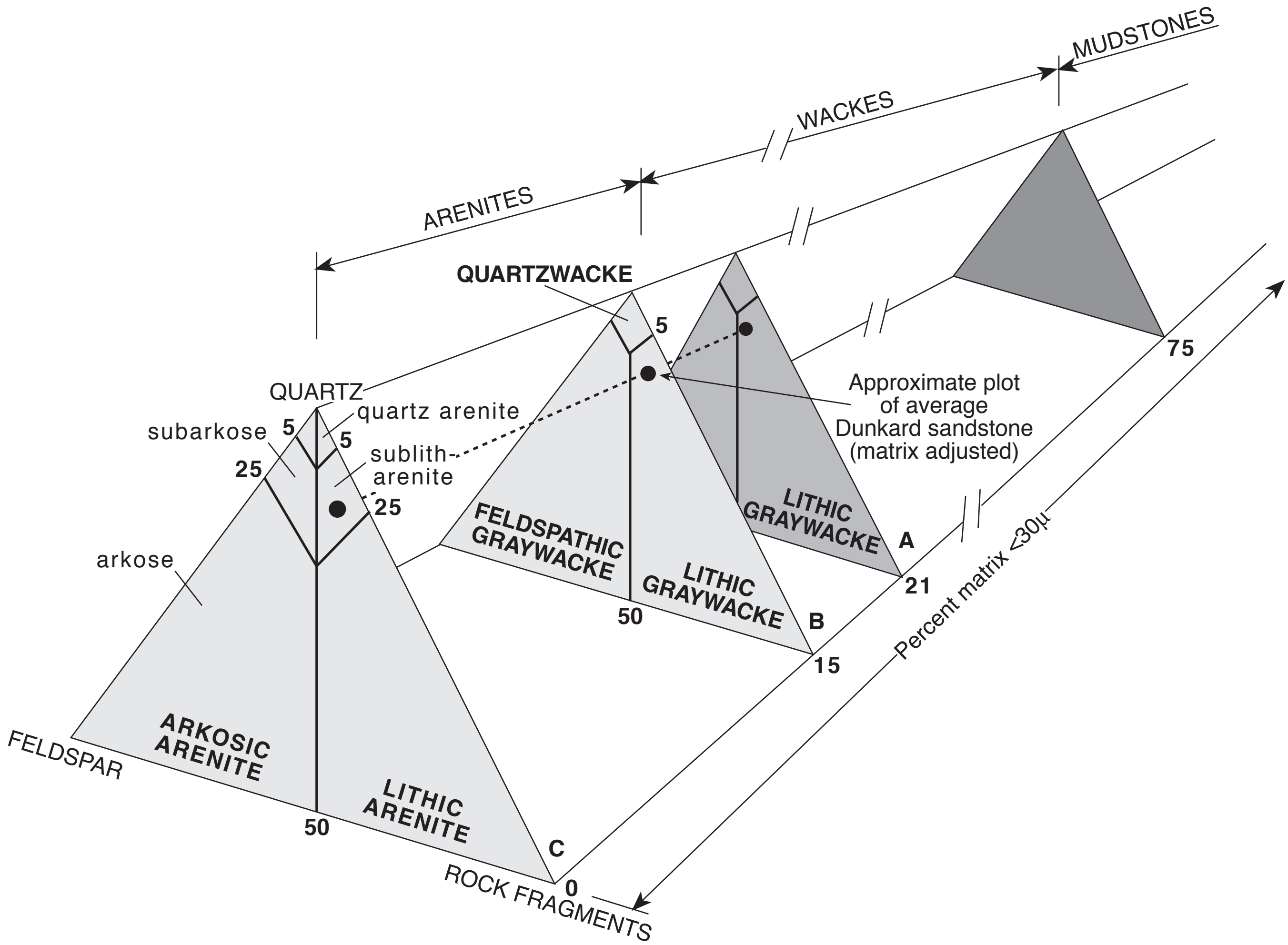


FIGURE 23.—QFL classification diagram of terrigenous sandstone (modified from Pettijohn and others, 1987). Triangle A shows a plot of the average Dunkard sandstone in the lithic graywacke field with matrix content unadjusted for diagenetic clays, which may constitute 6 to 7 percent (one-third) of a total of 21 percent matrix. Triangle B shows an approximate plot of the average Dunkard sandstone adjusted for clays of diagenetic origin. The average sandstone plots as a borderline sublitharenite-lithic graywacke at or near the upper limit of matrix content (15 percent) for a sublitharenite. The plot of the sandstone on triangle C in the sublitharenite field does not reflect the high (adjusted) matrix content (14 to 15 percent) of the rock. Considering total rock composition of less than 75 percent quartz (63.5 percent quartz, rock fragments exceeding feldspar, and approximately 14 to 15 percent matrix), a better name for the "average" sandstone is a "dirty" lithic arenite (litharenite), using the classification of Pettijohn (1957, p. 291).

sandstone contains 14 to 15 percent nondiagenetic matrix and still could be considered a borderline lithic graywacke, as plotted on triangle diagram B of figure 23. Plotting the average sandstone as a sublitharenite on triangle C of figure 23, even though sublitharenites can have up to 15 percent matrix, would not be the best fit in the classification of the average Dunkard sandstone owing to the high matrix component. The plot of the average Dunkard sandstone falls in the sublitharenite areas of the triangular diagrams of McBride (1963) and Folk (1968), in which the grain components of the poles are essentially the same as the QFL diagram of Pettijohn and others (1987, p. 145). However, the matrix content of a sandstone is not considered in these classifications.

Setting aside the QFL triangular diagrams and considering the total rock composition of 63.5 percent quartz, 14 to 15 percent matrix, and rock particles exceeding feldspar, a better classification of the average sandstone is that of a borderline lithic arenite-lithic graywacke, essentially a subgraywacke of the older classification scheme of Pettijohn (1949).

Pettijohn (1975, p. 219) pointed out that the term subgraywacke was first used for rocks transitional between quartz arenites and graywackes (Pettijohn, 1949, p. 255). Such a rock had less than 10 percent feldspar and over 20 percent matrix. In his redefinition of subgraywacke, Pettijohn (1954) considered it to be a sandstone having less than 15 percent matrix but containing 25 percent labile (easily decomposed) grains, of which rock particles exceed feldspar, and thus defined is essentially a lithic arenite (litharenite). The rock particles most commonly are very fine grained (pelitic) and include shale, siltstone, slate, phyllite, and mica schist (Pettijohn and others, 1987, p. 145). This rock would contain less than 75 percent quartz and less than 15 percent matrix according to Pettijohn (1957, p. 291). The average Dunkard sandstone contains less than 75 percent quartz (63.5 percent), approximately 14-15 percent nondiagenetic matrix, and rock particles and detrital mica exceeding feldspar, so it is best termed a "dirty" lithic arenite (litharenite). The rock is not as "clean" as a protoquartzite (sublitharenite), which should contain between 75 and 95 percent quartz. Folk (1968, p. 124) used the term phyllarenite for a sandstone, essentially a lithic arenite, that contains an abundance of low-grade metamorphic and pelitic detrital rock particles (slate, phyllite, and mica schist). Dunkard sandstones contain these rock particles along with fine-grained sedimentary-rock particles.

Pettijohn and others (1987, p. 156) pointed out that lithic arenites show the greatest diversity of all sandstones in both mineralogical and chemical composition. This variability reflects the importance and relative abundance of the diverse rock particles. If the rock-particle content is small, these sandstones pass over into quartz arenites or orthoquartzites. Pettijohn and others (1987, p. 156) noted that, with regard to matrix, a pseudomatrix (squashed shale particles) or authigenic precipitated clay may be present. The nonquartzose rock-particle content of the average Dunkard sandstone is relatively small—3.5 percent. Rendina (1985, p. 40) noted that some of the matrix of these sandstones is the result of squashing of poorly indurated pelitic particles and that diagenetic clay forms approximately one-third of the matrix.

Berryhill (1967) believed that the Permian sandstones of the Dunkard Group in the Allegheny region are mostly subgraywackes according to the definition of Pettijohn (1949, p. 256). He noted that the typical sandstone consists mainly of quartz grains but also contains feldspar, abundant mica, some rock fragments, and a clayey matrix.

Pettijohn and others (1987, p. 159) noted that lithic sandstones are very common, widespread, and of all ages. Well-known examples are various alluvial Paleozoic sandstones of the central Appalachians and include the Mississippian-age Pocono Formation (Pelletier, 1958) and Mauch Chunk Formation (Hoque, 1968) and Pennsylvanian-age Pottsville sandstones (Meckel, 1967). Most sandstones associated with coal measures throughout the world are lithic arenites and perhaps more are protoquartzites (sublitharenites) according to Pettijohn and others (1987, p. 161).

The lithic sandstones of the Dunkard Group are not as "clean" as some of the older, alluvial Paleozoic sublitharenite sandstones. The higher matrix content, reflecting poorer sorting in alluvial environments, may well be the result of increased tectonism in the Appalachian region during the late Paleozoic Alleghany orogeny.

HEAVY MINERALS

The heavy mineral suites of the various Dunkard sandstones are similar in regard to mineral species represented and are relatively simple. Heavy mineral grains were separated from the 0.062-0.5 mm size fractions of sandstone samples, and an average of 300 grains per slide were identified.

Opaque minerals as separate grains or as encrustations on nonopaque grains constitute approximately 70 percent of the heavy mineral suites of 141 sandstone samples (Thompson, 1963; Lambert, 1969; Martin and Lorenz, 1972). Most of the opaque mineral matter is probably ilmenite in various degrees of alteration to leucoxene (fig. 24). Magnetite, hematite, and limonite make up a few percent of some suites.

Tourmaline and zircon each constitute approximately 6 percent of the average suite. Tourmaline occurs in four to six varieties in most samples. Brown tourmaline is present in most samples and constitutes the major part of the tourmaline fraction. Tourmaline grains range in angularity from subangular to well rounded. Zircon occurs as colorless and slightly pink grains that are generally well rounded. Colorless and pink garnet grains are present in all samples but form only 2 to 3 percent of the suites. Most garnet grains are highly etched, and some contain inclusions.

The most abundant minor constituents of the nonopaque fractions, constituting a total of 5 percent of the average suite, are apatite, anatase, monazite, epidote, rutile, staurolite, biotite, and sphene. Of the minor mineral species, sphene is more common than others. Rendina (1985) determined that sphene is present in greater abundance in Dunkard sandstone and mudstone samples in the northern portion of the outcrop area than in samples from other areas.

Barite is present in nearly all samples and ranges in abundance from minor amounts to very abundant (30 percent, Lambert, 1969), averaging 8 percent. Lynn (1975), in his study of barite in Dunkard sandstones, determined that the mineral occurs as pure $BaSO_4$. The grains commonly exhibit iron staining, have a dusty appearance from inclusions, and are extremely angular. Lynn believed that the lack of statistical correlation of barite with other heavy minerals in regard to abundance, coupled with a high abundance variability and extremely angular shape, is suggestive of an authigenic origin. The low transport stability of barite also is indicative of an authigenic origin for the mineral.

ECONOMIC USES OF DUNKARD MUDSTONES AND SANDSTONES

Mudstones and sandstones of the Dunkard Group have not been quarried for commercial use in recent years. His-

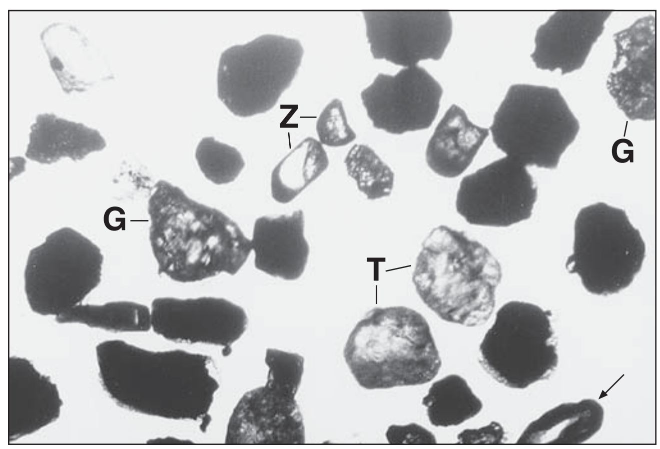


FIGURE 24.—Photomicrograph of a portion of a heavy mineral fraction of a sandstone sample from a dendroid sandstone body at Constitution, Ohio, 13 km (8 miles) southwest of Marietta, Ohio. Field of view = 2.5 cm across. This sandstone was referred to as the Upper Marietta sandstone by Stauffer and Schroyer (1920, p. 132) and Martin (1949, p. 30). Sample includes highly rounded, light-colored zircon grains (Z); two smooth, rounded tourmaline grains (T); a high-relief, "cloudy" garnet grain (G), and another garnet grain in the upper right corner. The opaque grains are ilmenite in various stages of alteration to leucoxene. Note the nearly complete encrustation of opaque mineral matter on a grain (arrow) near the lower right corner of the photomicrograph.

toric uses include ceramics, dimension stone, and abrasive stone (grindstones). The ceramic industry in Washington County, Ohio, dates back to the late 1700's (Webb, 1977). Bricks were made from Creston Reds strata, and as late as the 1950's fire clay and shale were quarried near Marietta. The fire clay was used for furnace lining and the shale for production of a lightweight, expanded shale aggregate. According to Collins and Smith (1977, p. 39), the "typical" Creston Reds is a very calcareous, red mudstone containing abundant limestone nodules and interbedded lenses of sandstone (see fig. 9).

A brief but very informative description of Ohio's sandstone industry was prepared by Van Buskirk (1982). An excellent, comprehensive history of the naturally occurring abrasive-stone industry, with a focus on quarries in the Dunkard Group sandstones, is that of Bond (1979).

Sandstones in the Dunkard Group that were quarried for dimension stone and grindstones include the Hockingport, Lower Marietta, Upper Marietta, Hundred, and Jollytown. Dimension stone was used in the foundations of buildings and in piers and bridge abutments, almost from the time of settlement of the region. The Hockingport Sandstone Lentil was widely used for bridge construction (Collins and Smith, 1977). Grindstones were produced in Ohio at least as early as 1819 (Hildreth, 1826). Sandstone from the southwestern third of the Dunkard Group outcrop area was quarried for industrial grindstones for a period of nearly 150 years, until 1966 (Bond, 1979, p. 103).

The grindstone industry developed in Nova Scotia in the late 1600's and continued until the expulsion of the Acadians in 1755 (Bond, 1979, p. 1). Within 30 years of the early settlement of the Northwest Territory, grindstones were being produced in the Marietta, Ohio, area, and in the Lake Erie and Michigan peninsula regions 10 years later. According to Bond, by 1912, approximately 65 percent of the grindstones produced and sold in the United States came from the Cleveland, Ohio, area, 25 percent from Washington County, Ohio, and 10 percent from Huron County, Michigan. The sandstone quarried to the greatest extent in the northern Ohio region for dimension stone and grindstones was the Berea Sandstone, traditionally considered to be early Mississippian in age.

Grindstone production in Washington County, Ohio, was centered in Warren, Dunham, and Barlow Townships, primarily along the Ohio River and the then-existing railroads. Units in the relative positions of the Lower Marietta and Upper Marietta sandstones and the Hundred sandstone have been most extensively quarried for grindstones (Martin, 1949; Collins and Smith, 1977; Bond, 1979). A major area of grindstone production was at Constitution, Ohio, 13 km (8.1 miles) southwest of Marietta. Quarries were developed in the bluffs above the Ohio River, and the stones were finished in mills nearby and shipped via railroad or boat.

In the early years, dimension stone for construction purposes and grindstones were hewn out of sandstone units by hand. Later, the ditching machine was developed and patented in 1874 (Bond, 1979). The device, driven by steam, held a drill bit that was moved up and down, like a slow jackhammer, and also moved along a circular channel (figs. 25A and 25B). Stone chips were removed from the channel with flat-bladed, curved scoops on the ends of the rods. The circular blocks were loosened at the base by a small explosive charge positioned in a horizontally drilled hole. Blocks that lacked imperfections were trimmed by hand and then moved to a finishing mill, where they were sawed to approximate thickness, then turned on a lathe and shaped to desired size and smoothness.

In order for a sandstone to be suitable for use as grindstones, it must be homogeneous and lack coarse cross-laminations, cracks, and large concentrations of chemical cements (Martin, 1949). A sandstone that contains concentrations of detrital mica in laminae is not suitable for grindstones. When the stone is turned rapidly, portions split off where laminae and cracks exist. Owing to imperfections, many quarried blocks of sandstone were rejected (figs. 14 and 25C).

The Dunkard sandstones are remarkably homogeneous. The larger sandstone bodies, the Hockingport and Mather (Waynesburg) Sandstone Lentils, are exceptions and have a greater range in composition, grain size, and structures (especially in the lower portions of the units). The typical Dunkard sandstone sample is composed of approximately 76 percent framework grains, 21 percent argillaceous-micaceous matrix, and 3 percent chemical cement, mostly calcite.

To serve as an abrasive stone, the bonding agents of a sandstone should not completely fill the pores; this preserved porosity allows the infiltration of coolant liquids. The partial dissolution and removal of matrix and dulled framework grains by coolant liquids is important in the grinding of metals. Grains at the surface will remain sharp, and the stone will not become "glazed" and lose its abrasive qualities. If the rock is too friable, it wears away too rapidly. If there are large concentrations of chemical cement (calcite), the stone will not wear evenly. Portions of some Dunkard sandstones having high concentrations of calcite, and up to 30 cm or more across, are a darker blue gray than the enclosing rock; these portions were termed "boulders" by the quarrymen.

The grindstone industry declined rapidly from 1920 to 1950 owing to the continued improvement and lower cost of manufactured abrasive materials. By 1950, the industry retained only about 10 percent of the former market, but for some types of grinding, the natural stone was preferred (Martin, 1949). The Hall Grindstone Company, established in 1910, operated quarries in the Dunkard sandstones at Constitution, Ohio, and at other sites in Washington County. Over a period of 56 years, this family-owned company produced more grindstones than any other company; it ceased operation in 1966.

Bond described the production of a particular type of grindstone (pulpstone) at Hundred and St. Mary's, West Virginia, for use in grinding wood to pulp for the paper industry. Crowell (1996a, 1996b) detailed the development of pulpstones from sandstones older (Pennsylvanian) than the Dunkard sandstones at several localities in eastern Ohio north of the Dunkard Group outcrop region and in Monongalia County, West Virginia. The sandstones that were quarried for pulpstones in Ohio are the Lower Freeport sandstone of the Allegheny Group and the Buffalo sandstone of the Conemaugh Group. In the grinding of wood, the stone "must be a harsh, tough stone" (Bond, 1979, p. 56). In the 1920's, synthetic abrasive stones began replacing the natural pulpstone because they could endure grinding three to four times longer than the natural stone. Also, according to Crowell (1996a, p. 6), "artificial pulpstones could withstand the higher stresses created by modern pulp mills better than natural pulpstones." The pulpstone industry essentially became nonexistent after the 1930's.

A

B

C

FIGURE 25.—**A**, grindstone quarry in a sandstone of the "Waynesburg" (Washington) Formation near Constitution, Ohio, 13 km (8 miles) southwest of Marietta, Ohio. Photo taken in 1949. Note the ditching machines at upper left. This unit was referred to as the Hundred sandstone by Stauffer and Schroyer (1920) and by Martin (1949). **B**, Constitution Stone Company grindstone quarry in Dunham Township, Washington County, about 1885. Photo and following description are from Crowell (1996, p. 53); original photo courtesy of the Ohio Historical Society. Note the ditching machine in center of photo. Michael J. O'Connor, in suit and derby to the right of the boiler, patented the machine in 1874. The grindstone on the right bears diagonal markings that show it was quarried by hand. **C**, cull pile of grindstones, rejected because of imperfections, at a quarry near Constitution, Ohio. Photo taken in 1949. This quarry was developed in a sandstone referred to as the Upper Marietta by Stauffer and Schroyer (1920) and Martin (1949).

Chapter 5

PALEOTECTONICS AND SOURCE TERRANES

As Dickinson and others (1983, p. 222) stated, provenance terranes and related basins of deposition can be classified according to their plate-tectonic settings. Detrital framework modes of sandstone suites provide information on the tectonic setting of the basins of sediment accumulation and sediment-contributing provenances (Dickinson, 1970; Graham and others, 1975, 1976; Dickinson and Suczek, 1979; Mack, 1981; Dickinson and others, 1983). The most significant compositional variations among terrigenous sandstones can be displayed as ternary plots on triangular diagrams (Dickinson, 1970). Dickinson and Suczek (1979, p. 2173) classified provenance types and derivative sandstone suites into three groups: (1) continental block, where sediment sources are on shields and platforms or in faulted basement blocks; (2) magmatic arc, where sediment sources are within active arc orogens of island arcs or active continental margins; and (3) recycled orogen, where source rocks are deformed and uplifted strata occur in subduction zones, along collision orogens, or within foreland fold-thrust belts.

Dickinson and others (1983, p. 229) concluded that the thrusts related to the Alleghany orogeny of the Appalachian region probably were emplaced mainly in the Pennsylvanian Period. Alleghanian thrusting probably reflected collision between Africa and North America (Donaldson and Shumaker, 1981; Dickinson and others, 1983). In the recycled-orogen provenance scenario of Dickinson and Suczek (1979) and Dickinson and others (1983), the collision orogen that developed along the eastern margin of the continent during the orogeny was bordered on the west by a suture belt, a fold-thrust belt, and a foreland basin; a big-river sediment-disposal system developed beyond the foreland basin (fig. 26).

The character of the Alleghany orogeny in the southern Appalachians has been described in detail in a series of papers by D. T. Secor and colleagues (Secor and others, 1986; Dallmeyer and others, 1986; and Secor, Snoke, and Dallmeyer, 1986). Secor, Snoke, and Dallmeyer (1986, p. 1345) stated "from southwestern Pennsylvania to Alabama, the base of the Permian-Carboniferous clastic wedge is marked by an upward transition from marine limestone (Loyalhanna, Maxville, Greenbrier, Newman, Bangor) to marine or brackish shale (Pennington, Mauch Chunk)." These formations are all Mississippian in age. The Pennsylvanian System, including the Pennsylvanian-Permian Dunkard Group, is composed for the most part of muddy and sandy facies. According to Secor, Snoke, and Dallmeyer (1986, p. 1345), "petrologic studies and facies analysis in the Carboniferous Pocahontas basin in Kentucky, Virginia, and West Virginia suggest the progressive unroofing of a 'batholithic' source terrane located in the Piedmont of the Carolinas during the Namurian and Westphalian [Lower-Middle Pennsylvanian] (Davis and Ehrlich, 1974; Ferm, 1974a)." From mid-Carboniferous to mid-Triassic time, sandstone "suites from the Appalachian basin and other foreland basins along the trend of the Allegheniann-Ouachita thrust front have framework compositions uniformly indicative of derivation from recycled orogenic sources" (Dickinson and others, 1983, p. 230).

Where the main source rocks of the orogenic provenances are uplifted terranes of folded and faulted strata, recycled sediments of sedimentary or metasedimentary origin may form the main deposits of the associated foreland basins. Dickinson and others (1983, p. 229-230) demonstrated that QFL plots of Carboniferous-Triassic sandstones in the Appalachian region are rich in recycled quartz grains, probably derived from "deformed and uplifted terranes of dominantly miogeoclinal character." Dickinson and others (1983, p. 230) pointed out that similar recycled sands which originally came from the Appalachian orogenic belt were transported to the Illinois Basin by rivers draining around or across the Appalachian Basin (Potter and Pryor, 1961; Pryor and Sable, 1974).

A plot of the average Dunkard Group sandstone (Martin and Lorenz, 1972) lies well within the field designated as a recycled orogenic source on the QFL triangular diagram (fig. 27A) and reflects derivation of these main framework components from collision-orogen and fold-thrust-belt source terranes. A standard QFL count, and a special count of quartz grains, indicate that the Dunkard sandstones are rich in quartz, sedimentary and metasedimentary lithic fragments, and detrital mica, but poor in feldspar and igneous lithic fragments. Chert is present in the sandstones as sand-size and larger fragments.

Rendina (1985) compared the composition of sandstone and mudstone samples collected in the northwestern part of the Dunkard basin to samples obtained from around the margin but mostly well within the outcrop boundary of the rock sequence. He determined that plots of the Dunkard detrital mode on provenance diagrams reveal a separation of samples into two groups, a geographically restricted "northern" group and a more extensive "southern" group. This discrimination is consistent with paleocurrent and facies distribution data, which indicate that two sources of sediments contributed to the foreland basin during Dunkard time, a dominant southeastern source and a subordinate northern source (fig. 28).

The plots of "southern" (southeastern source) sandstone samples on the QFL diagram show that many samples contain larger quantities of total lithic fragments compared to total quartz (fig. 27B). As Rendina (1985) noted, the close cluster of plots of most northern-source and southeastern-source samples indicates a relative compositional homogeneity among samples collected from all parts of the outcrop area. This low degree of compositional variation suggests that the grains were supplied by a single provenance terrane. However, Dickinson and others (1983) indicated that the QFL diagram does not discriminate subtle differences in provenance, as the emphasis may rest on grain stability rather than on source-rock composition. They pointed out (p. 224) that "sedimentological factors may locally enhance the quartz content of sands such as beach-barrier deposits by selective removal of lithic grains and feldspars."

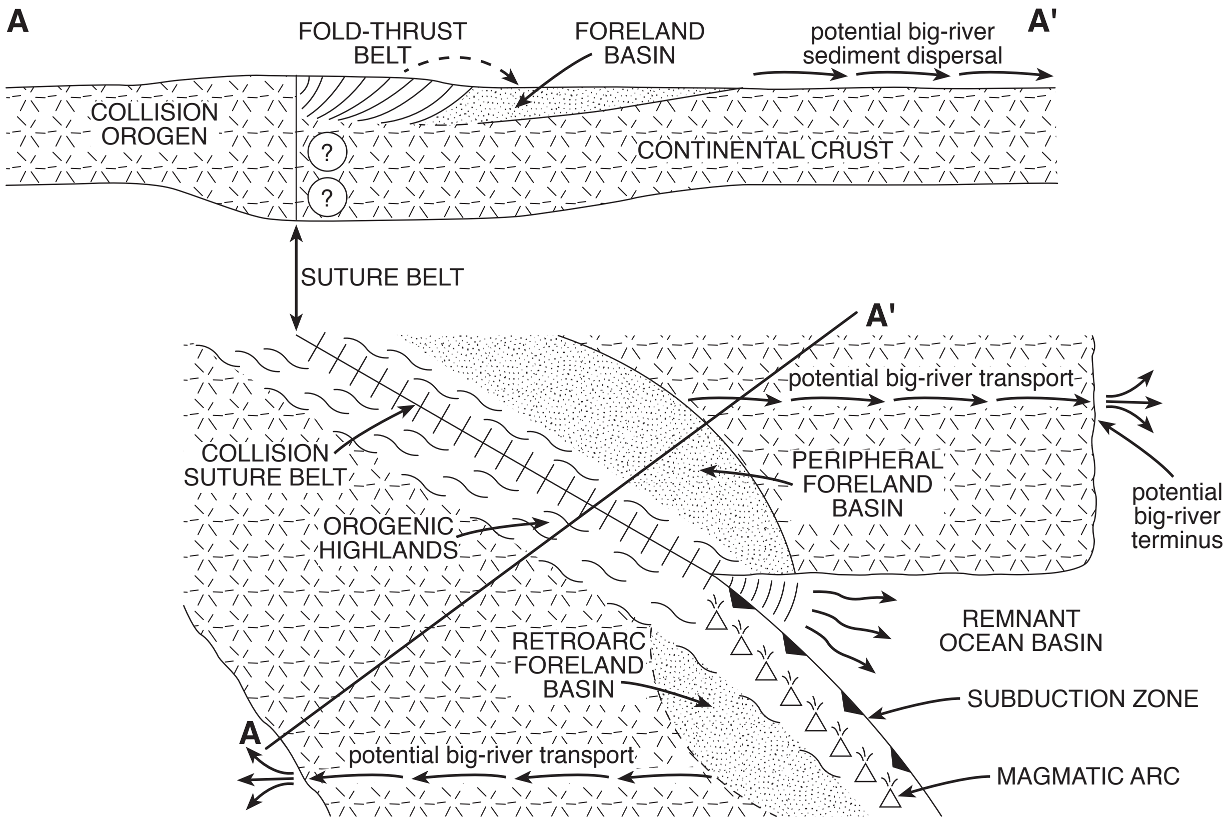


FIGURE 26.—Diagram showing key recycled orogen provenances and selected types of associated basins. Modified from Dickinson and Suczek (1979); reprinted by permission of the American Association of Petroleum Geologists. Plan view (bottom) shows continent-continent collision. Profile (top) shows foreland uplift and basin flanking the collision orogen. Dashed arrow on profile denotes dispersal of recycled sediment from foreland fold-thrust belt into the foreland basin. Consider the left sides of the illustrations (the collision orogen) as existing to the southeast of the foreland basin (Dunkard basin), and the view of the profile being from the northeast to the southwest.

In the QmFLt diagram (fig. 27C), monocrystalline quartz (Qm) is equated to feldspar and total lithic (Lt) fragments. This diagram displays a compositional range which is greater than that of the QFL diagram and provides quartzose, transitional, and lithic recycled subdivisions of the recycled orogen category. Northern-source samples tend to cluster toward the monocrystalline quartz pole, whereas samples from other parts of the basin tend toward the total lithics pole. Rendina (1985) believed that the monocrystalline-quartz-rich northern-source samples indicate additional quartz contributions from a cratonic source of pre-existing sedimentary strata, rather than attrition of chemically and mechanically less stable grains from a southeastern source transported over a relatively short distance.

Figure 27D is a plot of the samples studied by Rendina (1985) as a QmQpL diagram. Here the total lithics pole of the QmFLt diagram (fig. 27C) is separated into two component modes: polycrystalline quartz (Qp) and lithic grains (L); the apex is monocrystalline quartz. A clear separation of most plots of northern-source and southeastern-source sandstone samples is indicated in figure 27D because of the higher content of monocrystalline quartz in northern-source samples and a shift toward the Qp pole evidenced by some plots of southeastern-source samples. Most of the plots on this diagram show essentially equivalent Qp/L ratios. The closely spaced plots of northern-source sandstone samples support the concept of an additional source of detritus that is not the result of attrition through transportation of grains derived from the southeastern source terrane.

The LmLvLs diagram (fig. 27E) divides the unstable lithic fraction, L, into three component modes of metamorphic (Lm), volcanic (Lv), and sedimentary (Ls) rock fragments. The plots are separated into two gradational but compositionally distinct suites on the basis of metamorphic and sedimentary rock fragments and reflecting the absence of volcanic lithics. The southeastern-source samples are rich in foliated quartz-mica and mica-phyllite and slate metamorphic fragments and plot closer to the Lm pole. The northern-source samples are enriched in sedimentary rock fragments, principally pelitic grains, and plot closer to the Ls pole. In addition to pelitic grains, the northern-source samples contain abundant monocrystalline quartz and have a low ratio (0.47) of metamorphic rock fragments to total rock fragments, indicating that the source area was dominated by sedimentary source rocks. A higher ratio (0.72) of metamorphic rock fragments to total rock fragments in the southeastern-source samples indicates a predominance of low-grade metamorphic source rocks over sedimentary source rocks (Rendina, 1985, p. 58).

Rendina (1985) used the four-variable quartz provenance diagram (fig. 29) of Basu and others (1975), on which medium-sand-size detrital quartz is discriminated as either

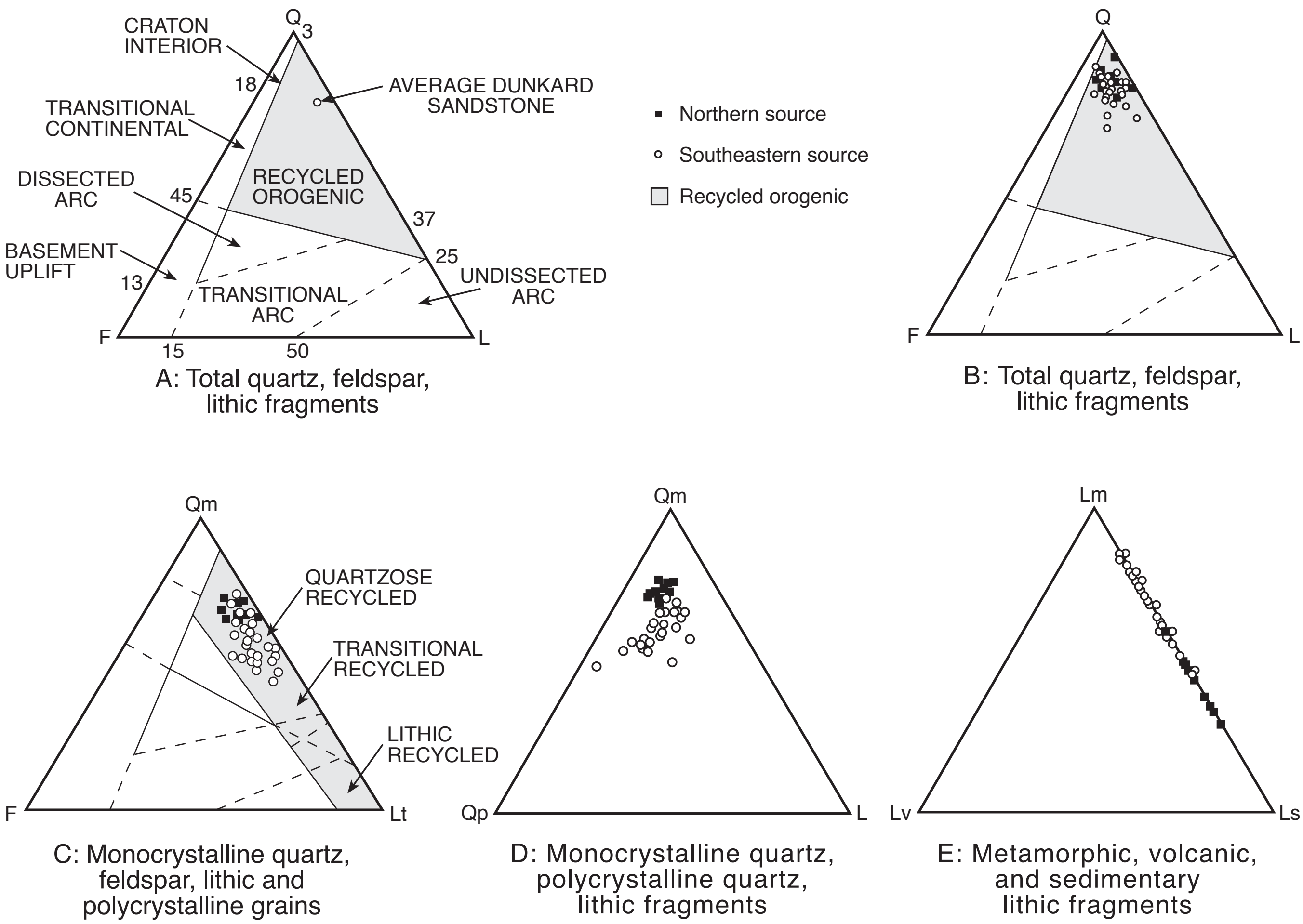


FIGURE 27.—Ternary plots of the composition of Dunkard Group sandstones on triangular provenance diagrams of Dickinson and others (1983) (**A**, **B**, and **C**); Graham and others (1976) (**D**); and Ingersoll and Suczek (1979) (**E**). **A**, average Dunkard sandstone (Martin and Lorenz, 1972) in recycled orogenic source-rock field. **B**-**E**, plots of northern-source and southeastern-source sandstones defined by Rendina (1985).

monocrystalline or polycrystalline. Monocrystalline grains are further subdivided into two populations, undulatory and nonundulatory quartz, and polycrystalline quartz is subdivided according to the amount and number of crystal units per grain. All of the Dunkard sandstone samples plot in the lower triangle, where more than three crystal units per grain form more than 25 percent of total polycrystalline quartz. The southeastern-source samples are characterized by an abundance of undulatory monocrystalline quartz grains and plot as low-rank metamorphic rock fragments. The plots of these samples grade to the left into those of samples collected in the northern part of the region. The northern-source samples have greater amounts of nonundulatory monocrystalline quartz and plot within both the low-rank metamorphic and middle- and upper-rank metamorphic fields.

Rendina (1985) suggested that it is essentially the ratio of undulatory to nonundulatory monocrystalline quartz that causes the separation of the plots of the northern-source and southeastern-source samples rather than source terranes of lower to higher metamorphic grade. He pointed out that there is no other evidence indicating a northern-source terrane of increased metamorphic grade and, therefore, suggested that the increased concentration of nonundulatory monocrystalline quartz is the result of derivation of the grains from pre-existing sedimentary strata. Because undulatory quartz should be less stable than nonundulatory quartz (Blatt and Christie, 1963), and polycrystalline quartz breaks down to form monocrystalline quartz (Harrell and Blatt, 1978; Suttner and others, 1981), the tendency of the northern-source samples to plot toward the nonundulatory corner suggests greater recycling of a quartz population that was originally derived from crystalline cratonic rocks.

Also shown in figure 29 is a plot of the composition of the Lower Pennsylvanian Sharon sandstone of northeastern Ohio, which plots in the plutonic field in the upper triangle. This supermature unit is typical of the Carboniferous stable-craton orthoquartzites in which recycling of sediments has removed unstable grains, including polycrystalline and undulatory quartz (Meckel, 1967). Rendina (1985) suggested that it is likely that some supermature quartz grains from the Sharon sandstone were incorporated in the sand forming the northern-source-area Dunkard deposits.

The typical heavy minerals and rock fragments, including detrital chert grains, of the average Dunkard sandstone occur mostly in the reworked sediments and low-rank metamorphic suites of Pettijohn (1975). The presence of chert grains in a sedimentary deposit is one of the best indicators that the containing rock has been derived at least in part

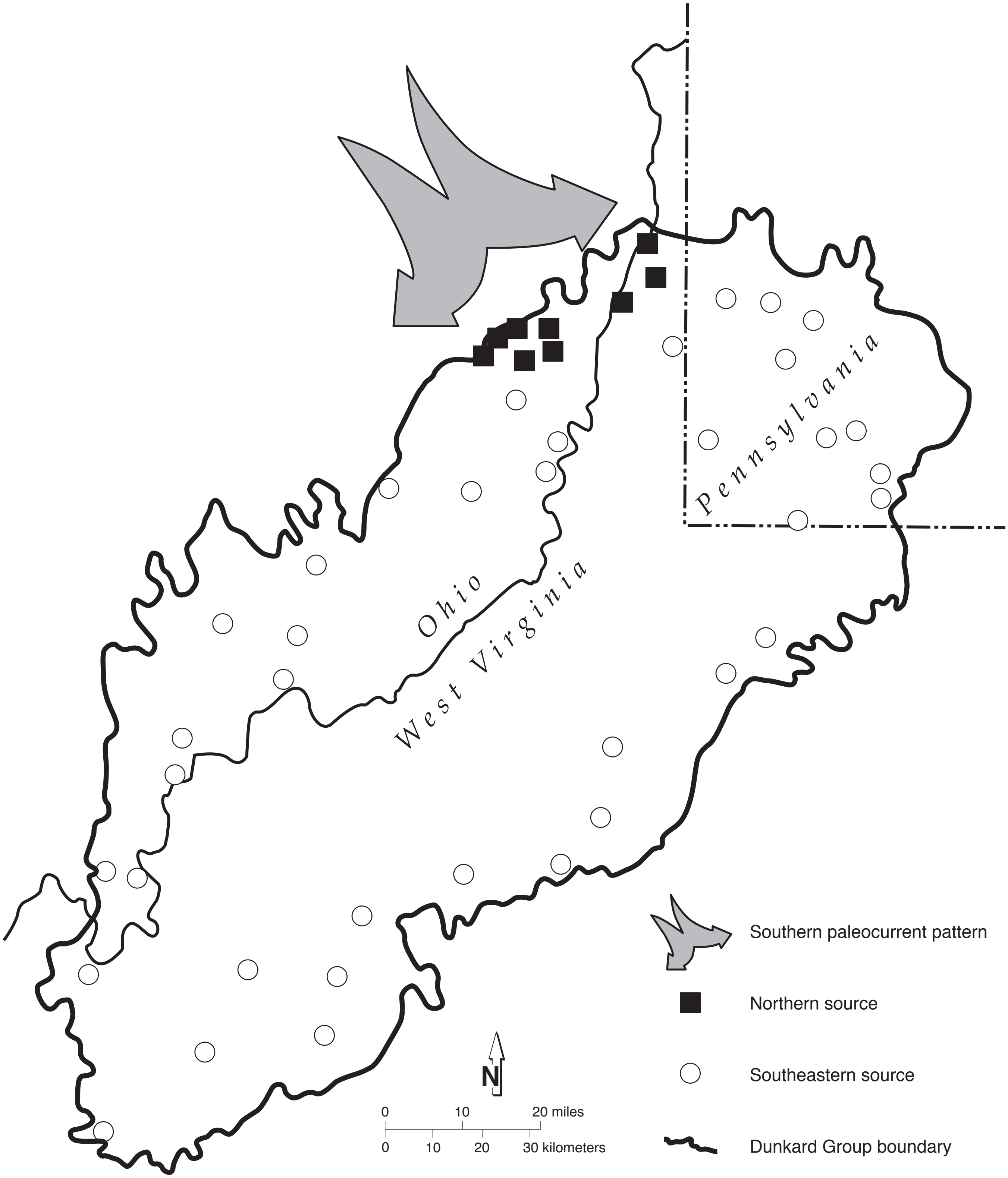


FIGURE 28.—Map showing Dunkard sandstone sampling localities of Rendina (1985). Sandstones that reflect northern sediment-source terrane differ in composition compared to sandstones that reflect a southeastern sediment-source terrane.

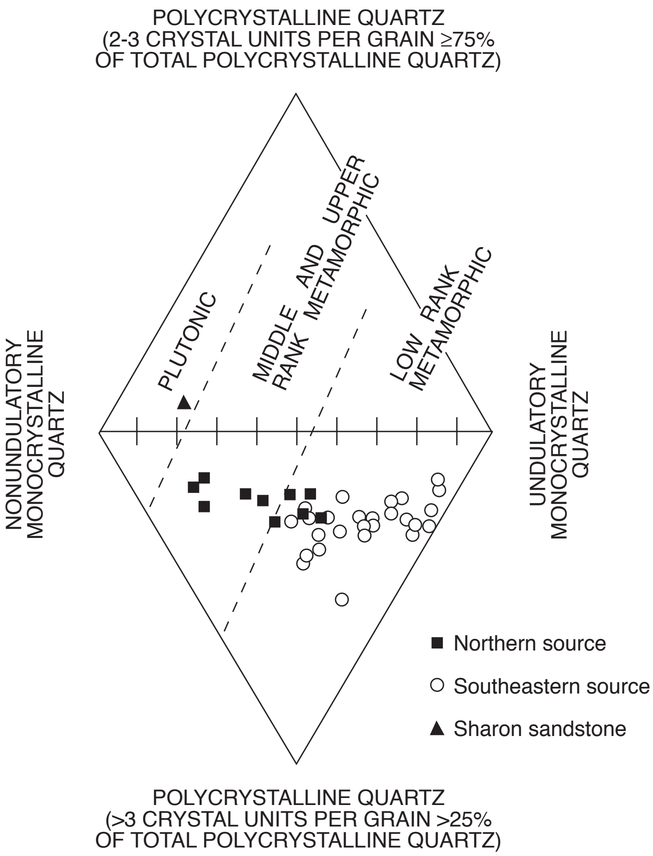


FIGURE 29.—Four-variable quartz-grain provenance diagram showing plots of southeastern-source sandstones and northern-source sandstones (modified from Rendina, 1985). A plot of the Lower Pennsylvanian Sharon sandstone is included for comparison.

from pre-existing sedimentary rocks. Dickinson and others (1983, p. 224) noted that chert grains may be derived from nodules in carbonate rocks, from phosphatic shelf deposits, and from "uplifted oceanic terranes of eugeosynclinal belts where radiolarian cherts occur." Garnet is the only nonopaque heavy mineral commonly present in Dunkard heavy mineral assemblages that is listed in the high-rank metamorphic suite. Tourmaline grains and especially zircon grains are rounded, indicating recycling. The low content of detrital chert and feldspar and the presence of detrital mica, metaquartzite, and slate and phyllite fragments indicate a low-rank metamorphic source. Leucoxene, which is expected to be present in both reworked sediments and low-rank metamorphic suites, constitutes nearly 70 percent of the heavy mineral fractions of Dunkard sandstones.

Rendina (1985) noted that, although it is apparent that the percentage of each heavy mineral species differs between the northern-source and southeastern-source samples, these differences are not pronounced enough to have statistical significance. He did find, however, that differences do exist in euhedralism and color of zircon grains, as well as in varietal characteristics and rounding of tourmaline grains in the northern-source samples compared to southeastern-source samples, indicating derivation from different source rocks. Rendina (1985) interpreted these differences to mean that multicycle sedimentary rocks and crystalline rocks were comparatively more important in the northern-source area.

To summarize, Dunkard Group sandstones are rich in quartz, pelitic sedimentary (including detrital chert) and micaceous metamorphic rock fragments, and detrital mica and are poor in feldspar and igneous lithic fragments. Matrix components in the sandstones are mainly micaceous minerals, illite and chlorite, detrital quartz, and pore-filling kaolinite. The principal nonclay minerals of the mudstones are quartz and feldspar, and the main clay minerals are kaolinite, illite, and mixed-layer material. The composition of the average Dunkard sandstone indicates derivation of detritus recycled from an orogenic source, including a collision orogen and fold-thrust-belt rocks. "Northern" sandstones are characterized by nonundulatory monocrystalline quartz and pelitic sedimentary rock fragments, indicating multicycle sedimentary rocks as the immediate source and crystalline rocks as the original source. "Southern" sandstones are characterized by undulatory, monocrystalline quartz and mica-rich, low-rank metamorphic rock fragments. Most of the detritus that forms the rocks of the Dunkard Group was derived from an orogenic highland composed of recycled rock materials located southeast of the foreland basin. A low-relief, stable craton containing sedimentary strata composed mainly of recycled detritus was present to the north and contributed sediments to the basin during the early part of Dunkard time (fig. 30).

Chert pebbles collected by John Ferm and Glen Merrill from the Hockingport Sandstone Lentil at the type locality northeast of Hockingport, Ohio, in the early 1960's contain ghosts of triaxion sponge spicules as well as other fossils. An invertebrate fossil taxa, excluding the spicules, was identified by Thomas Dutro, Jr., and assigned an Early Devonian age (Merrill and Dutro, in prep.). Subsequently, Merrill found chert clasts containing fossils in channel sandstones of older Pennsylvanian age (late Virgilian and early Missourian) at localities near Huntington, West Virginia. These taxa also were assigned an Early Devonian age by Dutro. Merrill and Dutro (in prep.) tentatively suggest that these pebbles indicate a correlation with and derivation from the Huntersville Chert, a Lower Devonian rock unit present near Huntersville, in southeastern Pocahontas County, West Virginia, and in southwestern Virginia. They believed that the clasts were derived from rock outcrops at least 175 km (110 miles) to the southeast in the Valley and Ridge Province, where the closest modern exposures of Devonian strata exist.

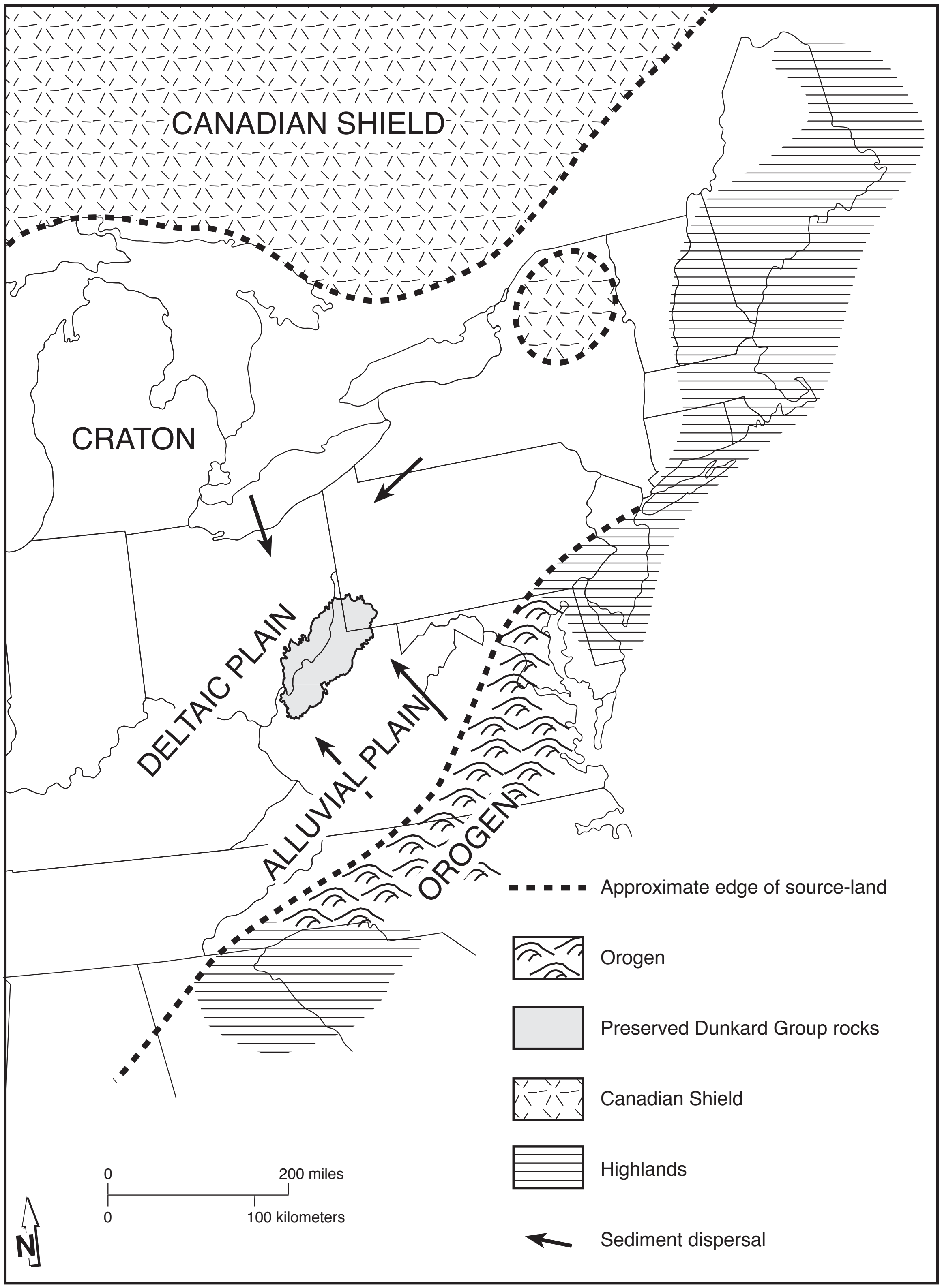


FIGURE 30.—Paleogeographic map for the Late Pennsylvanian-Early Permian. Modified from Rendina (1985). A collision orogen and adjacent highlands (fold-thrust belt) were developed during the Alleghany orogeny. The rocks of the fold-thrust belt were composed of recycled sediments and served as the principal source terrane for the late Paleozoic sediments. The preserved Dunkard Group strata are the youngest rocks of the former foreland basin that existed in the region (see fig. 26).

Chapter 6

FOSSILS AND THE AGE OF THE DUNKARD GROUP

Fossils in the Dunkard Group include plants, invertebrates, and vertebrates. The fossil flora and fauna of the Upper Pennsylvanian and Permian strata have been described in several abstracts and reference papers developed for the 1972 I. C. White Memorial Symposium on the age of the Dunkard (Barlow, 1972) and in the proceedings volume from the symposium (Barlow, 1975). Several of the plants and invertebrates are potentially age-diagnostic index fossils. Other Dunkard fossils may be good environmental indicators. Nevertheless, the age of the rocks in the Dunkard Group is still controversial.

In many parts of the world, there seems to be no significant sedimentologic break between the Pennsylvanian and Permian Systems, and the boundary between these systems has been a subject of much controversy. Most disputes involve a placement of the boundary based on index fossil plants (ferns, conifers and other plants), invertebrates (principally the fusulinids), and on aquatic and land vertebrates. There is no regional disconformity within the upper Paleozoic strata of the Appalachian Plateaus, and there have been numerous attempts to define the Pennsylvanian-Permian boundary using fossil evidence.

Cross (1979, p. 325) pointed out that the plants in the transitional Pennsylvanian-Permian strata of the Appalachian Plateaus are best represented by leaves, stems, pollen, and spores. He wrote that they are "generally dominated by a number of Late Pennsylvanian [plants] which lived on well past their time in this relatively unchallenging environment, such as *Pecopteris*, *Neuropteris*, *Odontopteris*, *Danaeites*, *Callipteridium*, *Sphenophyllum*, *Annularia*, [and] a few lycopods, mostly *Sigillaria*." The leaf and spore/pollen floras, according to Cross (1979), contain very low percentages of early Permian species. He wrote that "some species are typically Permian, but may also be found in late Pennsylvanian strata (*Callipteris*, *Taeniopteris*). Others of very rare occurrence (*Walchia*, *Plagiozamites*) first appear in the Permian."

Cross (1954) provided an extensive documentation of the genera and species of fossil plants from the Dunkard strata. Cross, Gillespie, and Taggart (1996) and Cross, Taggart, and Gillespie (1996) described Pennsylvanian and Permian plant fossils from Ohio. Other authors have provided historical accounts of the significance of fossil flora in the assignment of the Dunkard Group to the Permian System (Barlow, 1975; Darrah, 1975; Clendening, 1970, 1974, 1975; Gillespie and others, 1975). Clendening (1975) developed a generalized geologic section of the Conemaugh, Monongahela, and Dunkard Groups showing age designations of the strata by various authors from 1902 to 1975. The works that Clendening summarized were based mainly on studies of fossil flora, but also on invertebrate fossils, including conchostracan branchiopods (Tasch, 1975) and insects (Durden, 1969, 1975), and on vertebrate fossils (Lund, 1975).

PLANT FOSSILS

Fontaine and White (1880) published a monograph titled "The Permian or Upper Carboniferous flora of West Virginia and southwest Pennsylvania." However, as Clendening (1970, p. 3) pointed out, there is doubt as to the correct age of the fossil flora and the rock sequence in the title of their publication. Fontaine and White concluded that, in general, the new species from the strata, later named the Cassville shale, above the Waynesburg coal indicated proof of a Permian age. They regarded the seed fern *Callipteris conferta* as an infallible indicator of the Permian, although it had not been found in the Cassville shale. In 1891, I. C. White (p. 20), on the basis of plant fossils, considered the Dunkard rock sequence to be Carboniferous-Permian and to extend from the roof shales of the Waynesburg coal (Cassville shale) to the highest beds in the region (see fig. 2).

David White (1904, 1906) believed that the fossil plants of the Dunkard rock sequence represented a transitional flora and that the systemic boundary should be determined by plant species that also occur in the Rothliegendes, the continental Permian rock sequence of central Germany.

Darrah (1975, p. 92) pointed out that the International Congresses for Carboniferous Stratigraphy (Heerlen, 1927, 1935) arbitrarily accepted the genus *Callipteris* as an index of the Permian. Darrah (1975) further reported that at least three species of *Callipteris* had been collected from the Washington Formation. The diagnostic Permian species, *Callipteris conferta*, however, had not been discovered below the Washington coal according to Berryhill and Swanson (1962, p. C46).

Havlena (1975, p. 7) considered that *Callipteris conferta* is a typical index plant species in Europe inasmuch as it exists over a large area "in different paleo-biocoenological relations, in various lithofacies and structurally different types of basins." The plant marks the beginning of the Permian in European strata according to Havlena (1975). If the same approach is used to establish the Carboniferous-Permian boundary in the Dunkard Group, the boundary would be at the base of the Washington coal, because of the first existence of *Callipteris conferta* in this coal. Cross, Gillespie, and Taggart (1996, p. 413) reported that specimens of Autunia (Callipteris) conferta were found in Monongalia County, West Virginia, in a freshwater, or slightly brackish, limestone just above the top of the Washington coal. They stated that "this unit is a close stratigraphic equivalent of the horizon in which the only verifiable *Autunia* has been found in Ohio. Fragmentary specimens tentatively identified as *Autunia* (*Callipteris*) have been found in Ohio in a brackish-water zone in and above the Washington coal and at the top of the Lower Washington limestone at several localities in Belmont County and northeastern Monroe County."

Wilde (1975, p. 133) noted that *Callipteris conferta* was at one time considered an index for the Permian, but he considered it "a rather unsatisfactory and not reliable indicator." Kremp (1964) reported that a connection between *Calipteris conferta* and marine fossils had not been established in western Europe.

Cross (1975, p. 299) pointed out that several fossil plants, including *Callipteris conferta*, the conifer *Walchia*, and the cycad *Taeniopteris*, are present at several levels in the Dunkard Group, most importantly above the Washington coal, and indicate an Early Permian age for these strata. He considered the strata below the coal to be much more Pennsylvanian in nature.

Gillespie and Pfefferkorn (1979, p. 94) considered the fossil flora of the lower part of the Dunkard sequence to be a carryover of several species present in underlying units and are "virtually indistinguishable" from the older floras. The break in the nature of the flora, according to Darrah (1969), developed in mid-Conemaugh time as a result of the last extensive marine incursion, the Ames sea. Darrah (1975, p. 92) stated that "there is no significant stratigraphic or flora discontinuity from the upper Conemaugh Group through the highest Greene strata."

Gillespie and others (1975, p. 224) stated that the results of sporological studies (Gillespie and Clendening, 1969; Clendening, 1960, 1962, 1970, 1972) suggested that a break could not be demonstrated in the upper Paleozoic rock sequence later than mid-Conemaugh time.

Cross (1954) reported that the Dunkard flora were reduced remnants of late Pennsylvanian-age floras with a few Permian precursors. Cross (1975, p. 298-299) also believed that from mid-Conemaugh time on through the deposition of the sediments of the youngest rocks preserved in the region, there was a gradual change, a waning of the Pennsylvanian flora characteristic of the swamps. This change was cited by Cross as the most important aspect of the flora and as being apparent from leaves, as well as from spores and pollen independently.

Studies of fossil plants by Clendening (1960, 1962, 1967, 1969), Gillespie (1961), Gillespie and Latimer (1961), and Gillespie and Clendening (1969) indicated that all, or part, of the Dunkard Group should be considered Pennsylvanian in age. Later palynological studies by Clendening (1970, 1974, 1975) convinced him that all of the Dunkard Group is Pennsylvanian. According to Clendening (1974, p. 1), evidence in fossil plants for the age of the rock sequence was not fully utilized until that of palynological studies was included. In addition, palynological data do not support *Callipteris conferta* as a certain indicator of the Permian.

Berryhill and Swanson (1962, p. C46) wrote that, although plant fossils with Permian affinities exist above the Waynesburg coal, the overlying fossil flora contains all Pennsylvanian species that exist in the rocks below the Waynesburg coal. The transitional nature of the flora from Pennsylvanian to Permian, the existence of *Callipteris conferta* in the Washington coal, and the lack of an important lithologic change above the Washington coal led Berryhill and Swanson (1962) to designate the Waynesburg coal and the strata between the Waynesburg and Washington coals as Pennsylvanian and Permian, and the Washington coal and the strata above it as Early Permian (see fig. 2).

Remy (1975) compared the characteristics of the fossil flora and the sedimentary environments in which the plants lived in the late Paleozoic in Europe and North America. He believed that the Dunkard Group and the Lower Permian strata of Kansas were contemporaneous facies on the basis of palynological investigations and that some spores and pollen grains (as well as megafossils) indicate a Permian age for the Dunkard Group.

Gillespie and Pfefferkorn (1980, p. 232) reported that the existence of *Callipteris conferta* and the sphenopsid *Sphenophyllum thoni* in the lower and middle parts of the Dunkard Group in the Pennsylvanian System stratotype study area of central West Virginia allowed correlation of these strata within the Autunian Stage (Lower Permian) of western Europe and supported earlier observations that the rock sequence is, in part, Permian in age.

INVERTEBRATE FOSSILS

Fusulinids are a very important group of guide fossils in marine deposits because there are many distinctive short-range types that may be very widely distributed geographically (Moore, 1958, p. 258). *Pseudoschwagerina* is among several genera of fusulinids which presumably did not exist earlier than Permian time (Wilde, 1975). The Lower Permian (Wolfcampian Stage) rocks along the front of the Glass Mountains in Texas are noted for a prolific fauna of fusulinids, including *Pseudoschwagerina*, that, according to Dunbar and Waage (1969, p. 292), permit correlation with strata in other regions, not only North America but South America, Japan, and the type region of the Permian, in the Russian Platform and the Ural Mountains.

Pseudoschwagerina-bearing zones also are present in Kansas in the Council Grove Group, which is considered Lower Permian. However, Clendening (1975, p. 195) believed that *Pseudoschwagerina* is not an index to Permian time because the Council Grove Group also contains typical Pennsylvanian spore assemblages. Fusulinids are not present in the nonmarine rocks of the Dunkard Group, but fusulinid evidence for the age of the rock sequence is applied indirectly by the association of other fossils that exist in both the Dunkard and rock sequences elsewhere.

Tasch (1975) concluded that conchostracan branchiopod fossils (estheriids) collected from the Washington coal indicate an Early Permian age for that unit and the overlying strata. Egar (1975) investigated nonmarine bivalve fossil faunas from the middle of the Conemaugh Group up to the lower limestone member of the Washington Formation and concluded that the Dunkard Group is more likely to be Permian in age than late Pennsylvanian.

Durden (1975) studied fossil insects from the roof shales of the Waynesburg coal (Cassville shale) and compared the collections with an assemblage from a rock unit in the vicinity of Henrietta, Clay County, Texas, that also contains *Callipteris* and *Danaeites*. He concluded that the Cassville insect fauna is Lower Permian, late Wolfcampian Stage, and the youngest Dunkard strata belong in the Lower Permian, early Leonardian Stage.

Yochelson (1975) described the gastropods of the Monongahela and Dunkard Groups. Most of the gastropods collected from rocks of the Dunkard Group were from the Lower Washington limestone and the Nineveh limestone. Yochelson (1975, p. 249) considered all of the gastropods to be nonmarine and likely terrestrial in habitat. His conclusion was that the gastropods do not provide evidence that would allow the placement of the Pennsylvanian-Permian boundary in the Dunkard basin.

VERTEBRATE FOSSILS

The most common vertebrate fossils in late Paleozoic rocks are remains of sharks, reptiles, and amphibians. Hansen (1996) described in detail the vertebrate fossils of Ohio. Shark remains are found primarily in marine deposits, the limestones of the Conemaugh Group. However, Hansen (1996, p. 291) noted that "most xenacanth sharks lived in slow-moving nonmarine waters such as ponds and lakes associated with deltaic environments." According to Hansen (1996, p. 292), shark remains are generally uncommon in the Lower Permian rocks in Ohio but may be abundant locally, mostly as teeth and other elements.

Reptile fossils are rare in rocks of Permian age in Ohio, but the remains of pelycosaurs (*Edaphosaurus*, *Dimetrodon*, and *Ophiacodon*) have been collected from stream-channel exposures of Dunkard Group rocks near Belpre, Washington County, Ohio (Hansen, 1996). Reptile remains, including *Edaphosaurus*, have been discovered in nonmarine limestones and shales presumed to have formed from lake deposits of the Washington Formation in Monroe County, Ohio (Hansen, 1996, p. 296).

Amphibian fossils are diverse and abundant at a few localities in Ohio in rocks of Pennsylvanian age; only isolated bones have been found at widely scattered sites in Permian rocks (Hansen, 1996, p. 294). *Eryops* remains are the most common and were collected from Dunkard Group strata in Washington and Monroe Counties, Ohio (Hansen, 1996, p. 294).

Olson (1975, p. 157) wrote that "throughout North America and Europe, and even in South America, wherever Late Pennsylvanian and Early Permian vertebrates occur, very similar faunas are found." Olson (1975, table 2) provided a faunal list of vertebrates represented by fossils from the Dunkard Group according to stratigraphic interval, number of localities, and abundance of fossils. Freshwater sharks, various reptiles, fish, and amphibians were represented. Some forms are unique to the Dunkard rock sequence. Olson (1975, table 3) shows the ranges of fossil vertebrate taxa from the Dunkard and from Upper Pennsylvanian and Lower Permian rocks elsewhere.

Olson (1975) divided the vertebrates of the Dunkard Group into two distinct chronofaunal systems, a lake chronofauna and a stream chronofauna. The lake chronofauna evolved with little interaction with semi-aquatic or terrestrial plants or animals; this fauna developed more or less from Pennsylvanian-age predecessors. Fossils of the stream chronofauna in the Dunkard rock sequence are typically Carboniferous-Permian in nature. *Eryops* and *Edaphosaurus* were tetrapods that merged with the lake chronofauna. According to Olson (1975), the Dunkard vertebrate fossils of the lake chronofauna, other than *Edaphosaurus*, could not provide an age assignment more specific than Late Pennsylvanian or Early Permian. *Edaphosaurus* fossils are present in the Wichita Group of central Texas, which is considered Lower Permian (Wolfcampian Stage). The vertebrates from the Carboniferous-Permian stream chronofauna indicate the age to be equivalent to that of the Admiral Formation in the upper part of the Wichita Group.

AGE OF THE DUNKARD GROUP

Age assignments made by various workers studying Dunkard Group rocks, as summarized by Henry and others (1979), run the gamut and include assertions that: the entire Dunkard Group is Permian; the oldest Dunkard strata are Carboniferous or pre-Permian; the rock sequence is transitional between the Carboniferous and the Permian; and strata in older rock sequences, including part of the Conemaugh Group, are Permian correlatives.

Secor, Snoke, and Dallmeyer (1986, p. 1345) report age estimates of the Dunkard Group ranging from Late Pennsylvanian (286 ± 12 million years; Bode, 1975; Clendening, 1975) to Early Permian (266 ± 17 million years; Berman and Berman, 1975; Durden, 1975; Havlena, 1975; Lund, 1975; Remy, 1975; Tasch, 1975).

Henry and others (1979, p. 85) pointed out that the upper boundary of the Pennsylvanian System is yet to be selected but suggested that in the southern part of the Dunkard outcrop area it will most likely be near the position of the "Waynesburg Sandstone." This large, conglomeratic, dendroid or belt-type sandstone body is exposed in Jackson County, West Virginia, in the I-77 corridor region, where it is considered the basal unit of the Dunkard Group. Krebs (1911) correlated this unit with the Waynesburg Sandstone Member (Mather Sandstone Lentil of Martin and Henniger, 1969) of the Washington Formation of northwestern West Virginia and southwestern Pennsylvania. The Mather and Hockingport Sandstone Lentils (Martin and Henniger, 1969) and the "Waynesburg Sandstone" in Jackson County, West Virginia, are probably homotaxial units, that is, they have a similar order of arrangement in different localities but are not necessarily contemporaneous. All three of these lenticular sandstone units have been considered to be at the base of the Dunkard Group.

The Correlation of Stratigraphic Units of North America (COSUNA) chart for the northern Appalachians (Patchen and others, 1985), including southeastern Ohio, the Dunkard outcrop area in West Virginia, and southwestern Pennsylvania, shows the lower part of the Dunkard Group as Upper Carboniferous (Virgilian) and the remaining part as Lower Permian (Wolfcampian and Leonardian).

Darrah (1975, p. 92-93) remarked that "the age of the Dunkard, after nearly a century of research and controversy, stands just as Fontaine and I. C. White proposed it in 1880. Our problem is essentially the same as that which plagues every boundary question where no marked stratigraphic break is recognized . . . ." Thus, on the basis of the lithologic and paleontologic information presented here, the age of the Dunkard is still indeterminant.

Chapter 7

SUMMARY AND FINAL OBSERVATIONS

SUMMARY

Paleogeographic reconstruction of the sedimentary framework during the late Paleozoic Alleghany orogeny indicates that clastic sediments were transported by streams north and northwestward across the central Appalachians. The sediments were derived for the most part from collision orogen and fold-thrust terranes to the southeast and deposited in the Dunkard subbasin, the final remnant of the Appalachian foreland basin. Streams also flowed southward from the stable Canadian craton, but these contributed relatively small volumes of sediment to the basin.

A western outlet was most likely the only outlet of the shrinking epeiric sea, which ceased to exist after early Late Pennsylvanian time. By Dunkard time, a bay-lake remnant of the sea had become a fluvial-lacustrine-deltaic plain in the north. To the south were lower and upper fluvial plains. Through time, the fluvial plains shifted northward over the swamp and lacustrine environments. Freshwater limestones, coals, carbonaceous shales, and sheet sandstones of the northern part of the basin were replaced upward by the thicker, elongate sandstone bodies and the buff to red mudstones characteristic of the southern fluvial plains. Most of the nonlaminated red mudstones in the Dunkard Group represent paleosols.

That a major north-to-northwest paleoslope prevailed during Dunkard time is deduced primarily from orientation of cross-beds in large sandstone bodies. Other important lines of evidence supporting this paleoslope direction are the trend of elongate sandstone bodies, the decrease in grain size and a mineralogical difference in clastic sediments in a downslope direction, the composition of environmental facies and their relationships to each other, and the existence of fossils of the brackish-water brachiopod *Lingula*, suggesting proximity to a marine environment to the "west."

Mudstones and lesser thicknesses of shales constitute nearly two-thirds of the measured stratigraphic sections in the Dunkard Group, and sandstones nearly one-third. Coals and limestones average approximately 5 percent of the sections; they constitute less than 10 percent of the rock sequence in the north and are virtually absent in the southern part of the basin.

The most abundant nonclay component of the mudstones and shales is silt-size quartz. The principal clay minerals are kaolinite, illite, and mixed-layer clays. The sandstones are lithic arenites; the average composition is approximately 64 percent quartz and 15 percent nondiagenetic matrix. Pelitic sedimentary and micaceous, low-rank-metamorphic rock fragments are more abundant than feldspar, and detrital mica forms over 5 percent of the average sandstone. Sandstone samples from the northern part of the outcrop area are characterized by nonundulatory monocrystalline quartz grains and pelitic sedimentary rock fragments, indicating multicycle sedimentary rocks as the immediate source and crystalline rocks as the original source. Southern sandstones contain undulatory monocrystalline quartz grains, metaquartzite rock fragments, and mica-rich low-rank-metamorphic rock fragments. Chert pebbles derived from Devonian strata are present in some conglomeratic sandstone bodies. The main components of these sandstones were originally derived from an orogenic highland composed of recycled rock materials located to the southeast of a foreland basin.

The Dunkard rock sequence is transitional in nature owing to a lack of short-term tectonism and of important marine incursions and represents a gradual change from a seasonally dry, tropical climate to dryer climatic conditions. Regional disconformities that would help define the rock sequence are not present. The transition from marine to bay-lake to fluvial plain in the late Paleozoic Era is indicated in the rock facies developed and in the fossil fauna and flora. The presence of *Lingula* in Washington coal partings suggests that marine conditions existed nearby and probably indicates the final marine incursion into the region. Most other invertebrate faunal elements indicate nonmarine environmental conditions, and some (the gastropods) indicate a terrestrial habitat. Vertebrate fossils of the Dunkard suggest a wide range of environments, from lakes to terrestrial conditions.

Several kinds of invertebrate fossils—insects, bivalves, and conchostracans—indicate an Early Permian age for the Dunkard rock sequence. Gastropod fossils are inconclusive with respect to the placement of the systemic boundary. The vertebrate fossils also are inconclusive in a precise determination of the age of the Dunkard, having developed more or less from Pennsylvanian-age predecessors. Vertebrate faunas are typically Carboniferous-Permian in nature and are present in rocks formed from fluvial sediments.

Several investigators (David White, 1904, 1906; Cross, 1975; Gillespie and Pfefferkorn, 1979) believed that the fossil flora of the Dunkard is transitional, indicative of a gradual change and waning of the Pennsylvanian flora characteristic of the swamps. A number of authors consider all or part of the Dunkard Group to be Pennsylvanian in age (Clendening, 1960, 1962, 1967, 1969; Gillespie and Latimer, 1961; Gillespie and Clendening, 1969). Palynological studies conducted by Clendening (1970, 1974, and 1975) convinced him that all of the Dunkard is Pennsylvanian in age. However, Remy (1975), on the basis of his palynological investigations, considered the Dunkard Group to be Lower Permian and reported that some spores and pollen grains as well as the megafossils indicate a Permian age for the Dunkard.

Callipteris conferta, which is indicative of the Permian in Europe, is present in the Dunkard Group, more commonly in the Washington coal and overlying strata. However, the value of *Callipteris conferta* as an index plant to the Permian has been questioned (Clendening, 1974, 1975; Wilde, 1975). Nevertheless, Gillespie and Pfefferkorn (1980, p. 232) believed that the existence of *Callipteris conferta*, *Walchia*, and *Sphenophyllum thoni* in the lower and middle parts of the Dunkard Group in central West Virginia allowed correlation of the group within the Autunian Stage (Lower Permian) of western Europe and supported earlier observations that the sequence is, in part, Permian in age.

Berryhill and Swanson (1962) designated the Waynesburg coal (base of the Dunkard) and the strata between the Waynesburg and Washington coals as Pennsylvanian and Permian, and the Washington coal and the strata above it as Lower Permian. The Correlation of Stratigraphic Units of North America (COSUNA) chart for the northern Appalachians (Patchen and others, 1985), which includes the Dunkard outcrop area, shows the lower part of the Dunkard Group as Upper Carboniferous (Virgilian) and the remaining part as Lower Permian (Wolfcampian and Leonardian). Age estimates of the Dunkard Group have ranged from Late Pennsylvanian (286 ± 12 million years) to Early Permian (266 ± 17 million years) (Secor, Snoke, and Dallmeyer, 1986, p. 1345).

FINAL OBSERVATIONS

Viktoras Skema (Pennsylvania Geological Survey, personal commun., 1997) pointed out that very little is known about the upper part of the Dunkard Group. In Pennsylvania, there is as much as 240 meters of the Greene Formation above the Washington limestone (upper limestone member) of the Washington Formation (see fig. 2). He wrote that "the descriptions of the stratigraphy of these Permian rocks is sketchy and contradictory. The paleontology is probably equally poorly understood." This situation is not surprising, as the lower third of the Dunkard (Waynesburg and Washington Formations) in Pennsylvania contains the more economically important coal and limestone deposits and has been the focus of nearly all past research (Skema, personal commun., 1997).

Most studies of the rock sequence in Ohio and West Virginia also have been conducted in the northern part of the Dunkard outcrop area where the coal and limestone beds are. The results of some studies in other parts of the region have appeared in publications of state geological surveys, in theses resulting from graduate-student studies, and a few papers in scientific journals. The basal contact of the Dunkard Group is poorly defined in the field as well as in the literature outside of a portion of the northern third of the outcrop area where the more extensive marker beds are at or near the surface.

Either the top or the bottom of the Waynesburg (No. 11) coal has been considered the lower boundary of the Dunkard Group. However, Berryhill (1967, p. 2) pointed out that "little stratigraphic significance can be attributed to this boundary . . . because rock sequences both above and below contain similar cyclic beds." Furthermore, "field recognition of the boundary is not difficult over most of the northern part of the Dunkard basin, where the Waynesburg coal is prominent, but in other parts, where the coal is either thin or absent, the boundary is not readily apparent."

Collins and Smith (1977, note on geologic map) stated that because of the absence of mappable Waynesburg coal, a clear-cut boundary for the base of the Dunkard Group could not be drawn in Washington County, Ohio. Two coal beds are present in the upper part of the Monongahela Group in the southwestern part of the Dunkard basin, the Meigs Creek (No. 9) and the Uniontown (No. 10). If the rock sequence above either of these units were included in the Dunkard Group, the coal could be considered as the basal unit in that region.

In eastern Athens County, Ohio, the Meigs Creek coal lies approximately 45 meters below the uneven lower surface of the Hockingport Sandstone Lentil (see fig. 2). The coal was named for exposures along Meigs Creek, a tributary of the Muskingum River, in southeastern Morgan County, Ohio. The coal is present in two benches across part of Washington County, Ohio, and was considered the most important coal in that county (Collins and Smith, 1977, p. 18). Sturgeon and associates (1958, p. 225) reported the existence of the coal in two benches in Athens County, Ohio. Smith and others (1952) described the geology and reserves of the Meigs Creek coal in Ohio.

The type locality of the Uniontown coal is in Uniontown, Pennsylvania. This coal occurs in some sections just below the Hockingport Sandstone Lentil and ranges from a carbonaceous zone to blocky coal a meter or so in thickness in Washington County, Ohio (Collins and Smith, 1977, pl. 5 and p. 22). Sturgeon and associates (1958, p. 184) described the coal in Athens County, Ohio, as ranging in thickness from a paper-thin streak to approximately 33 cm.

A better understanding of the nature of the Dunkard Group has been hampered by the continued application by some workers of the layer-cake concept, that of extending rock-unit names regardless of the continuity of the units, and of the concern of time equivalence of lithostratigraphic units. This practice has been carried on since the beginning of studies of the upper Paleozoic rocks in the region, has led to a poor understanding of the real nature of the rock sequence, and added to the frustration of workers trying to solve problems in nomenclature and correlation. In describing stratigraphic sections, some workers have strived to place a name on practically every rock unit of significant thickness and areal extent, and on coal blossoms in attempts to identify coal horizons.

The extension of names of sandstone bodies from the type localities to other sandstone bodies in a similar stratigraphic position in other areas has not been a good practice. The sandstones in all but some areas of the northern portion of the region of outcrop are elongate, lenticular bodies. The use of the name Waynesburg sandstone (I. C. White, 1891, 1903) for units in different parts of the region implies blanket geometry of the sandstone. Stauffer and Schroyer (1920) reported the existence of the Waynesburg sandstone in 10 widely separated sections in Jefferson, Belmont, Monroe, Noble, and eastern Washington Counties, Ohio. The thicknesses of a few meters and other characteristics of these described units indicate that they are for the most part ribbons or pods of limited areal extent.

The Jollytown and Hundred sandstones were named for villages in southwestern Pennsylvania and northern West Virginia, respectively. These two names were applied to sandstone bodies in the hills at Marietta, Washington County, Ohio (Stauffer and Schroyer, 1920). The name "Upper Marietta sandstone" was applied to another dendroid sandstone body near New Martinsville, West Virginia, several tens of kilometers to the north of the type locality (Thoms, 1956). The name "Lower Marietta sandstone" was associated with a dendroid body in Meigs County, Ohio, and adjacent Jackson County, West Virginia, a few tens of kilometers to the south of Marietta. Healy (1959) suggested the informal name "Sherman sandstone" from the village of that name in Jackson County for this latter sandstone body.

The naming of rock units of limited areal extent for geographic localities, for example, the Sherman sandstone, adds additional names within rock sequences; however, such names are more meaningful than the extension of a name from the type locality of the unit to other localities. Nearly all of the names that have been applied to lithologic units of the upper Paleozoic rock sequence in the Dunkard basin were in place prior to 1961, when the first stratigraphic code was published by the American Commission on Stratigraphic Nomenclature (1961). This code and its successor published by the North American Commission on Stratigraphic Nomenclature (1983) established common procedures for the definition, classification, and naming of rock-stratigraphic units and their fossils and the time spans represented by them. According to the stratigraphic codes, boundaries of rock-stratigraphic units are placed at positions of lithologic change, at sharp contacts, or within a zone of gradation. Time spans, however measured, have no part in differentiating or determining the boundaries of the units.

Homotaxial rock units are defined in the 1961 Code of Stratigraphic Nomenclature (p. 648) as rock-stratigraphic or biostratigraphic units having a similar order of arrangement in different localities, and they do not have to be contemporaneous. Accordingly, several of the sandstone bodies and other lithologic units of the Dunkard Group are considered as homotaxial units.

Dunbar and Rogers (1957, p. 288) noted that "the importance of facies is now universally acknowledged, though still perhaps not universally put into practice in stratigraphic interpretations." Arkle (1959) defined Dunkard Group facies from north to south in the outcrop area as gray, transitional, and red. The environments of sedimentation and characteristics of the rock sequences within Arkle's broad classification of Dunkard facies have been described in this bulletin.

The recommendation is made that persons engaged in studies of the upper Paleozoic rock sequence of the Dunkard basin follow the procedures established by the North American Commission on Stratigraphic Nomenclature.

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