COAL-BEARING UPPER PENNSYLVANIAN AND LOWER PERMIAN ROCKS

WASHINGTON AREA, PENNSYLVANIA

U. S. DEPARTMENT OF THE INTERIOR
March 3, 1849

Work done in cooperation with
the Pennsylvania Bureau of
Topographic and Geologic Survey

GEOLOGICAL SURVEY PROFESSIONAL PAPER 621

Coal-Bearing Upper Pennsylvanian and Lower Permian Rocks, Washington Area, Pennsylvania

Part 1. Lithofacies
Part 2. Economic and Engineering Geology

By HENRY L. BERRYHILL, JR., STANLEY P. SCHWEINFURTH,
and BION H. KENT

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COAL-BEARING UPPER PENNSYLVANIAN AND LOWER PERMIAN ROCKS, WASHINGTON AREA, PENNSYLVANIA

By HENRY L. BERRYHILL, JR., STANLEY P. SCHWEINFURTH, and BION H. KENT

ABSTRACT

The Washington area is near the southwest corner of Pennsylvania and covers an area of 229 square miles. It comprises the Washington West, Washington East, Amity, and Prosperity 7½-minute quadrangles. In terms of human resources and population density, the Washington area can be considered a part of the greater Pittsburgh residential-industrial complex.

The report includes descriptions of the types of rock; lithologic maps for the Washington West, Washington East, and Amity quadrangles; maps showing lithofacies relations in each member of the Pittsburgh, Uniontown, Waynesburg, and Washington Formations; a summary of sedimentation and paleogeography; a discussion of the economic aspects of the rocks, including properties that are pertinent to preliminary engineering planning; and estimates of coal resources of the Pittsburgh and Waynesburg coal beds.

Rocks at the surface consist of alternating sandstone, siltstone, mudstone, claystone, limestone, and coal. Average aggregate thickness of the exposed sequence is about 1,070 feet; thickness increases in general from north to south. Sequences of beds of the same rock type range in thickness from a few feet to 90 feet. Vertical repetition of the several types of rock in a somewhat cyclic pattern is characteristic of the overall sequence, but the general cyclic aspect is modified by a general upward increase in the amount of sandstone, siltstone, and mudstone and by lateral differences due to variations in thickness and intertonguing.

Three predominant shapes of sandstone bodies are recognized: sheetlike, elongate, and lobate. Sheetlike bodies are generally 4.5–8.5 miles wide; elongate bodies are generally 0.2–4 miles wide and more than 6 miles long; and lobate accumulations are typically less than 1 mile wide and less than 3 miles long. The larger elongate bodies are segments of extensive bodies that traverse the Washington area. The sandstone bodies trend in one of two general directions: west-northwest or north-northeast. Two types of crossbedding are recognized—festoon, or cut and fill, in the elongate bodies, and tabular, or torrential, in the sheetlike bodies. Median diameter of grains in the sandstone ranges from 0.062 mm to 0.25 mm, and grain size decreases upward in the thicker sandstone bodies. The sandstone generally is well sorted; the coefficient of sorting is less than 2.50. Composition of grains, in order of decreasing abundance, is quartz (60–75 percent), feldspar (10–20 percent), clay minerals (1–15 percent), muscovite (3–7 percent), opaque minerals (1–3 percent), and heavy minerals (a trace to 1 percent).

The siltstones generally are sheetlike or lenticular, but many flank the elongate sandstones and, thus, are also somewhat elongate in form. Composition of the siltstone is similar to the sandstone, except that the siltstone contains larger amounts of clay minerals.

The mudstones lie as thin layers above coal beds and between limestone beds, and some are lenses that tongue into both sandstone and siltstone bodies. The claystones generally are lenticular and thin, but some of the underclays beneath coal beds are sheetlike units that cover large areas. The clay minerals in mudstone and claystone, in general order of abundance, are illite, chlorite, kaolinite, mixed-layer illite-chlorite, and two other minerals tentatively identified as vermiculite and montmorillonite.

Most limestone bodies are sheetlike and are made up of beds that are a few inches to 3 feet thick. The fabric of most combines a microcrystalline calcite matrix with various amounts of detrital particles that range from clay size to several inches in diameter. Distinctive features are the fine laminations in many beds believed to be of algal origin and the breccia-conglomeratic nature of others. Calcite content varies from 57 to about 95 percent; dolomite, from a trace to 8.1 percent; and insoluble minerals, from 10 to 20 percent.

Fossil remains of both animal and plant types are present in some of the mudstones and limestones and in a few sandstones. The animal remains are ostracodes, fish scales and bone fragments, small gastropods, small pelecypods, and *Spirorbis*, a partly coiled worm tube; plant remains are leaves, stems, and logs. The fossils are a nondiversified fresh-water suite of late Paleozoic age. Identifiable plant remains are relatively scarce; two assemblages—one from above the Waynesburg coal bed and the other from above the Washington coal bed—contained forms of Late Pennsylvanian age.

Within the interval from one coal bed to another, the sandstones, siltstones, mudstones, claystones, and limestones intergrade and intertongue. Four principal lithofacies are present. They are sandstone, interbedded sandstone and fine-grained clastic rocks, fine-grained clastic rocks, and limestone.

The stratigraphic classification of exposed rocks is as follows: Conemaugh, Pittsburgh, and Uniontown Formations of Pennsylvanian age; Waynesburg Formation of Pennsylvanian and Permian age; and Washington and Greene Formations of Permian age. The Pittsburgh and Uniontown Formations compose the Monongahela Group; the Waynesburg, Washington, and Greene Formations make up the Dunkard Group. Only the upper 60 feet of the Conemaugh is exposed. The formations other than the Conemaugh and Greene are named for the coal bed at their base and have been subdivided into various members.

Tectonically, the Washington area was part of a subsiding basin that covered large adjacent parts of Ohio and West Virginia during Late Pennsylvanian and Early Permian time. The environment was an extensive but shallow fresh-water lake that at times became a vast swamp. Depth of water was

probably never more than a few feet. The shoreline shifted frequently. During deposition of large quantities of detritus, the shoreline prograded as the sediment built outward to form a fluvial-delta complex.

The rocks have been folded into a series of gentle northeast-trending flexures with dips of 1° or less. The folding of the rocks was not contemporaneous with deposition; it took place after late Early Permian time.

Of the 17 coal beds that crop out, only the Pittsburgh, which contains by far the largest quantity of resources, is now mined commercially. The Waynesburg also contains sizable resources but is not mined. Original resources of coal in these two beds in the Washington area total 1,959.5 million tons, of which 1,688.6 million tons is classified as "measured," 166.2 million tons as "indicated," and 104.7 million tons as "inferred." Included in the 1,688.6 million tons of measured coal is 197.5 million tons of coal in the Pittsburgh bed that has been mined and lost in mining; thus, the remaining measured resources as of January 1, 1966, total 1,491.1 million tons.

Sandstone and limestone have been quarried in recent years for base course material in highway construction. Mudstone is quarried at two localities for making brick. Tests indicate that several mudstone units are potential sources of lightweight aggregate. Limestone, particularly that of the upper member of the Washington Formation, may some day prove to be a valuable resource.

Physical characteristics of the rock sequence of most concern in engineering planning are the wide range in porosity and permeability. The juxtaposition of permeable and impermeable units markedly affects movement of percolating subsurface water. The limestone, claystone, and mudstone units are relatively impervious; consequently the thicker limestone units, and the underclays in particular, are sites of seepage and slumping.

INTRODUCTION

Washington, Pa., bears the marks of both the advance of modern civilization and a past that is deeply rooted in American history. Pioneers moving westward across the Allegheny Mountains to seek new fortune and to fight the Indians and the French followed a natural route that led into southwestern Pennsylvania. Washington, for a time the northwest terminus of what later became the first National road, was a thriving frontier town in the late 18th century. The earliest settlers used the readily available rock materials for construction and fuel. The still-standing Bradford House, home of one of the leaders of the Whiskey Rebellion in 1794, is built of limestone from the upper member of the Washington Formation. Distinguished visitors, such as General Lafayette and Gen. Andrew Jackson, probably warmed themselves by fires fed by local coal. A century after earliest settlement, both gas and oil were found in the Washington area, and in the 1890's the Washington field was one of the country's principal producers. Gas was first produced from a well on the Hess farm, 1 mile west of Washington, on April 30, 1884; initial oil production was from the Gantz well opposite the Chestnut Street Station of the Pennsylvania Railroad in Washington on December 31, 1884.

Abundant resources in the local rocks still contribute to the economy of Washington. Underlying the area is the great Pittsburgh coal bed, not only the world's most valuable coal bed but also one of the world's most valuable mineral deposits. Oil and gas are still taken from some of the earliest wells drilled in the Washington field. Modern traffic through Washington on Interstate Highway 70, built in 1960–63, moves over material supplied in part from local quarries.

PURPOSE AND SCOPE OF REPORT

The investigations here reported are a restudy of the stratigraphy and economic geology of a part of the bituminous coal field of western Pennsylvania, a district that has undergone intensive industrial development during the past 100 years and one that received extensive geologic study in the period from the latter part of the last century through the first decade of this century. Geologically, the Washington area, which includes the town and environs covering about 229 square miles, is in the type area of the Pennsylvanian System and of the Washington Formation of Permian age. Geographically, the area is near the residential-industrial complex of metropolitan Pittsburgh, and, in terms of human resources and population density, it can be included as a part of the greater Pittsburgh area.

Proximity of the Washington area to metropolitan Pittsburgh, plus strategic location at a major junction of north-south and east-west highway traffic, will influence future growth. Indeed, outward-reaching suburban development of Pittsburgh, typical of all major population centers in the United States, is even now almost within sight of Washington. A thorough understanding of the area's geology is essential to the efficient development of both mineral resources and land use. Planning for land use, whether for industrial, residential, or recreational development, should be based equally on several factors: physical properties of, and differences between, rock formations; landform; and drainage. Since publication of geologic maps and reports on the Washington area more than 50 years ago, accumulated drill data and new topographic base maps at a larger scale (1 in. equals 0.38 mile) make possible both an updating of information on the stratigraphy of the Pennsylvanian and Permian rocks and the preparation of more detailed maps of the geologic formations and coal beds.

The investigations for the present report were made (1) to obtain additional data on the stratigraphy and sedimentation of the Upper Pennsylvanian and Lower Permian sequence that might be applied to development of the economy of the Washington area; (2) to prepare geologic and lithofacies maps showing the different rock types in sufficient detail to be used in preliminary engineering planning and as a basis for studying mine subsidence and stream pollution from drainage of acid mine waters; and (3) to appraise the coal resources of both the Pittsburgh and lesser known coal beds and to relate the coal quality and thickness to the lithofacies patterns of the associated rocks.

PREVIOUS WORK

Abundant resources of coal, oil, and gas have attracted geologists to southwestern Pennsylvania for many years, and these commodities have provided the impetus for most of the geologic literature on the region. During most of the 19th century, evaluation of coal beds and classification of coal-bearing strata were the bases for investigations. From about 1880 to 1920, the increasing demand for oil and gas was a primary stimulus for exploration. In the early part of the 20th century, a series of reports and maps summarized the geology of coal-, oil-, and gas-bearing rocks.

Geologic publications of regional scope that include the Washington area are numerous; therefore, reference is limited in this publication to selected accounts that apply specifically to the geology of Washington and vicinity or that have influenced geologic interpretation of the area.

The earliest published geologic reference to the Washington area was made by Pomeroy (1832), who noted the many outcrops of coal along Chartiers Creek north of Washington. To Pomeroy belongs credit for the first published appraisal of the coal resources of western Pennsylvania; his statement (p. 347) was, "the sun and the bituminous coal of Western Pennsylvania will burn out together."

Stevenson (1876) made the first systematic classification and description of rocks in the Washington area. His stratigraphic classification included names for all principal coal beds and was a refinement of earlier classifications by Rogers (1839, 1840, 1858).

Fontaine and White (1880) divided the coal-bearing strata on the basis of geologic age. Reporting on a study of fossil plants, they assigned a Permian age to strata above the Waynesburg coal bed. Though their work was based largely on fossil plants from West Virginia, the age designation which they assigned was intended for the entire bituminous coal field of West Virginia, Pennsylvania, and Ohio.

White (1891) included the Washington area in a summary study of the stratigraphy of the central part of the Appalachian basin and presented names for many strata left unnamed by Stevenson. White's report and that by Stevenson (1907) established the stratigraphic nomenclature that was to continue in use for more than 50 years.

Clapp (1907a, b) and Munn (1912) produced the first areal geologic maps for the Washington area in the days when Washington was "a great camp of oil prospectors." These maps, at a scale of 1 inch to 1 mile, were accompanied by texts describing the types of rock, the stratigraphic relations, and the coal, oil, and gas resources.

Berryhill and Swanson (1962) revised the stratigraphic nomenclature for Upper Pennsylvanian and Lower Permian rocks of Washington County, Pa. Individual geologic quadrangle maps for the Washington area, at a scale of 1 inch equals 0.38 mile, have been prepared by Berryhill and Swanson (1964), Berryhill (1964), and Swanson and Berryhill (1964).

ACKNOWLEDGMENTS

The geology of the Washington area was studied by the U.S. Geological Survey in cooperation with the Pennsylvania Topographic and Geologic Survey. Many individuals contributed to the report, and several colleagues gave substantial technical assistance by providing analytical data.

Diamond-drill core logs and mine data were generously contributed by several companies: Berkshire Land Co.; Bethlehem Mines Corp.; Consolidation Coal Co.; Hillman Coal & Coke Co.; and the Jones & Laughlin Steel Corp. The availability of these data greatly facilitated the preparation of the report. A large measure of appreciation is extended to company officials who granted permission to use the data, and to company employees who prepared and made the data available. Special thanks are expressed to J. M. Vonfeld, not only for his very generous cooperation in providing data, but also for his personal interest and suggestions.

Some of the field investigations were made by V. E. Swanson, and the results of his efforts are incorporated in the lithologic maps. Technical assistance in the preparation of data for use in the report was rendered by L. G. Schultz, who helped with the preparation of material for X-ray diffraction studies

and with interpretation of the results; by R. F. Gantnier and J. A. Thomas, who made the mechanical separations for grain-size studies and who ran analyses and computed calcium-magnesium ratios for limestone; by T. C. Nichols, who made physical-properties tests of various types of rock; and by Douglas Müller, who helped with statistical computations. Fossils were studied by E. L. Yochelson, I. G. Sohn, and S. H. Mamay. We acknowledge with much gratitude the significant contributions made by these individuals. However, we assume full responsibility for statements of fact and opinion that are not specifically credited to others.

A statement of acknowledgment would be incomplete without mention of the impact of the early work of J. J. Stevenson and I. C. White on the geology of southwestern Pennsylvania. Theirs were classic studies of coal-bearing rocks, assiduous in effort and sound in concept. The present report can be considered a refinement of, and an addition to, their work.

GEOGRAPHY

LOCATION

The Washington area comprises the Washington West, Washington East, Amity, and Prosperity 7½-minute quadrangles. It is near the southwest corner of Pennsylvania and includes the central and south-central parts of Washington County and the extreme north-central part of Greene County. The city of Washington, at the junction of Interstate Highways 70 and 79, U.S. Highways 40 and 19, and State Highways 31 and 18, is 27 miles southwest of Pittsburgh. Figure 1 shows the location of the Washington area relative to the greater Pittsburgh area and to the counties and principal towns of southwestern Pennsylvania.

PHYSIOGRAPHIC SETTING, TOPOGRAPHY, AND DRAINAGE

In a regional sense, the Washington area is in the Appalachian Plateaus physiographic province (Fenneman, 1938), a province having a plateau surface that is everywhere dissected by rivers and streams. Because the degree of dissection varies from place to place, the province has been subdivided into several sections. The Washington area is in the Unglaciated Allegheny Plateau section (fig. 2), a maturely dissected plateau, extending from northeastern Kentucky to southern New York State, in which valleys have been carved in a nearly flat lying rock sequence that contains more mudstone and fine-grained rocks than sandstone. The drainage pattern is dendritic and generally is more intricate than in neighboring sections, where both the more massive rocks and the geologic structure influence the drainage patterns.

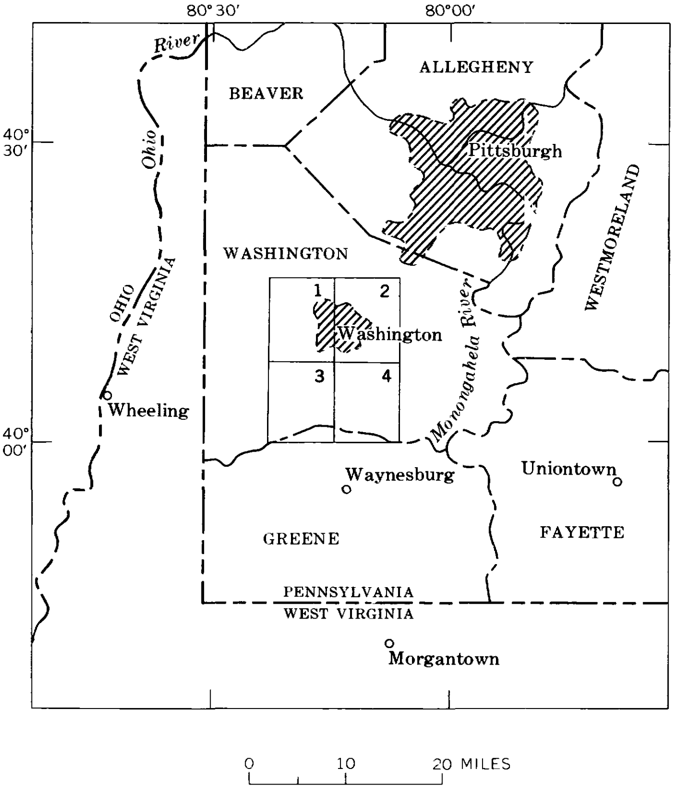


FIGURE 1.—Location of the Washington area, Washington and Greene Counties, Pa. Quadrangles included in report: 1, Washington West; 2, Washington East; 3, Prosperity; 4, Amity.

The surface of the Washington area is hilly with broad rounded ridges and intervening, generally V-shaped valleys. Stream dissection has largely destroyed the original plateau surface, and only in panoramic view from ridgetops are the concordant summits and plateau character evident. Maximum relief is about 620 feet; altitudes range from about 900 to 1,520 feet. Summits of most main ridges have a rather uniform altitude of slightly less than 1,300 feet.

Geologic structure has had little influence in the drainage pattern. Variations in resistance of rock types to weathering has determined the profile of ridges. Sandstones and some limestones form the knobs or small hills on ridgetops and the benches along the ridge slopes; more easily weathered rocks form saddles.

The Washington area is on the drainage divide between the Ohio River, which lies to the west and north, and the Monongahela River, one of the principal tributaries to the Ohio, which lies to the east (fig. 1). Drainage from the area is by three main streams: north-northeastward via Chartiers Creek; northwestward via Buffalo Creek; and east-southeastward via Tenmile Creek. Tributary streams are in narrow V-shaped valleys; main streams are in broader U-shaped valleys that have narrow flood plains. The incised meander pattern of the principal streams indicates recent stream rejuvenation.

Part 1. Lithofacies

DESCRIPTION OF SEDIMENTARY ROCKS

GENERAL FEATURES

The Unglaciated Allegheny Plateau (Fenneman, 1938) is formed of stratified rocks that are generally flat lying, in contrast to the folded rocks of the Allegheny Mountains and the Valley and Ridge province which lie to the east. Rocks of the Allegheny Plateau have been subjected to gentle bending and form a broad and gentle syncline, or depression, known as the Appalachian basin. The general outline of the northern part of the Appalachian basin and the position of Washington, Pa., within it are shown in figure 2. Within this structural basin are a number of subsidiary flexures of low amplitude.

Strata at the surface everywhere in the Appalachian basin are of sedimentary origin and were deposited during the Paleozoic Era. The uppermost, or youngest, strata in the basin are of late Paleozoic age and range from Early Pennsylvanian to Early Permian. Those in the Washington area, near the northeast-trending axis, or trough line, of the Appalachian basin, are of Late Pennsylvanian and Early Permian age (fig. 2, stippled areas).

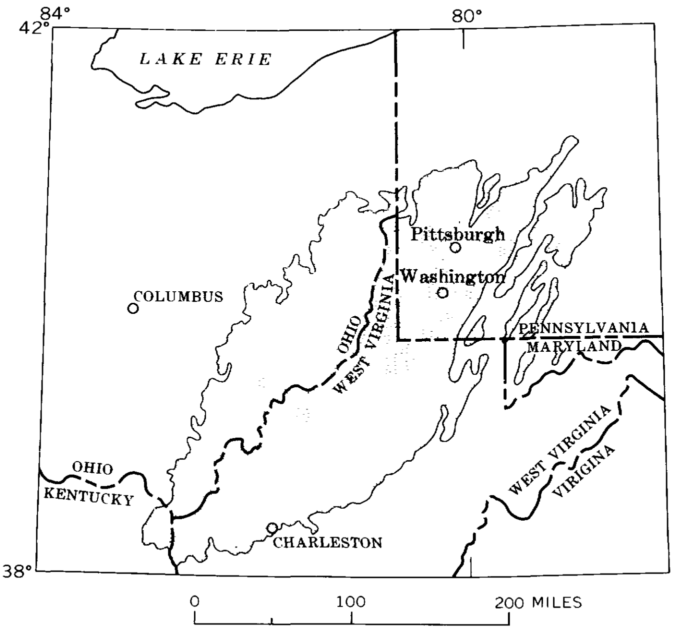


FIGURE 2.—Area underlain by Upper Pennsylvanian and Lower Permian rocks, northern part of Appalachian basin (stippled pattern). Stippled area also coincides with the northern part of the Unglaciated Allegheny Plateau section (Fenneman, 1938).

ROCKS EXPOSED

Rocks at the surface in the Washington area consist of alternating layers of sandstone, siltstone, mudstone, claystone, limestone, and coal. Average aggregate thickness of the exposed sequence is about 1,070 feet; in general, thickness increases from north to south. Sequences of beds of the same rock type range in thickness from a few feet to 90 feet.

Vertical repetition of the types of rock in a somewhat cyclic pattern is characteristic of the overall sequence. However, the general cyclic pattern is modified by two factors: an upward increase in the amount of sandstone, siltstone, and mudstone relative to the amount of limestone; and lateral differences in the sequential arrangement of the several types of rock because of intertonguing. The present report deals primarily with the rocks above the base of the Pittsburgh coal bed.

ROCKS NOT EXPOSED

Rocks in the subsurface below the Pittsburgh coal bed are coal-bearing sandstone, mudstone, and limestone of Early and Middle Pennsylvanian age and somewhat thicker sandstone, mudstone, and limestone of Mississippian, Devonian, and Late Silurian age that have an aggregate thickness of about 7,700 feet. The deepest drilling in the Washington area penetrated to the Salina Formation of Late Silurian age in a well in the Amity quadrangle (Lytle, 1962). Crystalline rocks of presumed Precambrian age were reached at 12,565 feet beneath the Pittsburgh coal bed in the Sand Hill well of the Hope Natural Gas Co. in Wood County, W. Va., about 70 miles southwest of the Washington area (West Virginia Geol. Survey, 1959). The depth, contact, and stratigraphic relations of Paleozoic and Precambrian rocks in the Washington area are not known, but the depth to the Precambrian rocks is estimated to be about 14,000 feet on the basis of an interpretation of the results of an aeromagnetic survey made by the U.S. Geological Survey in 1960 (Popenoe and others, 1964; Beck and Mattick, 1964).

METHOD OF PRESENTATION

In the following sections of the text, the sandstone, siltstone, mudstone, claystone, and limestone are described in detail before the discussion of the stratigraphic and spatial relations of the named formations and members. Separation of the two kinds of interrelated data avoids much repetition, because individual types of rock in the sequence in the Washington area are marked by similarities in geometry, internal structures, grain size, and composition, regardless of their stratigraphic position. Locations of the more prominent rock exposures are included in the discussion of individual stratigraphic units in the section "Stratigraphy."

Several types of maps accompany the text. These are 1, lithologic maps (pls. 1, 2), which show the distribution at the surface of each type of rock in a member; 2, lithofacies and thickness maps (pls. 3, 4, 5), which show the lateral lithologic and thickness variations in each member over the Washington area; 3, sandstone thickness maps (pls. 6, 7), which show the thickness of discrete sandstone in each member; and 4, coal-bed thickness and lithofacies maps for the six principal beds (pl. 8). The lithologic descriptions of the rocks in specific numbers are in the stratigraphic and lithologic charts (tables 1, 2).

SANDSTONE AND SILTSTONE

GEOMETRY

Shape, size, and orientation of sandstone and siltstone bodies in the Washington area are variable. Three predominant shapes are recognized: sheetlike, elongate, and lobate; a few are pod shaped. These shapes are shown schematically in figure 3. Most elongate sandstones either branch to form distributary patterns or interconnect to form anastomosing, or braided, patterns.

In cross section the sandstone units are lenticular. The bases of most are well defined. Because maximum thickness of any sandstone in the Washington area is about 64 feet, ratio of length or width to thickness in most elongate units and in all sheetlike ones is very large; in pods this ratio is considerably less. All sandstone bodies interfinger along the edges with siltstone and mudstone.

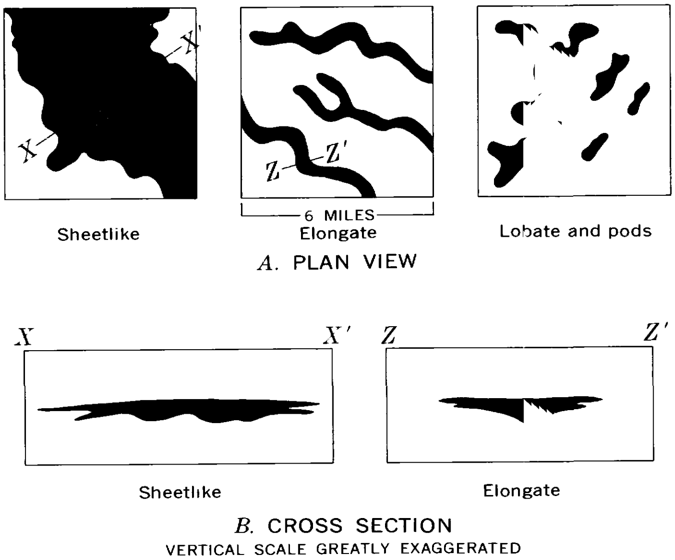


FIGURE 3.—Classification of sandstone bodies by shape.

Approximate dimensions of the sandstone bodies in the Washington area are as follows: sheetlike, length variable, width 4½–8½ miles; elongate, length 3–15 miles, width 0.2–4 miles; pods, length with few exceptions less than 3 miles, width a mile or less. The larger elongate sandstones are but segments of more extensive bodies that traverse the Washington area. Lobate forms include units that are irregularly elongate but terminate in directions of elongation within a few miles, as well as relatively short lateral extentions, or offshoots, from both sheetlike and elongate bodies.

The regional orientation of the elongate sandstone units is somewhat difficult to ascertain because many cross the Washington area in a meandering course. Two general trends can be identified, however, within the Washington area: west-northwest and north-northeast.

The shape, size, and orientation of the discrete sandstone bodies are shown on plates 6 and 7, and the variety of forms is illustrated by individual maps: a sheetlike body that has elongate parts is shown by map *B*, plate 7; elongate bodies by map *E*, plate 6; and elongate-lobate bodies by map *D*, plate 6.

The siltstones are more difficult to define geometrically than sandstones; most are sheetlike or lenticular, but many flank the elongate sandstone bodies and are somewhat elongate. The sandstone intertongues laterally with siltstone and also contains lenses of siltstone. Typically, the upper parts of most sandstones grade into sandy siltstone.

INTERNAL STRUCTURE

The sandstone and siltstone bodies are generally bedded, and only a few are nonbedded. The lateral extent of individual beds is difficult to determine; some can be traced for about a mile, and a few extend more than a mile, perhaps as much as 3 miles.

The thickness of beds is also variable. The classification used in this report to describe thickness of beds is as follows: thin, ½–6 inches; medium, 6–12 inches; and thick, 12–24 inches. Sandstone more than 2 feet thick without visible bedding is referred to as massive. Beds within a sandstone body vary in thickness both laterally and vertically. The thickest parts of some elongate sandstone bodies are massive, but laterally, where the form is more sheetlike, bedding generally is thin to medium. Upper parts of most bodies are thin bedded. Outcrops showing bedding characteristics of parts of sandstone and siltstone bodies are shown in figure 4.

Within many sandstone and siltstone beds are very thin internal substrata or laminae that are less than half an inch thick. Types vary from those parallel to bedding to those that have ripple (undulating) form and cross-laminated or inclined form. Cross laminations of two general types are common in sandstone bodies of the Washington area: those of tabular design in which laminae are inclined at a generally uniform angle to the base and the top of a bed, and those of festoon (trough) pattern in which laminae are arranged in a series of interlaced wedges or small lenses. Rarely is the form a true wedge; more commonly, the festoon pattern is a series of intertongued curved and concave tongues that are called cut-and-fill structure when related to the depositional process. Cross lamination is most common in medium and thick beds; some is of very small scale and can be seen only in thin section. Festooned cross laminations are most common in the thicker parts of elongate sandstones; tabular or inclined cross lamination is typical of the fringe parts of elongate bodies and of parts of the sheetlike bodies. Ripple laminations and rhythmic laminations parallel to bedding are characteristic of the sheetlike sandstones and siltstones. The more common types of crossbedding found in sandstones and siltstones of the Washington area are shown in figure 5.

Distinctiveness of bedding depends in part on the degree of weathering; for example, sandstone may appear massive and to have little internal structure where unweathered, but the same unit may show distinctive bedding where weathered. An example of the effect of weathering upon the appearance of a sandstone is the sheetlike sandstone in the upper part of figure *4D*; this layer, massive when first uncovered, is beginning to reveal both thin and medium beds under the influence of weathering.

Almost all siltstones are thin bedded to laminated and typically weather shaly. Rare beds of unweathered siltstone are massive. Both rhythmic laminations and ripple laminations are common in many siltstones, and the rhythmic ones have a distinctive varved appearance.

GRAIN SIZE

The median diameter of detrital grains in most of the sandstone in the Washington area falls within the range 0.062–0.25 mm, or, in terms of size classification, fine to very fine sand. The range in grain size within a sandstone unit, however, is generally from medium sand to clay-size particles of less than 0.002 mm. Grains of medium size, 0.25–0.5 mm, are generally concentrated near the base of more massive elongate sandstone bodies. A few sandstones have coarse grains, 0.5–1 mm as well as larger angular fragments and pebbles in the basal part, but neither the coarse grains nor the pebbles and fragments are common in any of the sandstones in the Washington area. Samples taken from near the base, middle, and top of the sandstone units indicated that an upward decrease in grain size is common in the thicker units.

The range of grain size in individual samples from a sandstone-siltstone unit and also the upward decrease in grain size are graphically shown by the three histograms in figure 6. The unit sampled is 15 feet thick and has beds mostly of medium thickness. The grain-size frequency in sample *B* probably is near the average for most sandstones in the Washington area. Sample *A* is siltstone and illustrates the typical upward gradation of sandstone to sandy siltstone.

Most sand in the sandstone bodies is moderately sorted to moderately well sorted, regardless of the grain size. The degree of sorting generally decreases upward and the upper parts of many sandstones are poorly sorted. Much of the clay-sized fraction in the sandstones comes from the weathering of feldspar after deposition; consequently, the clay-sized fractions, obtained by mechanical separation and sieving, are larger than the amount of clay actually deposited. Because the amount of feldspar varies from one sandstone unit to another, no attempt was made to compensate for the authigenic clay that is derived from the feldspar.

Most sandstone grains are equidimensional. A few

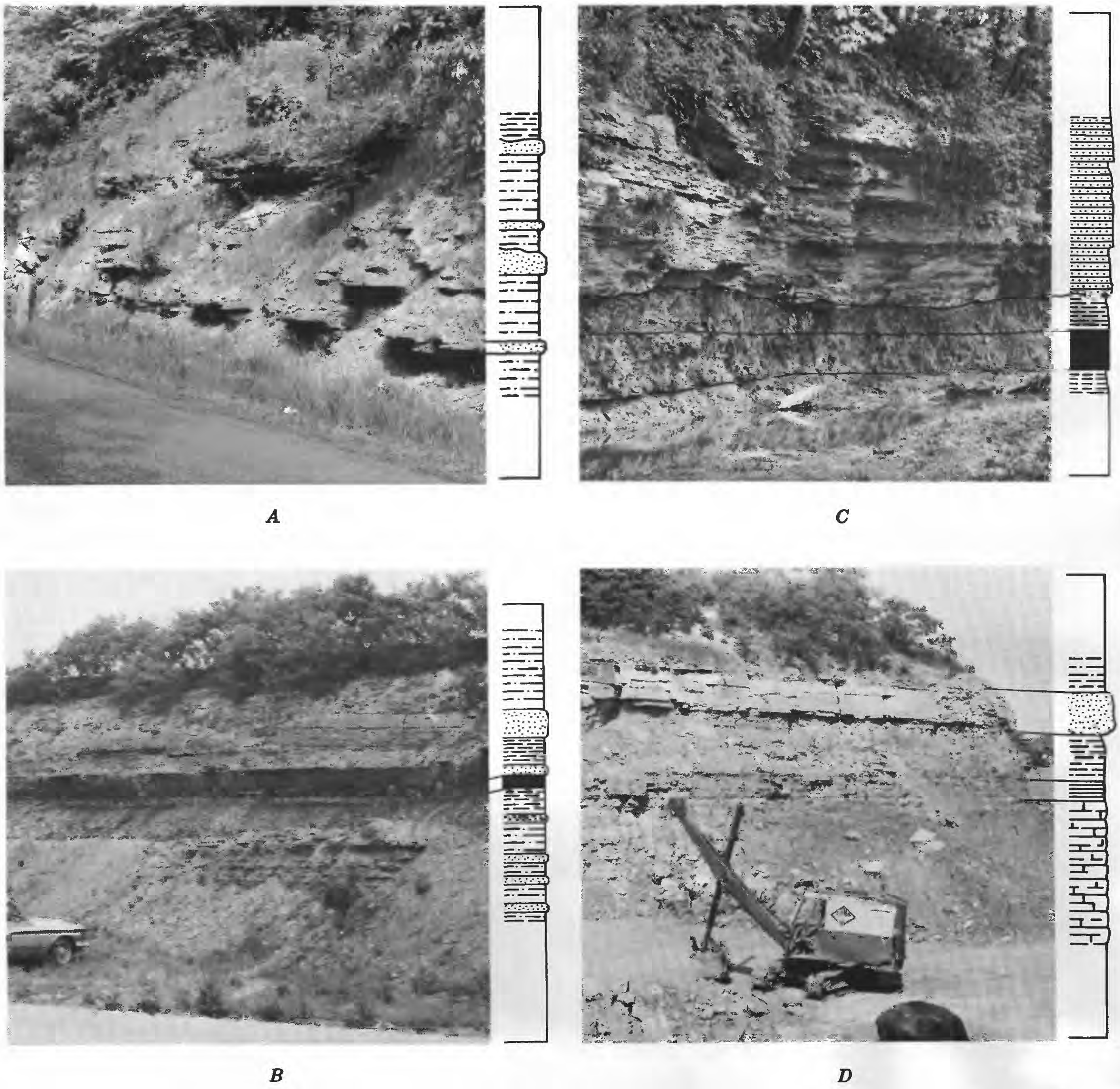


FIGURE 4.—Bedding characteristics of sandstone, siltstone, and limestone. *A*, Thin-bedded siltstone containing thin to thick, somewhat irregular beds of sandstone. Middle member, Washington Formation, north roadbank 0.3 mile east of Conger, Amity quadrangle. *B*, Thin-bedded siltstone containing thin even beds of sandstone; a single thick bed of sandstone pinches out to the left in the upper part of the photograph; a coal bed, a thin sandstone bed, and associated mudstone lie between the two sequences. Lower member, Waynesburg Formation, excavation on north side of State Route 18, 1.4 miles northwest of Wolfdale, Washington West quadrangle. *C*, Thin-bedded laminated sandstone overlying shaly mudstone along an uneven contact; basal sandstone beds are irregular in right half of photograph. Upper member, Waynesburg Formation, 3 miles east of Washington area. *D*, In upper part of photograph, single thick even bed of sandstone that represents the sheet part of a sandstone body; in lower part, even, closely spaced beds of limestone. Lower part of Greene Formation and upper limestone member, Washington Formation, quarry at Vance, Washington East quadrangle.

E

F

FIGURE 4.—Bedding characteristics of sandstone, siltstone, and limestone—Continued. *E*, Massive elongate sandstone body, in cross section, that has little visible bedding. Greene Formation, south bank of Interstate Highway 70, 1.4 miles west of interchange at Vance, Washington East quadrangle.

F, Sandstone characterized by festoon crossbedding. Lower member, Waynesburg Formation, 5 miles east of Washington area.

elongate, bladeshaped grains are in almost all thin sections studied, and many of the elongate grains have general alinement, which suggests preferred orientation parallel to bedding. The degree of roundness varies from angular to well rounded; most grains are either subangular or subround.

MINERALOGY

Composition of grains, in order of decreasing abundance, is quartz, feldspar, clay minerals, mica, opaque minerals, and heavy minerals. The average composition of a sandstone in the Washington area, based on microscopic study of thin sections and of mineral grains in samples from outcrops, is shown in figure 7. The general range in mineral composition of all sandstones examined is quartz, 60–75 percent; feldspar, 10–20 percent; clay minerals, 1–15 percent; muscovite, 3–7 percent; opaque minerals, 1–3 percent; and heavy minerals, from a trace to 1 percent. Generally the clay-mineral content of siltstone is higher than that of sandstone.

The quartz is generally clear, but some grains have inclusions. None of the grains are etched, and uniform extinction in polarized light indicates lack of strained varieties.

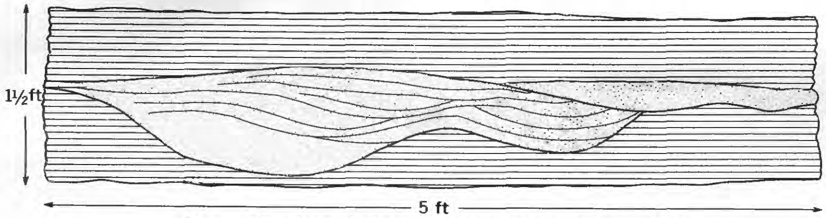
Of the two varieties of feldspar represented, plagioclase is the more abundant and is distributed throughout the sandstones exposed in the Washington area. The plagioclase is primarily the sodic or albitic type, but some calcic plagioclase is present. Potassium feldspar, probably orthoclase, commonly ranges from 3 to 5 percent, but the vertical distribution is uneven. All grains of potassium feldspar are partially altered to kaolinite. Because of the relatively high content of feldspar, the sandstone in the Washington area is classified as feldspathic sandstone.

The mica is largely muscovite in various stages of alteration to clay minerals; chlorite and biotite are also present. Much of the muscovite is concentrated and alined along bedding and lamination planes, but some is distributed through the sandstone as bent flakes. Mica is more abundant in the more even-bedded sheetlike sandstone bodies and is least abundant in the massive sandstone.

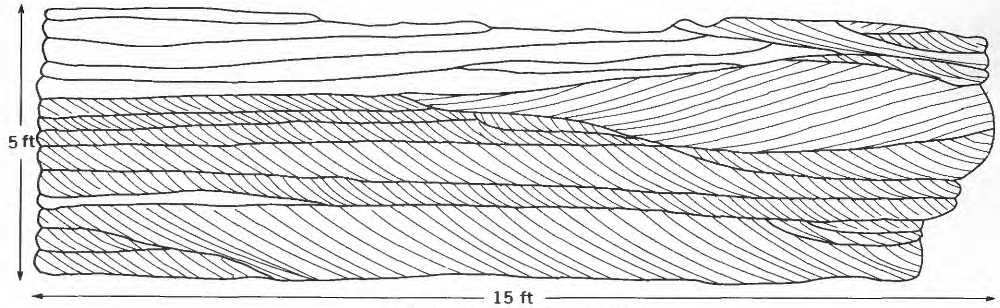
The clay minerals are kaolinite, illite, and chlorite. Kaolinite and illite are most abundant and in some sandstones are the only identifiable clay minerals.

The opaque substances are largely carbonaceous particles, probably coalified plant debris. Many samples contain masses of dark-reddish-brown material that probably is iron oxide. The carbonaceous particles are concentrated mainly near the base of massive sandstones and in laminated fine-grained sandstones.

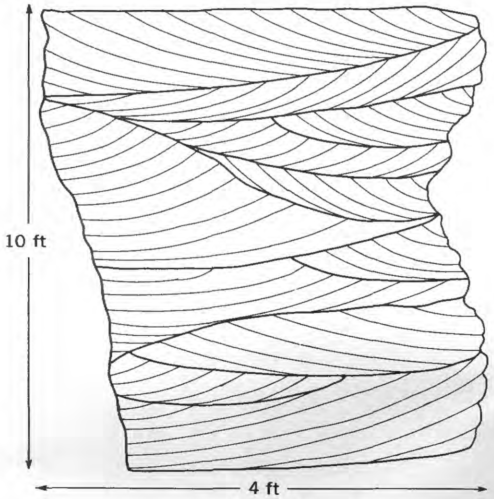
The heavy-mineral suite is a relatively small and



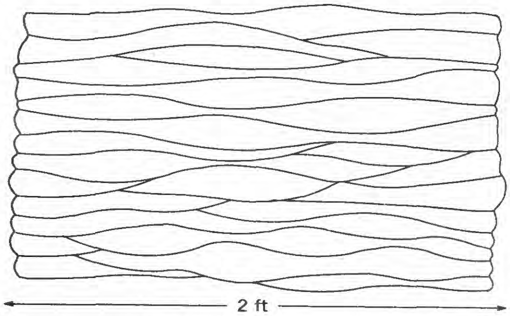
Trough fill. Irregular crossbedding in coarse sandstone that lies within a sequence of thin even beds



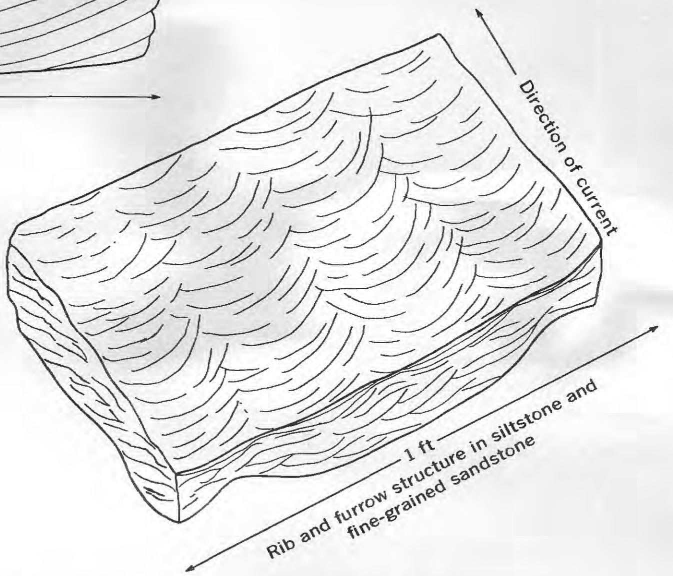
Tabular and irregular festoon



Festoon



Ripple bedding



Rib and furrow structure in siltstone and fine-grained sandstone

FIGURE 5.—Sketches showing types of crossbedding in sandstone and siltstone.

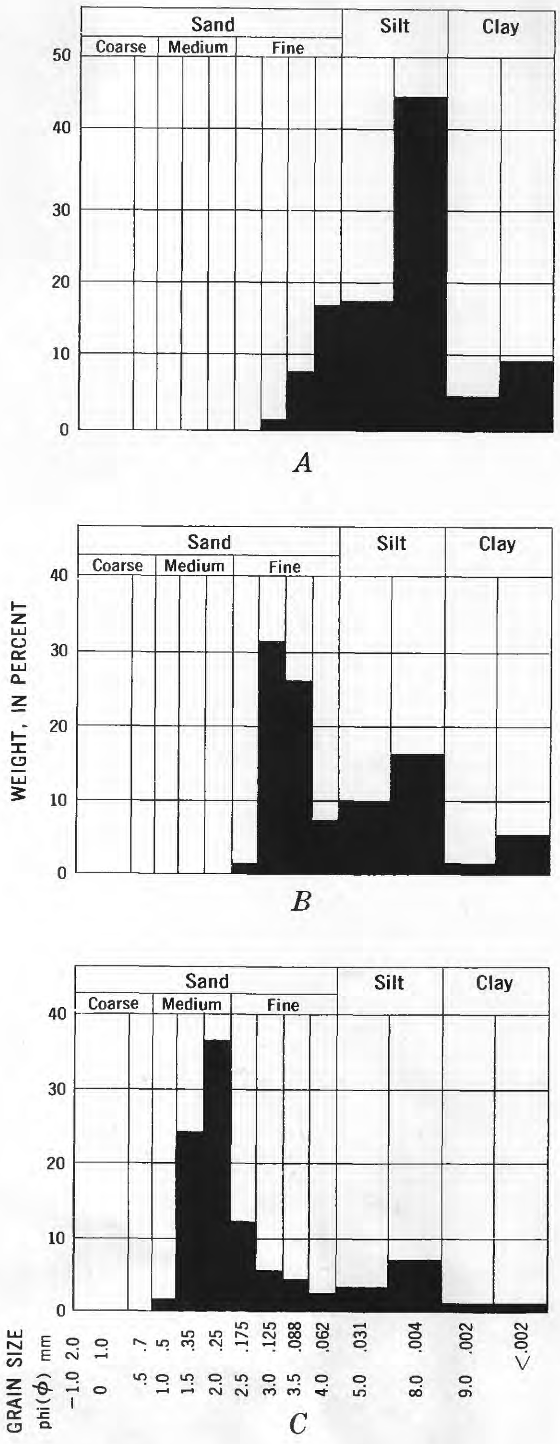


Figure 6.—Vertical distribution of grain size in a typical sandstone-siltstone body. *A*, Upper part. *B*, middle part. *C*, At base.

nondiversified group consisting of pyrite, ilmenite, leucoxene (titanomorphite), brown tourmaline, garnet, rutile, zircon, sphene, magnetite, apatite, chlorite, and biotite; however, not all these minerals are in every sample. Three varieties of garnet were recognized: red, rose, and clear. The brown tourmaline seems to be authigenic.

Fragments of older rocks are sparse. A few masses of fine-grained quartzite were identified in thin sections. The interstitial bonding material in some sandstones is calcite and clay; however, the bond of many sandstones is formed by the intermeshing of the mineral grains themselves. Much of the sandstone is friable.

MUDSTONE AND CLAYSTONE

In this report the term "mudstone" includes all very fine grained laminated rocks that are made up largely of clay-sized particles but that also contain some silt and sand particles. As used here, the term "mudstone" is applied to rocks commonly called shale. Mudstone is a more appropriate term than shale for the fine-grained thin-bedded rocks in the Washington area for two reasons: fissility is a distinctive property of shale, but, with few exceptions, these rocks are not so finely laminated as to become fissile upon weathering; and the term "shale" is more

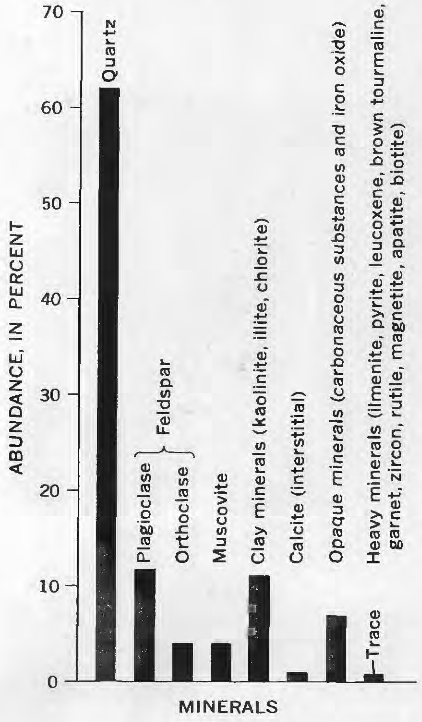


Figure 7.—Average composition of sandstone sampled from outcrops. Feldspar content is lower and clay-mineral content higher than would be expected in an unweathered sample.

descriptive of bedding and weathering characteristics than of composition.

Claystone, as used in this report, designates the extremely fine grained rocks that are made up largely of clay minerals. Carbonate minerals are common impurities. All claystones in the Washington area become soft and plastic when moist and then are simply termed "clay." Consequently, when encountered at weathered outcrops, clay is the appropriate descriptive term. Claystone is usually associated with limestone and coal. The claystone directly beneath coal beds is commonly referred to as *underclay*.

GEOMETRY

The shape of units of mudstone and claystone is less easily defined than that of other types of rock because both types of rock rapidly deteriorate on weathering and are soon masked by weathered rubble of either sandstone, siltstone, or limestone. The claystones generally are lenticular and thin, but some of the thin underclays are sheetlike units that cover large areas. The mudstones generally are large lens-shaped bodies, some of which are as much as 20 feet thick. Mudstone is generally gradational laterally or vertically with siltstone and commonly overlies coal beds. Figure 4 shows the relation of mudstone to several types of sandstone-siltstone bodies.

FIGURE 8.—Limestone beds separated by thin layers of shaly claystone. Note relatively even top and base of beds and the very irregular internal structures within upper bed. Upper member, Washington Formation, south bank of Interstate Highway 70, 1.5 miles west of Lincoln Hill, Washington West quadrangle.

Most mudstone and claystone bodies are bedded. The claystone is in single beds that range in thickness from a fraction of an inch to several feet. Almost

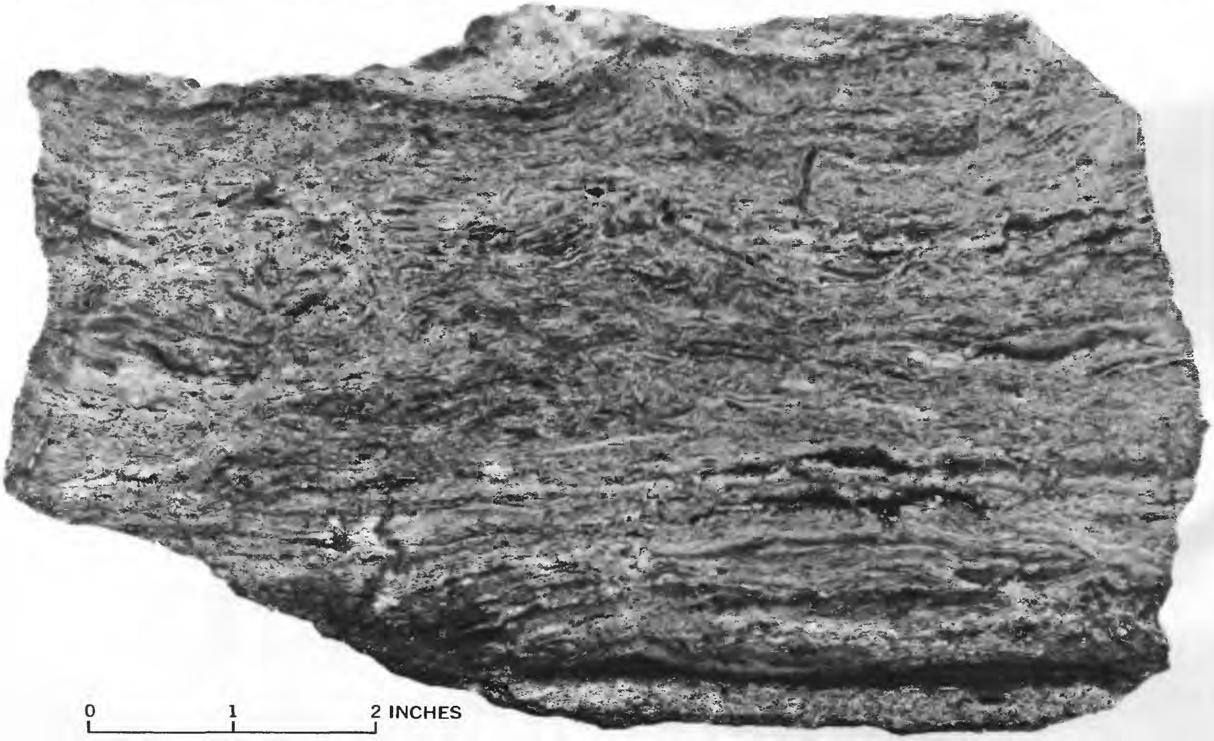


FIGURE 9.—Irregular distinctive laminae in limestone, probably formed by algae growing in extensive mats. Limestone was cut and photographed by Robert Bouman.

all claystones have laminations, but these commonly are destroyed by weathering because of the plasticity of the material. Some mudstone is finely laminated and weathers shaly; other mudstone bodies are massive and break down upon weathering into irregularly shaped fragments. A few mudstones occur as single beds with no internal structure. Claystone is light gray and generally weathers yellow; mudstone is light to medium gray when fresh but weathers to either yellowish or greenish gray. Thin units of mudstone above coal beds commonly are dark to very dark gray.

FIGURE 10.—Irregular less distinctive laminae in limestone, formed by ostracode shells arranged in crude layers. Note fish tooth near top of bed and dark irregular patches of calcite in lower half that possibly replaced bone fragments; disruption of laminae above tooth and in area of calcite patches suggests that animal remains may have sunk into lime mud. Limestone was cut and photographed by Robert Bouman.

MINERALOGY

The general mineral composition of the mudstone and claystone in the Washington area, as determined by X-ray diffraction and in order of decreasing abundance, is clay minerals, quartz, feldspar, and muscovite. The clay minerals, in general order of abundance, are illite, chlorite, kaolinite, mixed-layer illite-chlorite, and two other types tentatively identified as vermiculite and montmorillonite. Illite is by far the most abundant. The content of SiO_2 in two samples of mudstone and three of claystone is from 53 to 60.7 percent, and that of Al_2O_3, from 19 to 20.7 percent (O'Neill and others, 1965).

In general, quartz is more abundant in mudstone than in claystone. Locally both mudstone and claystone are calcareous, and in places they contain ironstone and limestone nodules. A few claystone beds and underclays contain numerous round hard particles, or galls, of claystone that were eroded from other beds and redeposited.

LIMESTONE

GEOMETRY AND INTERNAL STRUCTURE

Most limestone units in the Washington area have sheetlike form and extend throughout the area and well beyond, but a few are lenticular and of local extent. The limestone units range in thickness from a few feet to about 70 feet. Individual limestone bodies grade laterally into, and intertongue with, other types of rocks.

Limestone bodies also tend to grade into underlying rocks, but the contact with overlying rocks is commonly sharp. The basal bed (or beds) in many limestone units is nodular, indicating an intergradational relation to underlying rocks. Most limestones are separated from a coal bed above by an underclay whose basal part is commonly calcareous, but where the underclay is absent, the uppermost bed of limestone is commonly carbonaceous.

The limestone units each comprise from two to 25 individual beds, which range in thickness from a fraction of an inch to slightly more than 3 feet and average about 1 foot. The beds are generally separated by thin beds of mudstone or claystone. Very even and closely spaced beds typify the limestone shown in figure *4D*. Three relatively even limestone beds separated by thin layers of shaly mudstone are shown in figure 8. Some of the individual beds within a limestone body have a lateral extent that can be measured in miles; others are lenticular.

Structures within limestone beds differ from bed to bed, and a single bed may be either structureless or laminated or in part both. Common types of lamination are shown by the two cut sections in figures 9 and 10. The laminations shown in these photographs are irregular, but in some beds they are very even and may be offset in places by very small scale faults that resulted from differential compaction. Remnant desiccation cracks, as shown in figure 11, are in almost every limestone body.

TEXTURE

The fabric of most limestones in the Washington area is a combination of a microcrystalline calcite matrix and varying amounts of particles that range from clay size to rock fragments up to several inches in diameter. Few limestones are totally crystalline.

The size of particles other than calcite and dolomite was determined by mechanical analysis of residues insoluble in hydrochloric acid. For each of the 40 samples analyzed, median particle size ranges from 0.013 mm to slightly less than 0.002 mm. The average median particle size is very close to 0.004 mm, or very fine silt; maximum particle size of the insoluble fraction is 0.25 mm, or medium sand. The size distribution of insoluble residue from a limestone sample is shown in figure 12.

The rock fragments in the coarsely clastic limestone beds are all limestone. They range in size from 1 mm to 10 cm, and in shape from angular to round. A typical coarsely clastic limestone, best described as a breccia-conglomerate, is shown in figure 13*A*. Commonly, only the upper half or less of the bed is conglomeratic, and many of the fragments in the conglomeratic part can be matched with the limestone in underlying and laterally adjacent parts of the bed. Some fragments are rounded, probably the result of having been transported a considerable distance from their source. The contact between the conglomeratic and nonconglomeratic parts of the beds is uneven, and in many places conglomeratic limestone extends downward into the nonconglomeratic limestone, locally to the base of the bed, filling cracks or solution channels. Figure 13*B* is a sketch of a partly conglomeratic bed and shows the relations of the conglomeratic and nonconglomeratic parts. Nowhere does nonconglomeratic limestone overlie conglomeratic limestone within a bed. Almost every limestone unit in the Washington area contains beds that are in part conglomeratic, generally in the upper part; and in one or two units, every bed is conglomeratic. Some of these beds seem to persist throughout the Washington area; others change laterally to nonconglomeratic limestone.

FIGURE 11.—Desiccation cracks in limestone. Crenulated laminae along weathered edge of the limestone slab probably are of algal origin and are typical of many beds. Photograph by E. P. Krier.

MINERALOGY

The carbonate rocks of the Washington area are combinations of calcite, dolomite, and a variety of minerals that form an insoluble fraction. Samples of

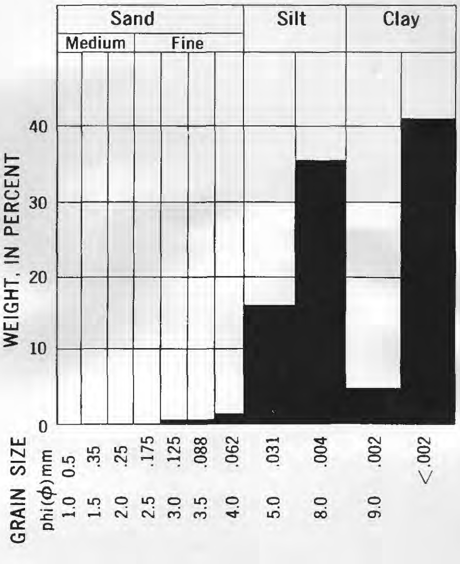


FIGURE 12.—Size distribution of insoluble residue from a limestone sample. Insoluble fraction, 23.5 percent.

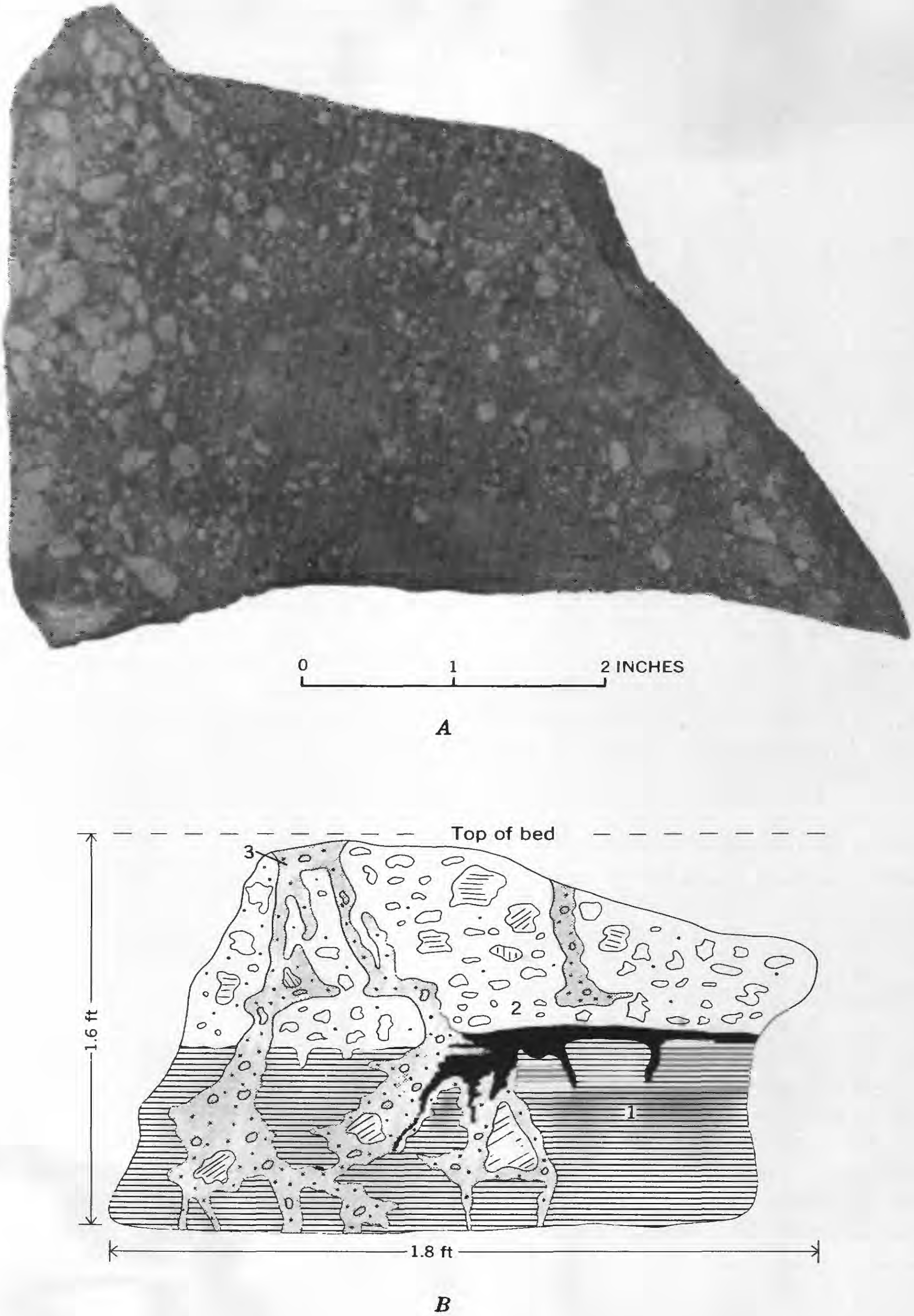


FIGURE 13.—Breccia-conglomerate structure in limestone. *A*, Cut section showing shape and size of limestone fragments. In some beds, fragments are as much as 3 inches across. Limestone was cut and photographed by Robert Bouman. *B*, Sketch of part of a limestone bed, showing sequences of breccia-conglomerate deposition. Deposition sequence was as follows:

1. Microcrystalline limestone, faintly laminated.
2. Breccia conglomerate in silty microcrystalline matrix, deposited after limestone of stage 1 had been exposed to desiccation and erosion. Black material is carbonaceous mudstone.
3. Breccia conglomerate in clayey and silty microcrystalline matrix, deposited after solution of limestone that was deposited during stages 1 and 2.

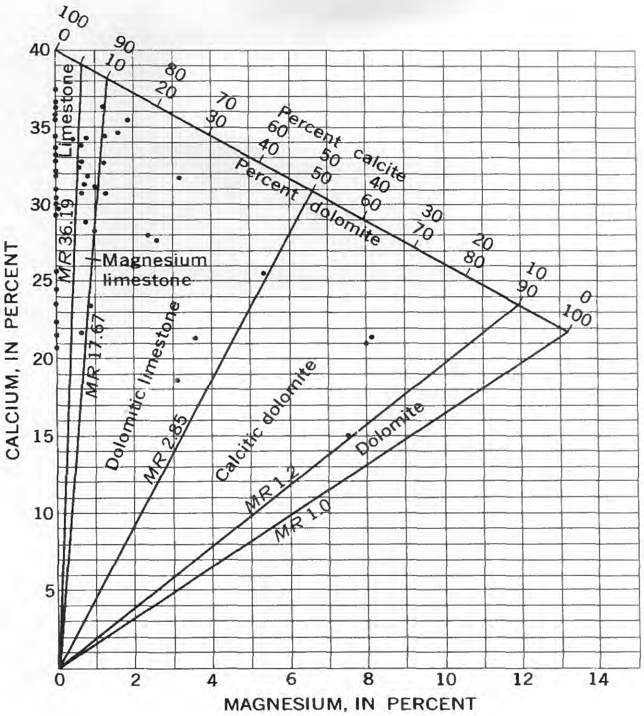


FIGURE 14.—Ratio of calcium to magnesium in 50 limestone samples. Each dot represents a sample. Limestone-dolomite classification from Pettijohn (1956); molal ratios, *MR*, from Guerrero and Kenner (1955).

81 limestone beds representing each of the more prominent limestone units were analyzed for calcium, magnesium, and insoluble-mineral content. Calcium content varies from about 21 percent to about 38 percent; magnesium, from a trace to 8.2 percent; and insoluble minerals, from 2.4 to 43 percent. Total carbonate content varies from about 57 percent to about 90 percent. The ratio of calcium to magnesium for 50 of the 81 limestone samples analyzed is shown in figure 14. On the basis of the ratio of calcium to magnesium content, the majority of samples represent either limestone or magnesium limestone, 13 samples are dolomitic limestone, and three are calcitic dolomite. Because the clay-mineral content of most of the carbonate rock is at least 10 percent, these rocks are further classified as marly.

The ratio of calcium to magnesium varies both from bed to bed within a limestone body and also laterally within a single bed. The maximum range of magnesium found within a limestone body was from a trace to 8.2 percent. The highest magnesium content is in a conglomeratic bed at the top of a limestone body; a bed near the middle of the same sequence had only a trace, and a bed near the base contained 1.6 percent magnesium. In the several beds where both the lower, microcrystalline part and the upper, conglomeratic part were sampled, the microcrystalline part has only a trace of magnesium, but the conglomeratic part has sufficient magnesium to be classified as dolomitic limestone. However, sampling has not been intensive enough to prove whether this is a general rule.

The silt-sized particles in the insoluble residues are largely quartz but include some feldspar, pyrite, mica, and carbonaceous material.

General mineral composition of the clay-sized fraction of the insoluble residues, as determined by X-ray diffraction, is clay minerals, quartz, and minor amounts of plagioclase, potash feldspar, mica, and pyrite. Goethite (?), siderite, and hematite were identified in a few samples. The ratio of clay minerals to quartz is about 1:1 in some samples, but in most, clay minerals make up 60 percent or more of the noncarbonate minerals. Clay minerals identified are illite, chlorite, kaolinite, and mixed-layer clay of two types —a montmorillonite-chlorite and an illite-chlorite. Montmorillonite, as a clay-mineral specie, was not identified with certainty and, if present, is a very minor constituent. Distribution of clay minerals in 37 samples representing 11 limestone units is as follows: Illite in all samples; chlorite in 29 samples; mixed-layer illite-chlorite in 26 samples; kaolinite in 18 samples; mixed-layer montmorillonite-chlorite in 8 samples; and montmorillonite (?) in 4 samples.

Vertical distribution of the several types of clay minerals, with the exception of kaolinite and mixed-layer montmorillonite-chlorite, is relatively even in the limestones. Kaolinite is absent from a limestone body that has mixed-layer montmorillonite-chlorite clay, and also from one that has questionable montmorillonite. The vertical distribution of kaolinite from one rock unit to another is shown on the stratigraphic charts (tables 1, 2).

Other mineral substances found in only a few samples are small amounts of phosphorite, calcium sulfate, and a greenish-gray precipitate that seems to be of organic origin. Microscope study of many thin sections of the highly laminated limestone revealed that each sample contained much brownish material that is unquestionably organic matter. The phosphorite and calcium sulfate are in samples taken from the base of the conglomeratic part of a bed immediately above the lower, microcrystalline part. Minor elements, as determined by semiquantitative spectrographic analyses of 46 limestone samples, are as follows (in percent; A. L. Sutton, Jr., analyst):

Element	*Range*	
	Low	*High*
Si	0.7	7.0
Al	.15	3.0
Fe	.7	5.0
Na	.15	2.0
K	<.7	3.0
Ti	.007	.1
Mn	.03	.2
Ba	.015	.07
Ce	0	.05
Co	<.0005	.0007
Cr	.0007	.005
Cu	.00015	.001
Ga	<.0002	.007
Ni	<.0003	.003
Sr	.05	.2
V	.0015	.01
Y	<.001	.002
Yb	<.0005	.0003
Zr	<.001	.005

Chert is locally distributed in only one limestone body, in the form of discoid nodules as much as 7 inches in diameter. A few thin lenticular chert beds occur locally in the same limestone unit.

FOSSILS

Rocks of the Washington area contain both plant and animal remains. The many coal beds attest to times of prodigious plant growth; however, during the transformation of the plant remains to coal, the identity of the plants was largely destroyed. The animal remains are characterized by few species and by the restricted occurrence of certain types.

PLANT REMAINS

Identifiable plant material includes carbonized leaf, stem, and branch fragments, which are mainly in the mudstones and siltstones, and trunk fragments, which are mainly in the lower part of sandstones. The following plants from three localities were identified by S. H. Mamay (written commun., 1962):

Collection 1, Washington East quadrangle, 0.5 mile north-northeast of Washington, north bank of Interstate Highway 70, 0.15 mile west of Route 19. Mudstone just above the Washington coal bed.

Neuropteris scheuchzeri
Neuropteris cf. *N. onata*
Pecopteris plumosa Artis
Pecopteris sp. indet.

Collection 2, Washington East quadrangle, 0.5 mile northeast of Washington, south bank of Interstate Highway 70, 0.7 mile east of Route 19. Siltstone and sandstone in basal part of Greene Formation. This collection is predominantly lycopod bark compressions.

Sigillaria brardii Brongniart
Sigillaria sp.
Lepidophyllum sp.
?*Alethopteris* sp.
?*Pecopteris* sp.

Collection 3, Amity quadrangle, 0.45 mile north-northeast of Lone Pine in bed of Brush Run. Mudstone just above the Waynesburg coal bed.

Neuropteris cf. *N. oriata* Hoffman
Neuropteris scheuchzeri Hoffman (most abundant form in collection)
Undeterminable *Neuropteris* spp.
Cyclopteris sp.
Calamites sp.
cf. *Pecopteris germari* (Weiss) Fontaine and White
cf. *Pecopteris rotundilaha* Fontaine and White
cf. *Callepteridium grandifolium* Fontaine and White
cf. *Danaeites emersoni* Lx.

Most of the plant fragments are so poorly preserved that Mamay considered his determinations largely tentative. The first two assemblages listed, according to Mamay, are Late Pennsylvanian and fall within floral zone 12, or the *Danaeites* zone, of Read and Mamay (1964).

Remains or impressions of plant roots are sparse. Although plant roots would be expected to be abundant in coal-bearing strata, they were found in only a few places, in underclay and limestone beneath coal beds.

The many thin, highly laminated limestone beds, such as those shown in figures 9, 10, and 11, probably were formed by algae that lived in extensive mats in shallow water. Thin-section study of a sample from the upper limestone member, Washington Formation, by J. L. Wray, revealed a calcareous algal form that he identified as *Girvanella* sp. aff. *G. ducii* Wethered (Wood, 1963, p. 269; identification by Wray, oral commun., 1967). Furthermore, a single flat algal head which had a concentric growth pattern and was 2 feet in diameter was found just east of the Washington area, in the western part of the Hackett quadrangle, in limestone from the middle member of the Washington Formation. This positive evidence, together with the conspicuous laminated structure and high content of brownish organic material in the limestones, suggests strongly that algae grew abundantly and were important both as lime-secreting agents and in trapping fine sediment.

ANIMAL REMAINS

Animal remains are fish scales and bone fragments, tiny gastropods, small pelecypods, ostracodes, and the worm tube *Spirorbis*. The suite is diminutive and nondiversified, identifiable specimens are scarce, and the fossils are of little or no value for determining the ages of the rocks.

Ostracodes are the most abundant fossils and are irregularly distributed in every limestone body. They are most abundant in, though not restricted to, the thin laminated algal(?) limestone beds, where they form coquinoid laminae. In some of the desiccation-cracked limestones (fig. 11), the ostracodes make up most of the crack filling—in a few places to a depth of 1 foot below the top of the limestone bed. In at least one limestone body that has five or six beds, ostracodes are about equally abundant in all beds. Carbonaceous mudstone layers, both those associated with limestone beds and those associated with coal beds, also commonly have abundant ostracodes. Figure 10 shows irregular and somewhat indistinct ostracode laminae in a limestone that probably is not of algal origin. The ostracodes are all tiny smooth-shelled fresh-water forms that, according to I. G. Sohn (oral commun., 1961) lack the distinctive features necessary for correlating strata or for determining the age of the rocks.

Gastropods were found in only five limestone bodies. In these, the fossils are restricted to a few specific beds and to stratigraphic positions that persist over most of the Washington area; locally, the gastropods are absent even from these beds. Generally the gastropods are in highly argillaceous nodular limestone beds and in associated mudstone at the base of a limestone body, or in the conglomeratic part of a bed, commonly in the upper part of a limestone body. They were found in an underclay at one locality. All are small high-spired forms tentatively referred to *Anthracapupa ohioensis* Whitfield by E. L. Yochelson (written commun., 1963).

Pelecypods are sparse and were found in only three limestone bodies. They are restricted to a single conglomeratic bed within each limestone and have very uneven lateral distribution. The specimens are small thin-shelled forms, and many are crushed and fragmented. Similar specimens collected in Belmont County, Ohio, from strata correlative with those in the Washington area were referred to *Myalina* (*Myalinella*) cf. *M. meeki* Dunbar by Mackenzie Gordon, Jr. (Berryhill, 1963, p. 57).

The worm tube *Spirorbis* was found in six limestone bodies as isolated specimens. In each unit the fossil was found in a single bed, either an argillaceous bed in the lower part of the unit or a conglomeratic bed that may have been any place stratigraphically within the unit.

Fish fragments are moderately abundant locally and are in every limestone body, as well as in some claystones and mudstones. Fish remains generally are in conglomeratic parts of limestone beds and seem to be most prevalent at the top of the uppermost bed in a limestone body. Fragmented plates, spines, and teeth are most abundant; coprolites and bone fragments are sparse. (Note the large fish tooth shown in figure 10.)

LITHOFACIES RELATIONS

The sedimentary rocks in the Washington area have stratigraphic and geographic relations that reveal the depositional history of the overall sequence. The sandstone, siltstone, mudstone, claystone, and limestone represent episodes of sediment influx and accumulation. The coal beds represent pauses in active clastic-mineral sedimentation and punctuate the sequence and afford a convenient means of grouping the rocks stratigraphically. In the classification scheme used in the Washington area, the coal beds serve as key markers that separate the sedimentary units into subdivisions, each representing an episode of deposition.

Within the interval from one coal bed to another, the units composed of sandstone, siltstone, mudstone, claystone, and limestone both intergrade and intertongue. The lateral relation of the several types of rock that commonly separate two coal beds is shown in figure 15. Four principal types of rock sequences, or lithofacies, are shown in the diagram: sandstone; interbedded sandstone and fine-grained clastic rocks, including siltstone, mudstone, and claystone; fine-grained clastic rocks; and limestone. The diagram, which is somewhat oversimplified because of limitations of space and scale, is representative of actual conditions in the Washington area, where a lateral change from the sandstone at the left side of the diagram to the limestone at the far right takes place within approximately 6 miles. The diagram also indicates that lateral boundaries between the lithofacies are indefinite, a characteristic of every sedimentary unit. Some sedimentary units in the Washington area lack the diversity of the one shown in figure 15, but many include three of the principal lithologic associations. The lithofacies shown in columns 2 and 3 are the most prevalent.

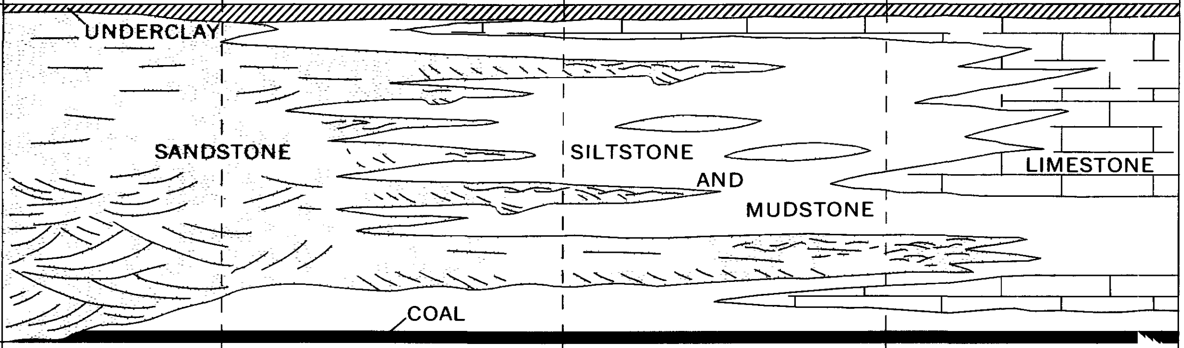
	Principal types of lithologic associations in the Washington area			
	1	2	3	4
Basic stratigraphic unit for field mapping Range in thickness generally 20 to 60 feet				
Lithology	Mostly sandstone.	Underclay. Limestone locally. Mudstone. Sandstone, siltstone, and mudstone. Mudstone.	Underclay. Limestone. Mudstone. Sandstone, siltstone, and mudstone. Limestone locally.	Limestone predominant; contains mudstone, sandstone, and siltstone locally.
Shape of rock units	Elongate and lobate.	Variable, irregular, and sheetlike.	Sandstone units generally sheetlike, or as pods and lobes.	Generally sheetlike.
Internal structures	Even to irregular bedding in upper part; festoon (trough) bedding in lower part.	Limestone, nodular to even-bedded. Mudstone, laminated. Siltstone, thin-bedded, laminated; ripple bedded locally. Sandstone, thin to medium-bedded; small-scale festoon and tabular crossbedding.	Limestone, even-bedded, laminated. Mudstone, laminated. Siltstone, laminated; ripple bedding and rib-and-furrow structure common. Sandstone, thin- to medium-bedded; ripple bedding locally.	Beds generally even and closely spaced. Breccia-conglomerate structure common.
Texture	Fine grained in upper part; medium to coarse grained in lower part; sorting generally good throughout.	Limestone, microgranular. Sandstone, fine-grained; commonly grades into siltstone; sorting good to fair.	Limestone, microgranular and breccia-conglomeratic. Sandstone, fine-grained to very fine grained; sorting fair.	Limestone, microgranular to microcrystalline. Sandstone, very fine grained.
Fossils	Casts and carbonized impressions of logs locally abundant in basal part.	Limestone; ostracodes, small gastropods locally, *Spirorbis*, and fish remains. Mudstone just above the coal bed locally has carbonized leaf and stem remains.	Limestone; ostracodes, small gastropods locally; *Spirorbis* locally; and fish remains. Siltstone and mudstone; macerated plant debris widespread in some units.	Same as in other facies; distribution uneven; generally less abundant.
Remarks	Mica abundant throughout; clay minerals more abundant in upper part.	General irregular bedding. Mica in the sandstone is mostly along bedding planes.	Thin carbonaceous claystone or mudstone common above lower limestone; thin carbonaceous mudstone and thin lenses of coal locally in mudstone and siltstone.	

FIGURE 15.—Lithofacies relations and summary of lithologic characteristics. Lateral span represented in diagram is approximately 6 miles.

The principal facies and subfacies within four of the six formations in the Washington area are shown on plates 3 and 4. Plate 3 includes six individual lithofacies maps for members of the Pittsburgh and Uniontown Formations; plate 4 includes six lithofacies maps for members of the Waynesburg and Washington Formations. Each lithofacies map shows the actual stratigraphic and textural relations (represented schematically in fig. 15) within a member. Because of the intricate lateral intertonguing of the different types of rock, the facies shown on plates 3 and 4 represent textural and compositional relations that are refinements of the principal facies.

STRATIGRAPHY

METHOD OF PRESENTATION

The rocks of the Washington area have been classified into mappable stratigraphic units that are shown on published geologic quadrangle maps at a scale of 1:24,000—Washington West (Berryhill and Swanson, 1964); Washington East (Swanson and Berryhill, 1964); and Amity (Berryhill, 1964). The published maps are suggested for supplemental use with maps in the present publication. For this publication, the physical variations within many of the stratigraphic units were studied in detail, and the results are shown by the series of special maps.

Accompanying the lithofacies maps are columnar sections which show the typical stratigraphic relations within a member and diagrams which show the percentages of sandstone, mudstone, and limestone at each data point used for facies determinations.

Because of the economic importance of the coal beds, rocks of the Pittsburgh, Uniontown, Waynesburg, and Washington Formations have been penetrated many places by the diamond drill. The core records from these holes permitted detailed lithofacies analysis that could not be applied to the underlying Conemaugh and the overlying Greene Formations, which have not been drilled extensively. Consequently, the stratigraphy of the Conemaugh and Greene Formations is described in text, but the stratigraphic and statistical lithologic data for the other four formations are listed in charts (tables 1, 2), and only the most salient features are summarized and compared in text. The stratigraphic and lithologic data listed on the charts include sequence of beds, thickness, mineralogy, lithofacies relations, thickness of coal beds, fossils, and distinctive features.

HISTORY OF NOMENCLATURE

Strata equivalent to those in the Washington area were first named by Rogers (1839), who referred to them as the "Pittsburgh series." The name included all strata from the river bottoms to the hilltops in the Pittsburgh area. The "coal measures," including older coal-bearing rocks not exposed in the Pittsburgh area, were subsequently classified into subdivisions, or groups, on the basis of the presence or absence of minable coal (Rogers, 1858), and the terms "barren" and "productive" were used, as appropriate, to describe the strata of a group. All subsequent classifications have been refinements of that of Rogers, and the boundaries of his four subdivisions, each at a principal coal bed, have remained unchanged.

The systemic assignment "Carboniferous" was given to the "coal measures" of southwestern Pennsylvania by J. P. Lesley, in the preface to a report by Franklin Platt and W. G. Platt (1877). Presumably, use of the term "Carboniferous" implied a comparison with the Carboniferous or coal-bearing strata of Great Britain. Williams (1891, p. 83, 102, 106) called the "coal measures" the "Pennsylvania (n) series," a designation synonymous with Carboniferous, and thus established the State of Pennsylvania as the type area for these strata in the United States. Earlier, Fontaine and White (1880), on the basis of fossil-plant studies, had assigned a Permian or "Upper Carboniferous" age to the strata of the "Upper Barren Group" above the Waynesburg coal bed. Eventually, in the United States the designation Carboniferous System included the Mississippian, Pennsylvanian, and Permian Series (Wilmarth, 1925). These series have subsequently been redesignated as systems. The Mississippian and Pennsylvanian make up the Carboniferous System.

Rocks of the Washington area are Late Pennsylvanian and Early Permian. The history of stratigraphic nomenclature for rocks exposed in the Washington area is summarized in figure 16.

RECENT REVISIONS

In early work, names were given first to the minable coal beds, and subsequently to most of the thicker and more persistent limestone units and to a few of the sandstone units. Most of the sandstone, siltstone, and mudstone units were not named. Elsewhere in southwestern Pennsylvania and in eastern Ohio and West Virginia, more than 80 names have been applied to these strata. Many of these names are no longer used because the units cannot be mapped, cannot be reliably correlated, or overlap each other from one area to another.

As in the past, mapping in the Washington area has demonstrated that coal beds are the most distinctive and most easily correlated units. Indeed, the many intervening sandstone and limestone units are so similar that most can be correlated only when related to an underlying or overlying coal bed. The basic mapping unit for field classification, therefore, includes, with one exception, the rock types between coal beds, and the basic units represent a sedimentary cycle (fig. 15). This unit is defined as the rock sequence from the base of a coal bed or carbonaceous layer to the base of the next overlying carbonaceous unit. The single exception is a sequence of beds without an underlying coal bed; such a sequence has been designated a separate stratigraphic unit because of lithologic characteristics that are recognizable not only in the Washington area but beyond. Because many units thus defined represent relatively thin or incomplete cycles, and because facies changes are common within many of the coal-to-coal sequences, these units are designated as members rather than as formations. Figure 15 shows diagrammatically the possible range of facies in a member. Where possible the member has been assigned the name of the coal

Rogers (1839)	Rogers (1840)	Rogers (1858)	Age			Stevenson (1876)	Age				White (1891)	Age				Clapp (1907a) Munn (1912)	Age				Present report
Pittsburgh Series	Monongahela Series	Upper Barren Group	Upper Carboniferous	Upper Barren Series	Greene County Group	Fish Creek Sandstone	Carboniferous	Permo-Carboniferous	Dunkard Creek Series	Bellton coal group	Fish Creek sandstone	Carboniferous	Permian	Dunkard Group	Greene formation	Claysville limestone member		Early Permian	Dunkard Group	Greene Formation	Limestone D
						Dunkard Coal					Dunkard coal bed										
						Limestone IXb										Dunkard(?) coal					
						Unnamed Sandstone and Shale										Prosperity limestone member					Limestone C
						Limestone IXa															Limestone B
						Unnamed Sandy Shale					Jollytown limestone										
						Limestone VIII															
						Unnamed Sandstone															
						Unnamed Coal Bed										Ten Mile coal					
						Limestone VII										Donley limestone member					Limestone A
						Unnamed Shale and Iron Ore					Jollytown coal bed					Upper Washington coal					
					Washington County Group	Limestone VI-Upper Washington Limestone				Marietta sandstones	Upper Washington limestone				Washington formation	Upper Washington limestone member				Washington Formation	Upper limestone member
						Unnamed Sandstone															
						Jollytown Coal Bed					Washington "A" coal bed					Jollytown coal					
						Unnamed Sandstone					Middle Washington limestone					Middle Washington limestone member					
						Limestone IV-Middle Washington Limestone															Washington "A" coal bed Middle member
						Unnamed Sandstone and Shale															
						Limestone III					Blacksville limestone										
						Unnamed Sandstone and Shale															
						Unnamed Coal Bed															
						Limestone II-Lower Washington Limestone					Lower Washington limestone					Lower Washington limestone member					Lower limestone member Washington coal bed
						Washington Coal Bed					Washington coal bed					Washington coal		Late Pennsylvanian and Early Permian		Waynesburg Formation	
						Washington Sandstone					Washington sandstone										
						Little Washington Coal Bed					Little Washington coal bed					Little Washington coal					Upper member Little Washington coal bed
						Unnamed Shale															
						Limestone Ib															
						Waynesburg "B" Coal Bed					Waynesburg "B" coal bed					Waynesburg "B" coal	?				Waynesburg "B" coal bed Middle member
						Unnamed Sandstone															
						Limestone Ia					Colvin Run limestone										
						Waynesburg "A" Coal Bed					Waynesburg "A" coal bed					Waynesburg "A" coal					Waynesburg "A" coal bed
						Waynesburg Sandstone					Waynesburg sandstone Cassville plant shale		?			Washington sandstone Cassville shale member					
		Upper Coal Measures		Upper Productive Coal Measures		Waynesburg Coal Bed		Monongahela River Series			Waynesburg coal bed		Pennsylvanian	Monongahela formation		Waynesburg coal	Carboniferous				Lower member Waynesburg coal bed
																		Late Pennsylvanian	Monongahela Group	Uniontown Fm.	Upper member
						Unnamed Fire-Clay															
						Unnamed Sandstone					Browntown sandstone										
						Unnamed Limestone					Little Waynesburg coal bed					Little Waynesburg coal					
						Unnamed Sandstone and Shale					Waynesburg limestone					Waynesburg limestone					Lower member Uniontown coal bed
						Uniontown Coal Bed					Uniontown sandstone										
						Great Limestone					Uniontown coal bed					Uniontown coal				Pittsburgh Formation	Upper member
						Sewickley Coal Bed					Uniontown limestone					Uniontown limestone member					Limestone D
						Unnamed Sandstone					Great limestone					Benwood limestone member					Limestone C
						Unnamed Limestone					Sewickley coal bed					Sewickley coal					Limestone B
						Unnamed Sandstone or Sandy Shale					Sewickley sandstone										Limestone A
						Redstone Coal Bed					Sewickley limestone					Fishpot limestone					Sewickley Member
						Unnamed Limestone					Redstone coal bed					Redstone coal					Sewickley coal bed
						Pittsburgh (Upper) Sandstone					Redstone limestone										Fishpot Member
						Unnamed Shale					Pittsburgh sandstone					Pittsburgh sandstone					Redstone Member Redstone coal bed
						Pittsburgh Coal Bed					Pittsburgh coal bed					Pittsburgh coal					Lower member Pittsburgh coal bed
		Lower Barren Group				Lower Barren Series					Barren Measures or Elk River Series					Conemaugh formation					Conemaugh Formation

FIGURE 16.—History and classification of the stratigraphic nomenclature for rocks exposed in the Washington area, Pennsylvania.

bed at its base, so that the long-established name is retained and the member name is related to the most easily mapped unit of the member. Where coal beds are not persistent or where closely spaced facies changes preclude positive correlation, members have not been named but are informally designated as upper, middle, or lower.

Because the basal unit of a member as here defined is a coal bed, it follows that the basal unit of a formation must also be a coal bed. The formation boundaries are placed at the base of the most important and persistent thick coal beds, and the name assigned to the formation is that of this basal coal bed. Further, the formation includes two or more members that represent sets of similar and related sedimentary cycles. By applying the above principles, Berryhill and Swanson (1962) established the stratigraphic nomenclature that is followed in this publication for strata between the Pittsburgh coal bed and the top of the upper limestone member of the Washington Formation.

Flint (1965) raised the Conemaugh Formation to group rank and divided it into the Glenshaw and Casselman Formations. In the present publication, however, the Conemaugh in the Washington area is treated as a formation because only the upper 60 feet is exposed, and the fieldwork was completed before Flint's report was published.

PENNSYLVANIAN SYSTEM

CONEMAUGH FORMATION

The name "Conemaugh" was first used by Platt (1875, p. 8) for the strata between the Upper Freeport and Pittsburgh coal beds along the Conemaugh River; this name is in general use today for equivalent strata throughout the Appalachian basin.

Approximately the upper 60 feet of the Conemaugh Formation is exposed in the Washington area. Outcrops are largely obscured by settlement and by mine dumps, but the few scattered exposures generally reveal limestone float a few feet below the Pittsburgh coal bed, two beds of limestone 27 feet below the coal, and a thin- to thick-bedded partly crossbedded sandstone 30–35 feet below the coal bed. One exposure of the limestone about 27 feet below the Pittsburgh coal is in the upper part of the roadbanks 0.2–0.5 mile south of Moninger, but here there is only one limestone bed. The limestone float a few feet below the Pittsburgh coal bed probably is from the Upper Pittsburgh Limestone Member. The bed or beds of limestone 27 feet below are the Lower Pittsburgh Limestone Member, and the sandstone is part of the Connellsville Sandstone Member. A few feet of the siltstone and partly grayish-red mudstone below the Connellsville Sandstone Member crop out 70 feet south of the bridge that crosses Chartiers Creek at Houston.

Additional descriptions of the Conemaugh Formation in and near the Washington area were given by Sisler (1932), Fettke and others (1946), and Flint (1965).

MONONGAHELA GROUP

The term "Monongahela," as applied to stratigraphic nomenclature, has evolved from its earliest usage for all strata above the Pittsburgh coal bed. Its current usage is for rocks between the base of the Pittsburgh coal bed and the base of the Waynesburg coal bed. (See fig. 16 for history of usage.) The Monongahela was raised from formation to group rank in western Pennsylvania by Berryhill and Swanson (1962) and divided into two formations: the Pittsburgh, which includes the Pittsburgh coal bed and the dominantly limy rocks to the base of the Uniontown coal bed; and the Uniontown, which comprises the coal bed and overlying dominantly sandy rocks to the base of the Waynesburg coal bed. (See fig. 17*C, D* for the distribution of lithologic components in the Monongahela.) The thickness of the Monongahela Group is 275 feet in the northern part of the Washington area and increases to 337 feet in the southern part.

PITTSBURGH FORMATION

The thickness of the Pittsburgh Formation ranges from 215 feet in the western part of the Washington area to 264 feet in the east-southeastern part (pl. 5), a rate of increase toward the southeast of about 3½ feet per mile. The formation has been divided into five members: lower, Redstone, Fishpot, Sewickley, and upper. Descriptive data for the Pittsburgh Formation are given in table 1.

The lower member comprises the thick and persistent Pittsburgh coal bed at its base and an overlying thick sandstone that is informally the Pittsburgh sandstone. This sandstone is the thickest and most extensive sandstone in the Monongahela Group (pl. 6, map *A*). In the northeastern part of the Washington area the sandstone is predominantly crossbedded and is similar to that in the lower member of the Waynesburg Formation 5 miles east of the area (fig. 4*F*). It thins southwestward, but retains its position just above the Pittsburgh coal bed, and grades into siltstone and fine-grained even-bedded sandstone in the southwestern part of the Washington area. There, it is similar to sandstone in the upper member of the Waynesburg Formation 3 miles east of the area (fig. 4*C*). The sandstone of the lower member of the Pittsburgh Formation is well exposed in the walls of abandoned strip mines along Chartiers Creek north of Washington.

The Redstone Member is typically siltstone and mudstone overlain by persistent limestone, but near the middle of the member is a thin sandstone body whose distribution roughly corresponds to that of the underlying sandstone in the lower member (pl. 3, map *A*, sections 2, 3, 5). The lenticular Redstone coal at the base of the member is so spotty in its occurrence in the Washington area that the contact between the Redstone Member and underlying lower member rarely could be mapped. Consequently, the lower member and the Redstone Member are treated as one on the lithofacies map. The member is not well exposed in the Washington area. Parts of the Redstone are exposed in a few places along Chartiers Creek, and in roadcuts that lead away from the creek, Washington East quadrangle.

The Fishpot Member, the thinnest member in the Pittsburgh Formation, is mainly siltstone and mudstone; but several west-trending sinuous sandstone bodies, together with the relative thinness, characterize the member (pl. 3, map *B;* pl. 6, map *B*). The lenticular Fishpot coal bed, common at the base of the member in other areas, is absent from the Washington area. The Fishpot Member is exposed in a few outcrops in roads leading away from Chartiers Creek, Washington East quadrangle; in the bank near the east end of the Washington Racetrack; and in a small quarry 0.4 mile north of the racetrack, Washington West quadrangle. At the quarry the Fishpot is represented by massive sandstone.

The Sewickley Member contains the thickest limestone sequence exposed in the Washington area. The member is limestone in the north half of the area but changes to clayey limestone and calcareous mudstone in the south half (pl. 3, map *C*). The Sewickley coal bed, well developed in other parts of southwestern Pennsylvania and adjacent States, is either absent or contains many impurities over much of the Washington area (pl. 8, map *D*). The thick limestone sequence is known as the Benwood Limestone Bed. The member is not well exposed; the most extensive outcrops are along the west bank of Chartiers Creek southwest of the Washington Racetrack, Washington West quadrangle.

The upper member contains four limestone units

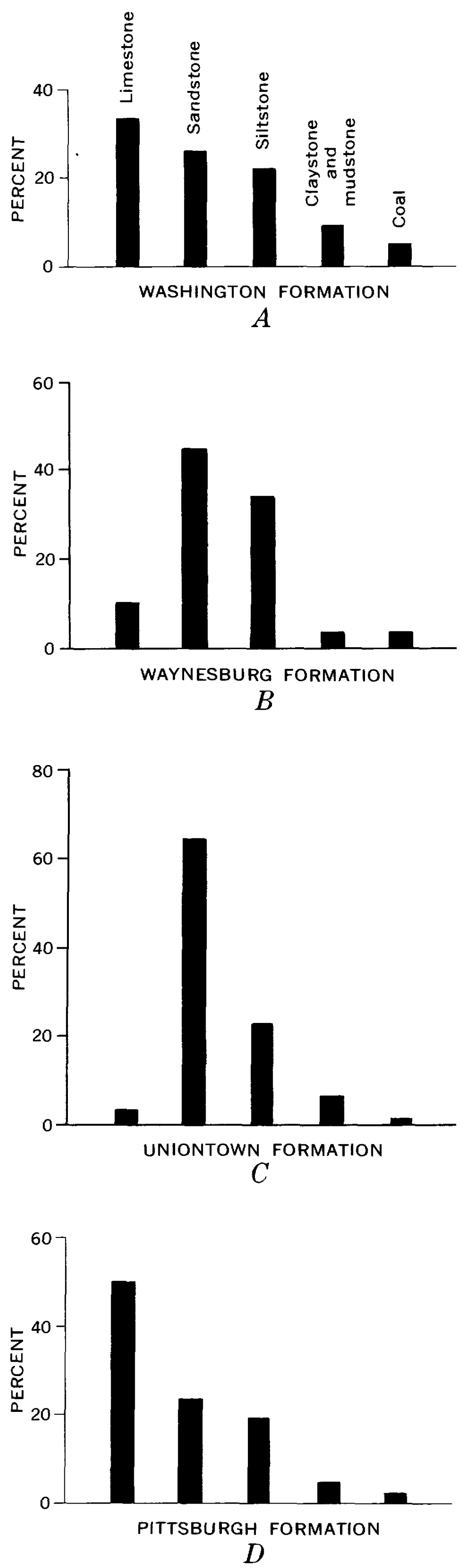


FIGURE 17.—Average distribution of lithologic components in the Washington, Waynesburg, Uniontown, and Pittsburgh Formations.

that have been informally designated in ascending order as A, B, C, and D and has no underlying coal. Persistence of the limestone units and the conspicuous greenish color of the siltstone units between the limestones, are typical features. Locally the green siltstone is represented by sandstone. Outcrops of parts of the upper member are in roadbanks on the northwestern outskirts of Washington, Washington West quadrangle. The brecciated limestone in figure 13*B* is from limestone C of the upper member and came from the roadbank near the curve 0.4 mile north-northeast of Oak Grove. Limestone D is exposed along the upper part of the east bank of the highway between Oak Grove and Gretna, where it contains small gastropods and is a conspicuous breccia-conglomerate in places.

UNIONTOWN FORMATION

The Uniontown consists of two members that have an aggregate thickness of 32 feet near the northeast corner of the Washington area and 93 feet in the southwestern part (pl. 5). In contrast to the Pittsburgh Formation, both the lower and upper members of the Uniontown Formation are thickest in the southwestern part of the Washington area and thin to the northeast (pl. 3). Descriptive data for the Uniontown Formation are given on plate 8, and the average composition is shown in figure 17*C*.

The lower member has four distinctive features: the sandstone unit locally fills channels that were eroded into underlying strata; coal occurs not only at the base of the member as a single stratum but also locally in lenses that are interbedded in the lower 12 feet of the sandstone unit; the lateral change in facies from sandstone and siltstone to predominantly limestone is unique to the lower member (pl. 3, map *E*) ; and chert is known only from the limestone in the upper part of the lower member. The distribution of the impure Uniontown coal bed is shown on plate 8, map *E*. The entire member is well exposed in the deep cut on Interstate Highway 79 just south of Chartiers Creek, Washington East quadrangle. In this cut the coal bed lies 12 feet above the base of the member in the east highway bank and is absent from the west bank. Neuripterid-type plant remains are abundant in the sandstone unit in the Interstate Highway 79 roadcut. The stone quarry just south of Meadowlands School, Washington East quadrangle, is in massive sandstone of the lower member. The chert-bearing limestone in the upper part of the member is exposed in the abandoned railroad cut near the northeast corner of the Washington East quadrangle.

The upper member is mostly laminated siltstone containing sinuous elongate bodies of thin-bedded sandstone a mile or less in width (pl. 3, map *F;* pl. 4, map *E*). In nearly all aspects the upper member bears a striking similarity to the Fishpot Member of the Pittsburgh Formation. The Little Waynesburg coal bed is at the base of the upper member outside the Washington area. The upper member is exposed in the lower part of the banks of Interstate Highway 70 just east of the interchange at the north edge of Washington, Washington East quadrangle; in the creek banks at Lone Pine, Amity quadrangle; and in an excavation on the north side of State Route 18, 1.4 miles northwest of Wolfdale, Washington West quadrangle (lower part of fig. 4*B*).

PENNSYLVANIAN AND PERMIAN SYSTEMS

DUNKARD GROUP

The term "Dunkard Group" represents a shortening of the original designation "Dunkard Creek series" for all strata above the Waynesburg coal bed. (See fig. 16.) As first defined, the name comprised the "Washington County group" and the "Greene County group." As recently redefined (Berryhill and Swanson, 1962), the Dunkard Group includes the Waynesburg Formation of Late Pennsylvanian and Early Permian age and the Washington and Greene Formations of Early Permian age.

In the Washington area where the upper part has been eroded, the thickness ranges from 0 to about 700 feet. Thickest sections are in the southern and southwestern parts of the area.

The rocks within the Dunkard Group represent a subtle change upward from more persistent coal-bearing rocks that resemble the strata of the Monongahela Group to the finer grained highly lenticular strata of the Greene Formation, which contains only thin lenses of impure coal.

WAYNESBURG FORMATION

The Waynesburg Formation extends from the base of the Waynesburg coal bed to the base of the Washington coal bed. Descriptive data for the formation are listed in table 2. Rock types within the formation are similar to those in the underlying Uniontown Formation. The Waynesburg Formation cannot be dated more accurately than Late Pennsylvanian and Early Permian because of lack of evidence for drawing a systemic boundary.

The Waynesburg was once included as a part of the Washington Formation, and its age was believed to be Permian (Fontaine and White, 1880) on the basis of fossil plants collected mainly in West Virginia. However, fossils collected over the intervening years indicate that the strata in question contain Pennsylvanian types of plants as well as those of Permian affinity. Any systemic boundary drawn within the sequence would imply greater precision than the data permit.

The thickness of the Waynesburg ranges from 172 feet in the extreme east-southeastern part of the Washington area to 112 feet in the northwestern part, a northwestward thinning at the rate of about 3⅛ feet per mile (pl. 5). The predominant constituents are sandstone and siltstone, and these make up about 84 percent of the formation (fig. 17*B*). The formation has been divided into the lower, middle, and upper members.

The lower member has two distinctive features: the thick Waynesburg coal bed (pl. 8, map *F*), and the massive crossbedded sandstone in the southeastern part of the Washington area (pl. 4, map *A;* pl. 7, map *A*). In general form the sandstone is sheetlike, but a single elongate tongue extends westward from the main body in the Amity quadrangle and bifurcates into southwest- and northwest-trending branches (pl. 7, map *A*). Limestone, represented by a few thin impure beds in the lower half of the member, extends into the Washington area from the southwest as tonguelike lenses that pinch out north of Washington. Several limestone beds also occur near the top of the member locally. The lower member is exposed at the north edge of Washington in the banks of Interstate Highway 70 just east of the interchange. At this locality, which is in the Washington East quadrangle, the Waynesburg coal bed is in two benches separated by fine-grained sandstone, and the overlying sandstone is thin bedded and fine grained. The coal bed is also exposed in the small mine at the east edge of Lone Pine, and the massive phase of the sandstone is exposed in the creekbank at the west edge of Lone Pine, Amity quadrangle. The massive crossbedded sandstone at Lone Pine is similar to that shown in figure 4*F*. The coal bed and overlying siltstone are exposed in the north bank of State Route 18, 1.4 miles northwest of Wolfdale, Washington West quadrangle (fig. 4*B*).

The middle member is a composite sequence consisting of two parts: a lower part in which the Waynesburg "A" coal bed and two overlying bodies of limestone are distinctive; and an upper part, which has, at the base, the thin and very lenticular Waynesburg "B" coal bed and overlying siltstone and sandstone. (See pl. 4, map *B*.) The limestones in the lower part are thickest in the northwestern part of the Washington area and pinch out southeastward. The rocks between the limestone and the Waynesburg "B" coal bed are typically thin-bedded sandstone and siltstone. Ripple bedding, ripple marks, and small-scale tabular bedding are common in these rocks. The Waynesburg "B" coal bed at the base of the upper part varies from thin coal in the southeastern part of the Washington area to impure coal or carbonaceous mudstone in the northern part; it is absent in and near the town of Washington. The location and area covered by the thin sandstone unit in the upper part of the middle member is nearly the same as that of the siltstone facies shown on the lithofacies map (pl. 4, map *B*). Excellent exposures of the lower part of the member, including the Waynesburg "A" coal bed and prominent limestone beds above, can be seen in the east banks of Interstate Highway 70 near the Hays Avenue School, west side of Washington, Washington West quadrangle. At this locality the underclay contains *Spirorbis.*

The upper member is dominated by conspicuously laminated fine-grained sandstone and siltstone that contain several lobate bodies of thin-bedded partly crossbedded sandstone. The laminated sandstone characteristic of the member is shown in figure 4*C*. The Little Washington coal bed at the base of the member (lower part of fig. 4*C*) thins from northeast to southwest across the Washington area. The member has an average thickness of about 12 feet. The maximum thickness is 23 feet in the southeastern and northwestern parts of the area, and the minimum thickness is 3 feet at several places in the southwestern part. The upper member is similar in its relative thinness and in the pattern of elongate sandstones within it to both the upper member of the Uniontown Formation and the Fishpot Member of the Pittsburgh Formation. (Compare maps on pls. 3 and 4.) The upper member is exposed in two cuts of the Baltimore & Ohio Railroad in southwestern Washington: just east of the Interstate Highway 70 overpass; and at the east end of the cut just south of West Chestnut Street, 0.2 mile southeast of the Eighth Ward School, Washington West quadrangle.

PERMIAN SYSTEM

DUNKARD GROUP

WASHINGTON FORMATION

The Washington Formation includes the strata from the base of the Washington coal bed to the base of the Greene Formation. Descriptive data for the formation are listed in table 2. The thickness of the Washington Formation ranges from 215 feet in the southeastern part of the Washington area to 156 feet in the northwestern part (pl. 5), a rate of thinning of about 5 feet per mile. Limestone is the distinctive rock type (fig. 17*A*), and subdivision of the formation has been made to delineate the two main limestone bodies. The Washington was named by Stevenson (1876) for outcrops in and near the town of Washington and was redefined by Berryhill and Swanson (1962). Subdivisions are the lower limestone member, middle member, and upper limestone member.

Lower limestone member

"Limestone" has been a part of the name of the lower member since the original designation as "Lower Washington limestone member" (Stevenson, 1876). Subsequent detailed study has shown that mudstone is predominant in much of the Washington area; thus, use of "limestone" in the name is somewhat misleading. However, because limestone predominates at Washington (pl. 4, map *D*, section 2) and because several key beds of limestone near the top of the member are widespread, the lithologic term is retained. The Wasington coal bed, the basal stratum of the member, is stratigraphically the highest of the three thickest coal beds in the Washington area. Thickness of the bed is as much as 10 feet locally, but impurities of mudstone are abundant and widespread (pl. 8, map *H*). Above the coal bed, limestone is predominant in most of the central part of the Washington area (pl. 4, map *D*). The limestone changes to a mudstone to the east, south, and west. Tongues of sandstone extend into the Washington area from the northeast and from the northwest; the tongue of sandstone and associated siltstone near the northeast corner makes up the entire member in that area. The member, including the coal bed and overlying limestone beds, is exposed in the cut of the Baltimore & Ohio Railroad 0.2 mile southeast of the Eighth Ward School in southwest Washington, Washington West quadrangle. The sandstone that locally represents the member is well exposed in the north bank of the highway 0.25 mile west of Eightyfour, Washington East quadrangle. Small gastropods occur in the basal nodular limestone bed at many localities, including the Baltimore & Ohio Railroad cut in Washington.

Middle member

The middle member is made up of a lower, a middle, and an upper part. (See columnar sections on pl. 4, map *E*.) Individual rock units within the member characteristically thicken and thin over short distances.

The lower part of the middle member is the thickest of the three parts and has as distinctive components an impure but persistent unnamed coal bed at the base, a sandstone, and a limestone. The sandstone is a thick crossbedded unit in the west-central part of the Washington area but thins to the southeast, where the facies equivalent is siltstone and mudstone (pl. 4, map *E;* pl. 7, map *D*). The overlying limestone is commonly in two multibedded units separated by claystone, mudstone, or thin sandstone. A thick bed near the top of the uppermost unit is typically a breccia-conglomerate that weathers a distinctive yellowish orange. In the northwestern part of the Washington area the limestones merge to form a single unit that has a maximum thickness of 28 feet (pl. 4, map *E*, section 2).

The middle part of the middle member is marked by variation in thickness from about 50 to 90 feet. (See columnar sections, pl. 4.) The rock components range from massive crossbedded sandstone to mudstone. The sandstone is most prevalent in the western part of the Washington area (pl. 4, map *F*), where a thin coal bed at the base, locally and informally called the Washington "A," has a maximum thickness of 3 feet. Elsewhere the coal bed is carbonaceous mudstone and impure coal; locally it is absent.

The upper part of the middle member is distinguished by the thick laminated shaly mudstone and the locally associated thin coal bed at the base (Jollytown coal bed of Stevenson, 1876). The position of the prominent carbonaceous mudstone and locally associated thin coal, even where the rocks are deeply weathered, generally is marked by a profusion of fissile black mudstone fragments in the soil. The lithology above the carbonaceous unit varies from place to place, but sandstone seems to be the most persistent component. The thickness of the upper part ranges from about 8 to 30 feet.

A complete stratigraphic section of the middle member is nowhere exposed in the Washington area. Massive sandstone in the lower part of the member and overlying beds of limestone are exposed in the quarry 0.3 mile north of Interstate Highway 70 in the southwestern part of the Washington West quadrangle. In an excavation on the south side of U.S. Highway 40 near the northeast corner of the Amity quadrangle, the limestone that forms the top of the lower part is a single sequence. At this locality (pl. 4, map *E*, section 2) the thick conglomeratic bed contains small gastropods, and the base of the limestone is only 15 feet above the lower limestone member. The middle and upper parts (including the Washington "A" coal and the black shale that represent the Jollytown coal of Stevenson) are exposed 0.2 mile southeast of Lincoln Hill, Washington West quadrangle, in the banks of Interstate Highway 70.

UPPER LIMESTONE MEMBER

The upper limestone member is the most prominent limestone in the Washington area, both because of its widespread exposure and because of the relatively high $CaCO_3$ content. The distinctive feature is the dark-gray beds in the upper part that have a whitish coating where weathered. Where the member is covered by soil, its position is marked by rounded whitish limestone fragments 3–6 inches in diameter. In the west-central and southeastern parts of the Washington area, a tongue of mudstone, siltstone, and, locally, sandstone separates the member into two parts (pl. 4, map *F*).

The member is widely exposed in the Washington area. Prominent outcrops are in the quarries in eastern Washington and at Vance, and in the banks of Interstate Highway 70 both east and west of Washington, Washington East and Washington West quadrangles. The two sequences of limestone and the siltstone tongue between are exposed in the south bank of Interstate 70 one-half mile northeast of Highland School, near the southwest corner of the Washington West quadrangle. In the small, abandoned quarry just east of Interstate Highway 79, in the southwestern part of the Washington East quadrangle, the upper part of the uppermost bed in the member contains numerous fragmented fish remains.

GREENE FORMATION

The Greene Formation is not well exposed in the Washington area because of its generally fine grained character and because of its topographic position on hill tops at many places. Both factors tend to hasten disintegration of the rock by weathering. The lack of adequate measured sections and core-hole data, plus the extensive removal of the formation by erosion, precluded the compilation of special maps similar to those prepared for other formations.

The Greene Formation includes all strata of Permian age above the upper limestone member of the Washington Formation, and in the Washington area is a remnant of rocks that originally were much thicker and more extensive. The thickest part of the Greene (about 350 ft) is along the Nineveh syncline in the southern part of the Prosperity quadrangle. No geologic map has been prepared for the Prosperity quadrangle, but the distribution of the Greene is shown on the lithologic maps for the other three quadrangles (pls. 1, 2). The Greene is about 300 feet thick in the northwest quarter of the Amity quadrangle, but northward from there erosion has progressively removed the formation, and it is absent from the northern third of the Washington area.

The rock types and facies relations in the Greene Formation resemble those in the underlying formations of Late Pennsylvanian and Early Permian age, except that the rock units in the Greene are generally thinner and much more irregular in thickness and distribution. The limestones are very impure, and the few coal beds are thin and lenticular. The brecciated structure common in limestones of underlying formations is not common in the Greene Formation. The generalized sequences of rocks in the Greene Formation, as pieced together from scattered outcrops, are shown by the columnar sections that accompany the lithologic maps (pls. 1, 2). The sequences plotted from two core logs are shown in figure 18. The highly irregular distribution of rock types within the Greene is clearly demonstrated in figure 18. Visual correlation of the units in the two columns suggests that the general direction of thinning within the formation is north-northeastward.

Correlation of units within the Greene is extremely difficult because exposures are generally deeply weathered and the available core data are scarce. Several units were tentatively correlated: a coal bed in the lower part of the formation and four limestone beds labeled A, B, C, and D on the columnar sections that accompany the lithologic maps for the Washington East and Amity quadrangles. To facilitate discussion of the stratigraphic relations, the formation is here informally divided into six sequences on the basis of these five key beds. The six sequences as listed below carry no regional correlative connotation.

Sequence	
1	Base of the formation to the base of the Tenmile coal bed of Clapp (1907a, b).
2	Base of the Tenmile coal bed to the base of limestone A.
3	Base of limestone A to the base of limestone B.
4	Base of limestone B to the base of limestone C.
5	Base of limestone C to the base of limestone D.
6	Rocks above the base of limestone D.

Sequence 1 has an average thickness of 25 feet. In the Washington West and Washington East quadrangles it has at the base a persistent carbonaceous mudstone which characteristically weathers slabby; overlying the carbonaceous mudstone are beds of mudstone, siltstone, and sandstone. In the Amity quadrangle the basal strata are commonly mudstone or siltstone. The typical stratigraphic arrangement of the several types of rock in sequence 1 in the Washington West and Washington East quadrangles is shown in the upper part of figure 4*D*. A thin coal bed is at the base of the basal carbonaceous mudstone locally, and a conspicuous bed of slabby carbonaceous sandstone is associated with the mudstone and coal in outcrops along Interstate Highway 70 about half a mile east of U.S. Highway 19, Washington East quadrangle, and also in the bank across the road from the entrance to the Washington Cemetery, Washington West quadrangle.

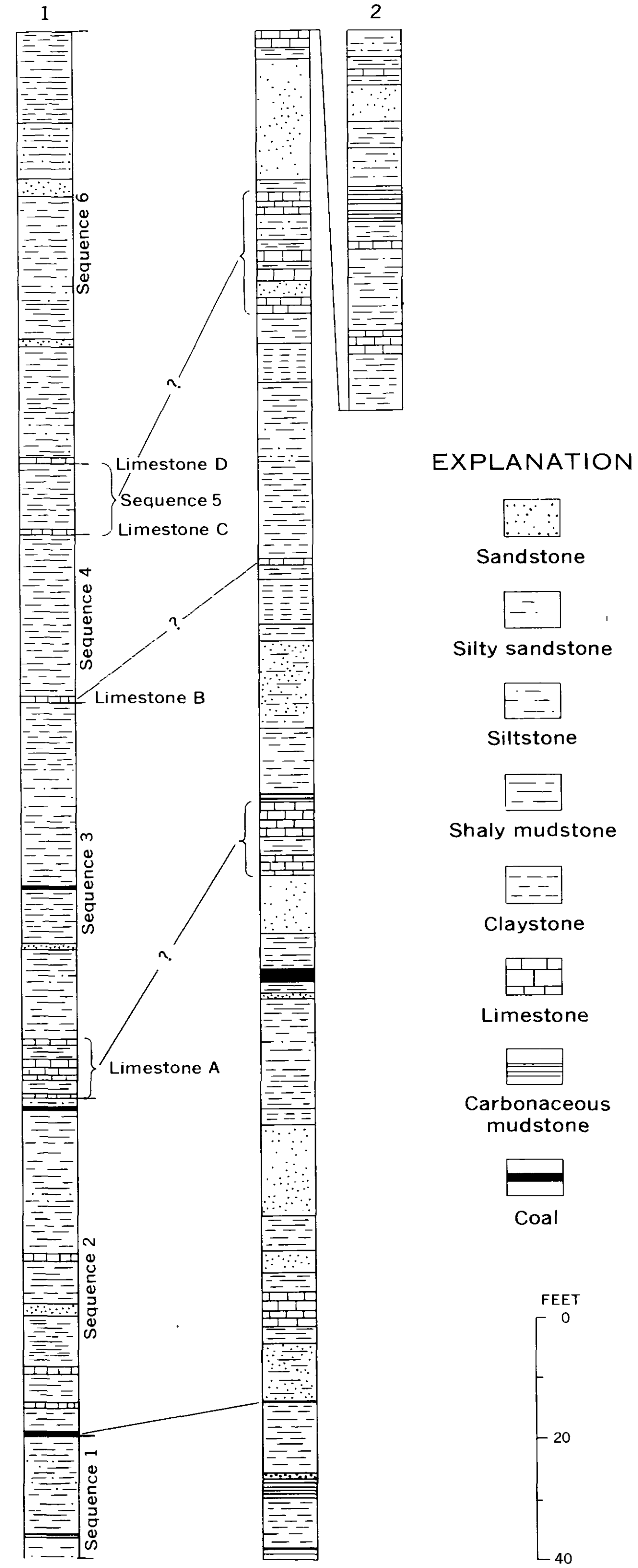


FIGURE 18.—Columnar sections of the Greene Formation, showing the lithologic sequence and the general lack of persistence of mappable rock units. Section 1 is from the NW¼ of the Amity quadrangle, and section 2 is 8 miles to the southwest, near the south-central boundary of the Prosperity quadrangle.

Sequence 2, which ranges in thickness from 45 to about 70 feet, has at its base the Tenmile coal bed (Clapp, 1907a, b), which is 1–2 feet thick and is overlain by mudstone, siltstone, sandstone, and limestone. The persistence and thickness of the Tenmile coal are greatest in the Amity quadrangle. Approximately the lower half of the sequence is siltstone containing lenses of impure limestone that grade laterally to shaly mudstone. The algal limestone that is 3–9 feet above the Tenmile coal bed is persistent in the Washington West and Washington East quadrangles. A local thin coal bed lies 50–60 feet above the Tenmile coal bed in the northwestern part of the Amity quadrangle.

Sequence 3 is about 25–40 feet thick, and its most persistent unit is limestone A, which lies at the base and has one to three beds. The rest of the sequence consists mostly of thin-bedded and locally crossbedded sandstone and siltstone that contain thin lenses of limestone and carbonaceous mudstone. The crossbedded sandstone is most extensive in the Washington West quadrangle. The carbonaceous mudstone in the upper part of the sequence is represented by a thin coal bed in the northwestern part of the Amity quadrangle. The sandstone units seem to be thinner in the Washington East and Amity quadrangles.

Sequence 4, which extends from the base of limestone B to the base of limestone C, ranges in thickness from about 35 to 60 feet. The order of lithologic sequence seems to vary from mostly sandstone to interbedded thin sandstone, siltstone, and mudstone that contain thin lenticular beds of limestone, coal, and carbonaceous mudstone.

Sequence 5 ranges in thickness from about 40 feet to about 55 feet. Limestone C is the most prominent unit in the sequence and has been recognized throughout the Washington area. Limestone C is typically a multibedded unit containing thin layers of claystone and mudstone; it may be equivalent to the Prosperity Limestone Member (Griswold and Munn, 1907). Rocks above are interbedded sandstone, siltstone, and mudstone containing in a few places thin beds of limestone.

Sequence 6 has at the base limestone D, which has been recognized in the Washington East and Amity quadrangles. Strata above seem to be mostly interbedded sandstone and siltstone containing thin lenses of mudstone and associated thin beds of limestone.

Fossils in the Greene are ostracodes, *Spirorbis,* and fish remains similar to those in underlying rocks; obstracodes are the most abundant fossil and are in nearly all the limestone beds. A few isolated specimens of gastropods in limestone are similar to those in older Upper Pennsylvanian and Lower Permian rocks. Scattered carbonized plant debris is in some of the mudstone units associated with thin coal beds. Many of the limestone beds have conspicuous laminations belived to represent algal-mat structure.

The Greene Formation, from the base to the siltstone above limestone C, is excellently exposed in the east banks of Interstate Highway 79 between Vance and U.S. Highway 40, Washington East quadrangle.

QUATERNARY SYSTEM

The unconsolidated sand and gravel and sporadic boulders along streams and stream valleys are the youngest deposits in the Washington area. These alluvial deposits, as well as numerous small composite alluvial-colluvial fans that have accumulated along the foot of slopes at the mouths of gullies, are presumed to be of Recent age. Local narrow terrace deposits above and adjacent to a few of the larger streams may be of Pleistocene age.

Landslide deposits are widespread in the Washington area. Most landslides are relatively small and are scattered along the ridge slopes.

Alluvium

Lenticular deposits of sand and gravel are most extensive along Chartiers, Little Chartiers, and Tenmile Creeks (pls. 1, 2). Maximum thickness of the alluvium is about 15 feet.

The colluvial material mixed with the flood-plain alluvium at the foot of slopes is largely angular fragments of rock that have been carried down the slope partly by surface erosion during heavy rains and partly by gravity creep. Thin patches of colluvium are common to all slopes, particularly those below prominent outcrops of either sandstone or limestone. The vegetal cover inhibits movement of this material, except during heavy rains.

Landslides

Masses of disturbed and intermixed soil and rock debris are common and range from a few tens of feet to half a mile in broadest horizontal dimension. Most of these landslides are on slopes underlain by the Washington and Greene Formations and are associated almost invariably with limestone units and adjacent mudstone. Some of the largest slides originate at or near the position of the upper limestone member, Washington Formation. Landslides in the Washington area are shown on the lithologic maps.

The disturbed material has moved largely by intermittent sliding during heavy rainfall. However, small scarps at the upper edge of some of these masses plus small crevices in them show that at times the material moved essentially as a body and can be properly called a landslide.

The landslides are mainly near accumulations of weathered clayey material that occur along the outcrops of limestone and associated claystone. During heavy rains and periods of prolonged rainfall the clay becomes saturated, and the limestone and clay move downhill. Because accumulations of weathered clay are largest at the thicker limestone units, these are the zones that have been most susceptible to sliding. However, some large slides have developed on thick units of mudstone that also are high in clay content. Where massive sandstone immediately overlies a limestone unit, the weight of the sandstone aids the sliding, and the sandstone contributes fragments to the mass.

All the landslides are probably of recent origin. Although some have been overgrown by trees and are largely stabilized, others are known to have moved during the last few years.

SUMMARY OF SEDIMENTATION AND PALEOGEOGRAPHY

Relation to regional paleogeography

Regionally, the Upper Pennsylvanian and Lower Permian sedimentary rocks of the Washington area are related to the large volume of sediments which accumulated in extensive shallow seas that covered much of the present area of the United States during late Paleozoic time. The general extent of the seas in central North America during Late Pennsylvanian time is shown in figure 19*A*. The sediments of the Appalachian basin were deposited in a very shallow swampy area that traditionally has been depicted as a northeastward extension of the epicontinental sea.

Since Permian time, rocks of Late Pennsylvanian and Early Permian age have been removed by erosion from large parts of central North America, and those in the Appalachian basin are now separated from the rocks of similar age in the central and western parts of the United States. The Upper Pennsylvanian and Lower Permian rocks of the Appalachian basin are confined to an elliptical area that covers several thousand square miles, principally in Ohio, Pennsylvania, and West Virginia. The major paleogeographic elements and the generalized lithofacies patterns relative to the Appalachian basin and to the Washington area are shown in figure 19*B*.

Paleogeography of the Washington area

The Washington area was near the center of the depositional basin and received sediments almost continuously during Late Pennsylvanian and Early Permian time (fig. 19*B*). Most of the area remained submerged, but surface features varied depending upon the type of sediment being laid down.

The nature and extent of the surface features during several stages of deposition are shown by the interpretative diagrams in figures 20 and 21. The diagrams are based on the lithofacies maps on plates 3 and 4, and they show the paleosurface suggested by the lithofacies pattern at a given stage of deposition. Figure 20 is taken from plate 3, maps *B* and *C*, and from plate 8, map *D*; figure 21 is taken from plate 4, maps *C*, *D*, and *E*, and from plate 8, map *H*.

Sandstone patterns

The bifurcating or distributary shape and the sinuous patterns of the thicker parts of sandstone bodies resemble channels of meandering streams and suggest either fluvial or deltaic deposition. The streamlike patterns of the sandstone bodies are shown in figure 22. However, two characteristics indicate that the sandstone bodies in the Washington area—which are but extensions of more extensive bodies—are not typical fluvial deposits: (1) the width of the lower part of each elongate sandstone body is considerably greater than that of normal stream channels, and the upper parts flare outward into broad sheets that lack the characteristics of flood-plain deposits; and (2) the sandstone units lack the extensive interwoven complex of braided and distributary channel deposits such as is formed by stream migration during building of a typical delta. These characteristics suggest that the sandstones

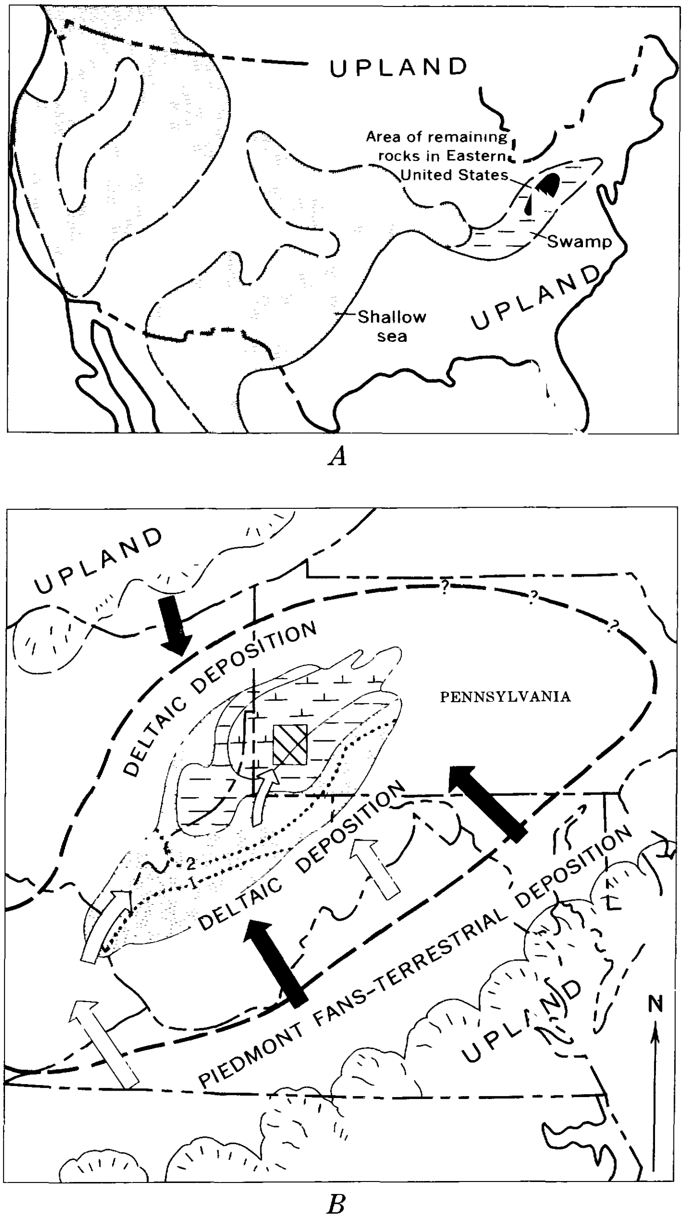


FIGURE 19.—Regional paleogeographic relations during Late Pennsylvanian and Early Permian time. *A*, Approximate extent of Late Pennsylvanian seas in central North America. Modified from Schuchert (1955). *B*, Paleogeographic elements in the Appalachian basin during Late Pennsylvanian and Early Permian time, and generalized lithofacies patterns of the rocks that remain. Heavy broken line outlines hypothetical area originally covered by Upper Pennsylvanian and Lower Permian sediments; black arrows indicate principal directions of sediment movement during Late Pennsylvanian time; white arrows indicate principal directions of sediment movement during Early Permian time; stippling indicates sandstone facies; broken lines indicate mudstone facies; bars and ticks indicate limy mudstone facies; lines of heavy dots indicate west and north limits of pebbly sandstone (1) during Late Pennsylvanian time, and (2) during Early Permian time. Modified from Arkle (1959) and Berryhill (1967).

were laid down in very shallow water as elongate subdeltas basinward from the mouths of streams.

The sandstone in each member represents the basinward extension of a stream-channel deposit; the thickest parts of each linear sandstone body represent the courses of the water which carried the sand. In their basal parts, many of the elongate sandstone bodies have angular fragments from the underlying mudstone and log casts which indicate that, during the initial stage of sand deposition, the heavily sediment laden water moved rapidly and scoured into underlying sediments. The channellike patterns of the elongate thicker parts of the sandstone bodies indicate also that the initial stage of sandstone deposition was regressive and that the shoreline prograded toward the center of the basin. The sandstones shown on maps *B*, *C*, and *D* of plate 6 represent the basinward termini of narrow deltaic lobes. That the positions of the courses for sand entering the basin did not change drastically with time is shown by the somewhat similar positions of the axes of elongate sandstone bodies in figure 22.

FEATURES OF LIMESTONE DEPOSITION

The waning of detrital deposition was probably accompanied by a rise in water level which caused a situation favorable for the deposition of calcium carbonate. As the depth of water increased, the shoreline receded, and only the very fine grained detritus reached the Washington area. The great lateral extent of many of the limestone units reveals the remarkable flatness and evenness of the basin floor. For example, the limestone in the Sewickley Member covers more than 4,000 square miles.

The sedimentary processes involved in limestone deposition can be interpreted from the two main features of the limestone—the conspicuous laminations in many beds, and the breccia-conglomeratic structure of others. The laminations are attributed to algal growth, and the breccia-conglomeratic structure, to frequent exposure of large parts of the basin as mud flats. The algae are believed to have grown as extensive mats. Rhythmic fluctuations in the growth pattern, possibly of a seasonal nature, caused the algal remains to accumulate in very thin layers that formed laminae. The breccia-conglomerate probably was formed in two stages—a drying up of parts of the basin, followed by renewed influx of water. Removal of water from the basin, presumably by evaporation, exposed extensive areas on the basin floor as vast mud flats, and desiccation cracks formed. (See fig. 10.) Some dry periods lasted only a brief period of time, but others were of sufficient duration to allow development of a small-scale karst surface. The lime mud hardened soon after the water evaporated, and during the longer periods of exposure a rubble of limestone fragments and powdery material was formed by mechanical weathering. Subsequent influx of water reworked and redeposited the limestone debris as an intrastratum breccia-conglomerate. (See fig. 13*B*.)

RELATION OF COAL THICKNESS TO LITHOFACIES PATTERNS

The coal represents metamorphosed plant debris that accumulated during times when extensive swamps existed and detrital sedimentation was at a minimum. The maps of the several coal beds on plate 8 indicate three things: the coal swamps were widespread; the amount of plant debris that was preserved varied from place to place; and the patterns of thickness of coal beds, including both the coal and the associated impurities, suggest that the courses for water entering the coal swamps apparently were generally similar to those during deposition of the sediments that lie between the coal beds. These general characteristics of the coal beds indicate, as might be assumed, that plant growth, or swamp development in a broad sense, did respond to physical conditions in the depositional basin, such as topography of the basin floor, position of drainageways, and depth of water.

An understanding of the relation of variations in coal thickness and in quality to the lithofacies patterns of associated rocks is important both in coal prospecting and in calculating resource tonnages. Correlations between coal-bed thickness and purity and lithofacies patterns of both the underlying and overlying rocks in the Washington area can be summarized as follows:

1. The trend of the thicker parts of the coal beds is normal to the trend of elongate sandstone bodies that lie beneath the coal, although the pattern is irregular. This feature is illustrated by the two maps in figure 23.
2. The coal beds are generally thickest where the associated sandstones also are thick. (See fig. 21.) The Pittsburgh, Waynesburg, and Washington coal beds are the best examples of this relationship.
3. The patterns of detrital impurities in the coal beds parallel the trends of underlying elongate sandstone bodies. For example, the parts of beds represented by carbonaceous mudstone either directly overlie the sandstone or lie above and to one side of the sandstone. Compare maps on plate 8 with those on plates 6 and 7.

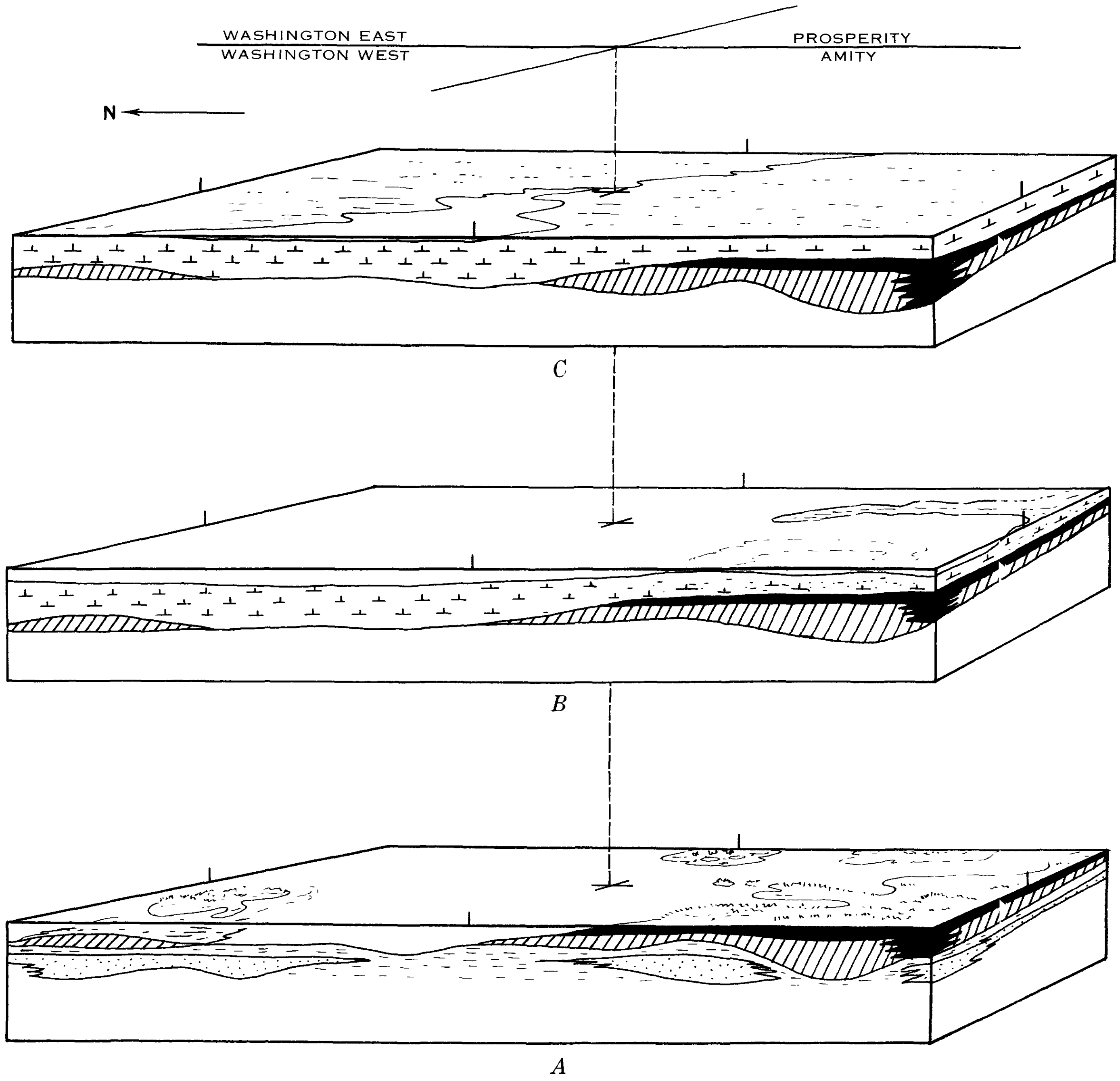


FIGURE 20.—Schematic diagrams showing surface features of the Washington area during three consecutive stages of sedimentation in Late Pennsylvanian time. Detritus was entering the area mainly from the east and southeast.

A, Area was part of a broad shallow bay or estuary fringed by swamps. (Sewickley coal swamp. See pl. 8, map *D*.) Carbonaceous mudstone and impure coal representing lower part of coal bed are composed of fine plant detritus carried in from swamps outside the area and indicate that depth of water was too great in the Washington area for plant growth during early stages of swamp development. Note that areas of plant growth overlie the previously deposited sandstone bodies of the Fishpot Member that seem to have formed shallow areas or shoals on the basin floor. (Compare map *H*, pl. 8, and map *B*, pl. 3.)

B, Area covered by water during deposition of the Sewickley Member. Rise in water level submerged the swamp and terminated plant growth. Shoals of limited extent probably lay in southeastern part of area above thickest part of Sewickley coal bed.

C, Area was largely an extensive mudflat. The numerous beds of breccia-conglomeratic limestone indicate frequent drying up of parts of the basin during deposition of limestone.

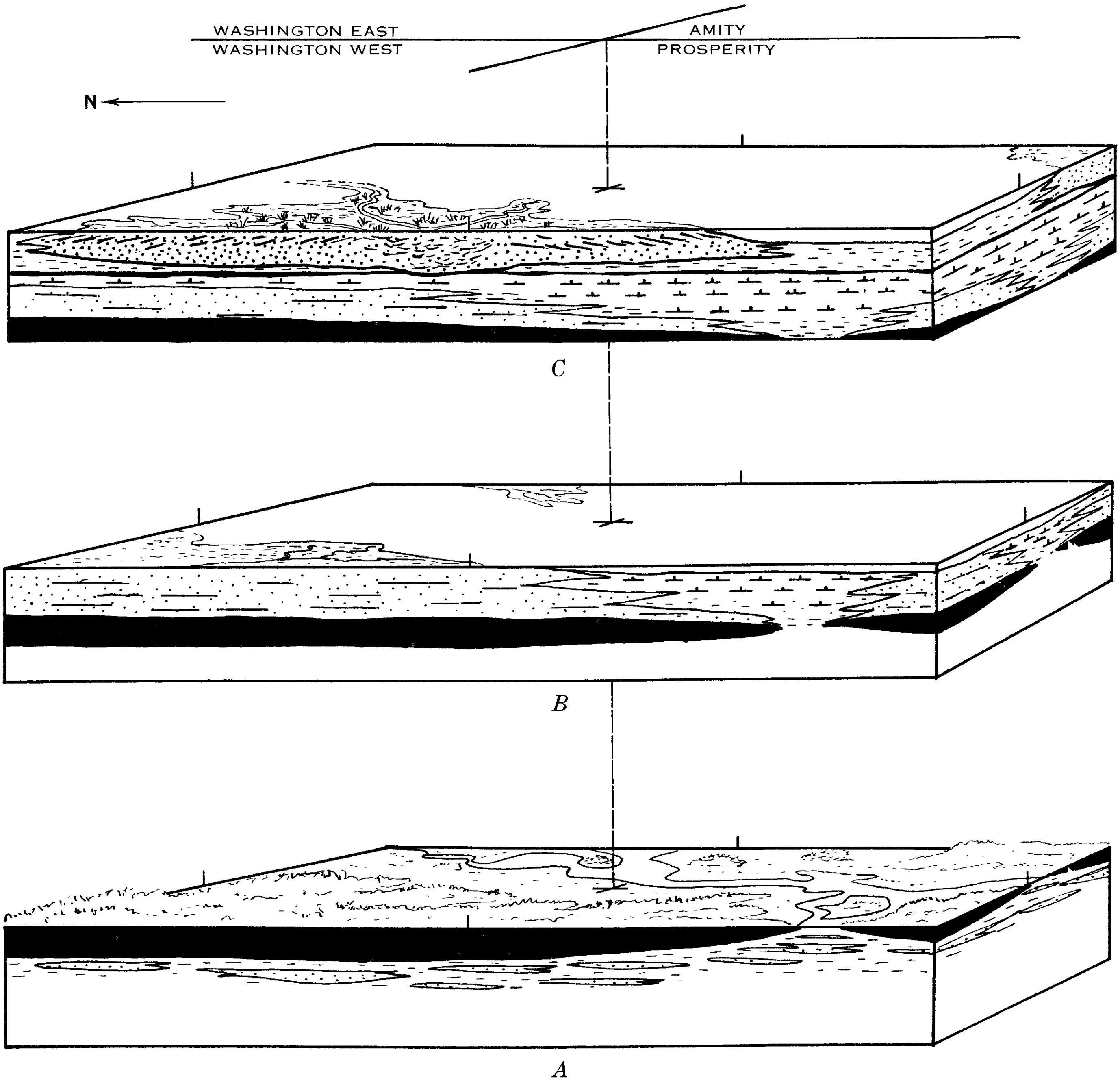


FIGURE 21.—Schematic diagrams showing surface features of the Washington area during three consecutive stages of sedimentation in Early Permian time. Detritus was entering the area mainly from the southwest and west but also from easterly directions.

A, Area was part of extensive swamp. (Washington coal swamp. See pl. 8, map *H*.) Large stream or bayou traversed the area from southwest to northeast. Plant growth was heaviest, and probably began, above the sandstone body in the underlying member that extended into the area from the northeast.

B, Area largely covered by water. Deltaic lobes extended into the area from the west and northeast. Limestone deposition was contemporaneous with sandstone and mudstone deposition over much of the area.

C, A prominent deltaic lobe extended into the area from the southwest, and the thick standstone of the middle member of the Washington Formation was deposited. Note that plant growth and accumulation was greatest in the west half of area and was associated with the basinward edge of a delta.

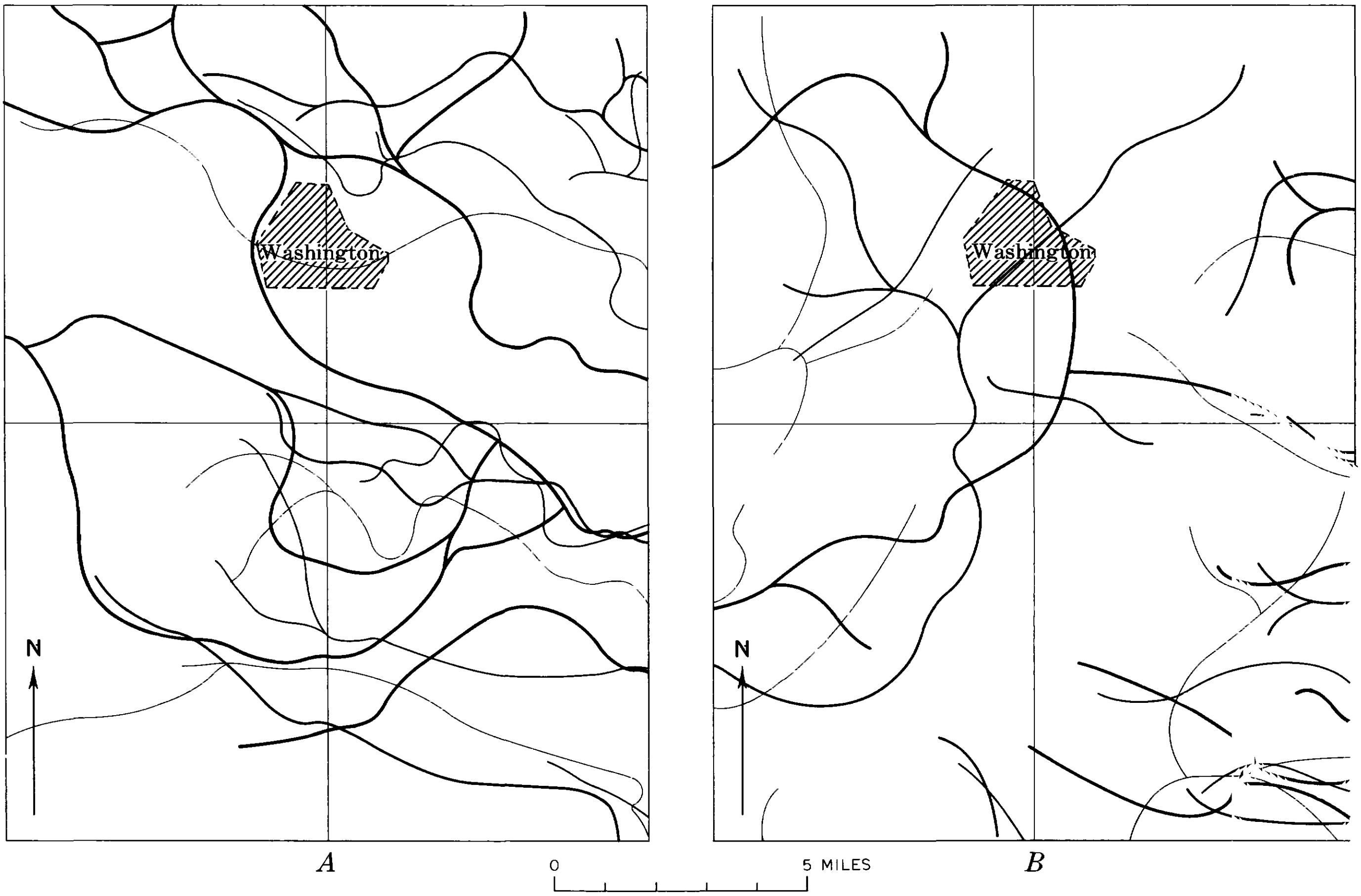


FIGURE 22.—Patterns of sandstone bodies in the several members, superimposed for comparison of geographic positions. Lines represent the thickest part of the sandstone in each member of the Uniontown and Pittsburgh Formations (*A*) and the Washington and Waynesburg Formations (*B*). Note the distributary and meandering patterns and the northwestward orientation in the western part of the area during Washington and Waynesburg time.

ENVIRONMENTAL INTERPRETATION

Tectonically, the Washington area during Late Pennsylvanian and Early Permian time was a part of a large subsiding basin. The rate of subsidence was barely sufficient to accommodate the detritus being carried to it.

The environment was an extensive shallow lake, probably comparable in size to present Lake Michigan or perhaps even larger, that was at times a vast swamp and at other times dried up almost completely. Depth of water probably never exceeded a few feet. Neither fossil evidence nor physical properties of the rocks indicates any influence of marine conditions. Water flowed into the lake from adjacent land that lay both to the north and to the east, and the inflow was sufficient to maintain some water in the lake most of the time. Rocks of contemporaneous age in the central part of the United States (fig. 19*A*) are wholly, or at least partly, marine; and drainages from the large lake-swamp area of the central Appalachians were presumably to the southwest into the epicontinental sea. However, the lithofacies relations, particularly the position of the pebbly sandstone at the southwest end of the basin, suggest that during Early Permian time the drainage from the basin was not southwestward but may have been northeastward.

STRUCTURE

Folds.—Rocks of the Allegheny region have been folded into a series of gentle flexures whose axes trend northeastward across the Washington area. The folds, from west to east, are named as follows: Claysville anticline, Finney syncline, Washington anticline, Nineveh syncline, and Amity anticline. The fold axes are shown on the lithofacies plates, and the geometry and amplitude of the folds are shown by the structure contours on the lithologic maps (pls. 1, 2).

Viewed in cross section the folds are generally symmetrical, but in plan view the axes are sinuous, and the flanks are irregular. In the Washington area the anticlines plunge gently southwestward, and the synclines plunge northeastward. The amplitude of folding, from the trough of the Nineveh syncline to the crest of the Washington anticline, is 400 feet within a distance of 5¾ miles; generally the dip of the rocks is less than 1°.

Age of folding.—The sedimentary patterns, including those of both thickness and shape, of rocks in the Washington area show little if any adherence to the structural patterns. The thickest parts of some members overlie the anticlines, and the trend of linear sandstone bodies in the Pittsburgh and Uniontown Formations is approximately perpendicular to the trend of the structural axes. (See pl. 6.) Thus, the distribution of sand was not influenced by folding during deposition. The thickness patterns of the Waynesburg and Washington Formations have no relation to the position of fold axes, but the trend of rock in these formations is approximately parallel to that of the folds. This crude parallelism is probably coincidental and not a result of any structural influence.

In terms of geologic time, deformation of the depositional basin took place either in very late Early Permian time or later.

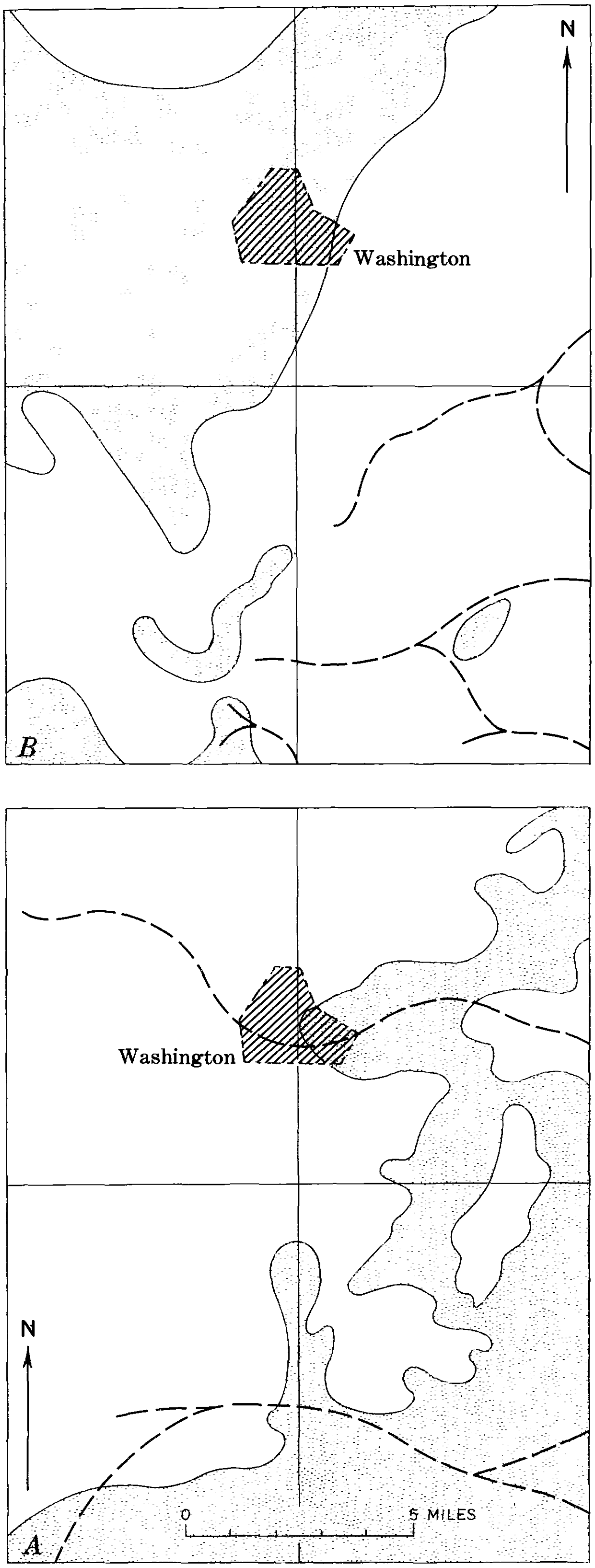


FIGURE 23.—Generalized thickness trends in the Waynesburg and Washington coal beds, showing irregular trend of the thickest parts of the bed normal to the trend of underlying elongate sandstone. *A*, Waynesburg coal bed. *B*, Washington coal bed. Stippled areas are those parts of the bed more than 5 feet thick. Heavy dashed lines represent the axes of the underlying elongate fluvial sandstones. The trend presumably roughly parallels the shoreline trend along the east side of the depositional basin.

Part 2. Economic and Engineering Geology

ECONOMIC GEOLOGY

The discussion of economic geology covers the commodities coal, sandstone, limestone, and mudstone. Oil and gas have been produced from the Washington area since the 1880's, but the production has been from rocks that underlie the Pittsburgh coal bed, which are beyond the scope of this report. A regional subsurface study of the oil-bearing rocks of southwestern Pennsylvania is being conducted by the Pennsylvania Bureau of Topographic and Geologic Survey.

USE OF THE SPECIAL MAPS

The maps have been prepared for use in relating the geology of the Washington area to the area's economic development. The lithologic maps (pls. 1, 2) are designed for use in both commodity and engineering geology. Because these maps show the location and distribution of the types of rock, they can serve as guides to prospecting, both on the surface and at depth. The thickness of most types of rock generally can be determined within about 10 feet of actual thickness; the lines representing the more important coal beds have been coded to show in a generalized manner the variations in thickness. The patterns representing types of rock have been placed on a topographic base so that the bedrock can be related to the terrain for engineering planning. A brief summary of the engineering properties of the rocks is included on the lithologic maps.

The lithofacies maps (pls. 3, 4) are supplemental to the lithologic maps. They show the lateral change in composition, texture, and thickness of individual rock units.

The sandstone thickness maps (pls. 6, 7) show the geometry of the individual sandstone bodies in each member, and they also are supplemental to the lithologic maps. These maps can be used for studies of the movement of subsurface water, the disposal of liquid wastes, and the sources for potable water. Where massive sandstone directly overlies a coal bed, the coal bed may be cut out locally by the sandstone, a factor which creates an economic problem in mining. Both the sandstone isopach maps and the lithofacies maps can be used in relating mine subsidence to the nature of the overlying rock.

The coal-bed maps (pl. 8) are lithofacies maps that show the thickness patterns of the coal beds and the lateral variations in their composition. These maps are designed for use in appraising the quantity and quality of the resources in a bed and as guides to detailed prospecting.

COMMODITY GEOLOGY

COAL RESOURCES

The stratigraphic positions of the 17 coal beds that crop out in the Washington area are shown by the columnar sections on plates 1 and 2. The geographic positions of the coal beds at the surface are shown on the lithologic maps (pls. 1, 2). Of these coal beds, only the Pittsburgh, which contains by far the largest quantity of resources, is now mined commercially. The Waynesburg coal bed also contains sizable resources, but it has not been mined commercially in the Washington area. The Waynesburg "A" and Washington coal beds underlie most of the area, but both, although locally thick, are highly variable in thickness and contain impurities to the extent that they are not likely to be mined in the foreseeable future. The Sewickley and Uniontown coal beds are absent from large parts of the Washington area; they are generally thin and commonly contain more clay and mudstone than coal. Maps and columnar sections showing the thickness of these six coal beds and the relative amounts of coal and impurities in them are on plate 8.

Resources were calculated for the Pittsburgh and Waynesburg coal beds. Original resources of coal in these two beds in the Washington area total 1,959.5 million tons, of which 1,688.6 million tons is classified as "measured," 166.2 million tons as "indicated," and 104.7 million tons as "inferred." Included in the 1,688.6 million tons of measured coal is 197.5 million tons of coal mined and lost in mining; thus, the remaining measured resources as of January 1, 1966, total 1,491.1 million tons.

Remaining measured resources of 1,491.1 million tons plus indicated resources of 166.2 million tons and inferred resources of 104.7 million tons give total remaining resources of 1,762 million tons as of January 1, 1966.

Table 3 shows the distribution of the resources for the Pittsburgh and Waynesburg coal beds within the four quadrangles that make up the Washington area, and the classification of the resources as to thickness and reliability of data upon which the estimates are based. Measured resources are those for which tonnage is computed from the thickness of the coal bed revealed in outcrops, trenches or prospect openings, mine workings, and drill holes. Points of observation are so closely spaced and thickness and extent of coal so well defined that computed tonnage is considered to be within 20 percent of true tonnage. Although spacing of points of observation necessary to demonstrate continuity of coal varies in different regions according to character of the coal beds and geologic structure, points of observation are, in general, about half a mile apart. In the Pittsburgh coal bed, the continuity of the coal has been demonstrated over such a wide area that almost all the resources are classified as measured, even though the spacing of data points is more than half a mile in some parts of the Washington area. Indicated resources are those for which tonnage is computed partly from specific measurements and partly from assumptions based on available data and on geologic evidence. Points of observation should be about 1 mile apart; however, if the beds are known to have continuity, points spaced 1½ miles apart are considered adequate control for indicated resources. Inferred resources are based on a broad knowledge of the character of the coal bed, on evidence of continuity, and on points of observation spaced more than 2 miles apart. In calculating tonnages for the Pittsburgh and Waynesburg coal beds, a weight of 1,800 tons per acre-foot was used.

PITTSBURGH COAL BED

Resources.—Original resources of coal in the Pittsburgh bed total 1,384.7 million tons, of which 1,301.7 million tons is classified as "measured" and 83 million tons as "indicated" (table 3). Included in the 1,301.7 million tons of measured coal is 197.5 million tons of coal mined and lost in mining; thus, the remaining resources as of January 1, 1966, total 1,104.2 million tons. The map on plate 8 shows the areas in which the Pittsburgh coal bed has been largely mined out.

Remaining measured resources of 1,104.2 million tons plus the indicated reserves of 83 million tons give total remaining resources of 1,187.2 million tons, as of January 1, 1966.

Physical characteristics.—The Pittsburgh coal bed generally occurs as two benches separated by a clay parting that ranges in thickness from about 3 inches to 2 feet. The lower bench, which ranges in thickness from about 4 feet to slightly more than 8 feet, forms the main part of the bed and contains all the minable coal. The resource tonnages in this report are based entirely on the lower bench. (See table 3.) The impure coal in the upper bench, which is left as roof during mining, is 0–5 feet thick.

General uniformity in thickness and areal continuity of thin partings characterize the Pittsburgh coal bed throughout the Washington area. Three maps on plate 8 show the distribution and thickness of the coal in the lower and upper benches, and the thickness of the clay parting between the two benches. No clear pattern of changes in thickness of the lower bench can be seen, though there is a suggestion of a northeastward trend. The structural irregularities

TABLE 3.—*Estimated original and remaining resources of coal, in millions of short tons, in the Pittsburgh coal bed and the Waynesburg coal bed in the Washington area, by quadrangle*

Quadrangle	Measured: In beds of indicated thickness, in inches				Measured: Total tonnage	Indicated: In beds of indicated thickness, in inches				Indicated: Total tonnage	Inferred: In beds of indicated thickness, in inches				Inferred: Total tonnage	Total original resources	Total mined and lost in mining as of Jan. 1, 1964	Total remaining resources as of Jan. 1, 1964
	14–28	28–42	42–60	>60		14–28	28–42	42–60	>60		14–28	28–42	42–60	>60				
Pittsburgh coal bed (Estimates are of coal in the lower bench only; upper benches or "roof coal" excluded)																		
Amity			20.6	342.3	362.9											362.9	76.0	286.9
Prosperity			38.3	294.6	332.9											332.9	2.6	330.3
Washington East			36.0	306.7	342.7											342.7	60.0	282.7
Washington West		0.8	18.2	244.2	263.2				83.0	83.0						346.2	58.9	287.3
Total		0.8	113.1	1,187.8	1,301.7				83.0	83.0						1,384.7	197.5	1,187.2
Waynesburg coal bed																		
Amity	0.4	60.0	114.2	17.8	192.4	5.4	12.7			18.1						210.5		210.5
Prosperity	42.6	16.4			59.0	7.5	16.8	0.8		25.1						84.1		84.1
Washington East	5.6	28.0	81.4		115.0	9.5	18.1			27.6	4.3	15.1			19.4	162.0		162.0
Washington West	20.5				20.5	12.4				12.4	9.6	75.7			85.3	118.2		118.2
Total	69.1	104.4	195.6	17.8	386.9	34.8	47.6	0.8		83.2	13.9	90.8			104.7	574.8		574.8

of the bed are shown by structure contours on plates 1 and 2.

Coal in the Pittsburgh bed is believed to be of high-volatile A bituminous rank throughout the Washington area. So few analyses were available for use in this report that the variations in ash and sulphur content and the heating or Btu values of the coal could not be studied in detail. The limited data available indicate that the range in heating value is 13,600–14,800 Btu, on the "as received" basis; the ash content ranges from about 4.5 to 8 percent and averages about 6 percent; and the sulphur content ranges from less than 1 percent to slightly more than 2 percent. In adjacent areas to the north and east, the Pittsburgh bed contains coal of coking quality (Wallace and others, 1955), and the reserves of the Washington area can be assumed to be of coking quality also.

Sandstone cutouts.—Sandstone overlies the Pittsburgh coal bed in most of the Washington area. (See pl. 6.) The base of the massive crossbedded sandstone is uneven, and its position relative to the underlying coal bed is variable. Throughout most of the Washington area a few feet of siltstone and shaly mudstone separate the base of the sandstone from the coal bed, but locally the base of the sandstone is within the coal bed, and at a few places on the rocks beneath the coal. Places where the sandstone thickens downward and replaces all or part of the coal are called cutouts.

A cutout indicates local removal of the peat or coal bed by erosion during deposition of the overlying sandstone, either by subaqueous scour or by stream channeling. Large or closely spaced cutouts seriously affect the economics of mining because they are costly impediments to a mechanized mining operation. The general positions of known cutouts in the Washington area are shown for the Pittsburgh coal bed on plate 8.

Cutouts are less common in the lower bench of the bed in the Washington area than in the upper bench. A geographic correlation exists between the position of cutouts and the thicker elongate, channellike parts of the overlying sandstone; the correlation is based on a comparison of the maps on plate 8 with the sandstone map of the lower member and Redstone Member on plate 6. Consequently, a thorough knowledge of the regional thickness pattern of the sandstone is a valuable aid in planning mine layouts, because areas underlain by the thick linear parts of the sandstone could be drilled to determine whether or not cutouts do exist.

The relation of the cutouts in the Pittsburgh coal bed to the distribution of the sandstone above, and the relation of the thickness and distribution of the other coal beds in the Washington area to the rocks immediately above and below, can be used as a valuable aid in both prospecting for coal and planning mine layouts.

WAYNESBURG COAL BED

Resources.—Original resources of coal in the Waynesburg bed total 574.8 million tons, of which 386.9 is classified as "measured," 83.2 million tons as "indicated," and 104.7 million tons as "inferred" (table 3). Because the Waynesburg bed has not been mined commercially, little coal has been removed, and remaining resources can be considered the same as original resources. The Amity and Washington East quadrangles contain much larger resources than the Prosperity and Washington West quadrangles.

Physical characteristics.—The Waynesburg coal bed is in two benches separated by a persistent clay parting in the eastern half and the west-central part of the Washington area. The clay parting, which generally ranges in thickness from 2 to 15 inches, is absent from the southwestern and northwestern parts. (See pl. 8.) The lower bench is the thicker of the two benches and contains the larger resources. Another clay parting, ranging in thickness from a fraction of an inch to 8 inches, is common, though not everywhere present, in the lower part of the lower bench. The upper bench generally contains a number of very thin partings. Sections 6 and 7 for the Waynesburg coal bed on plate 8 are typical of the bed in the eastern part of the Washington area and in areas to the east.

Coal from the Waynesburg bed is probably high-volatile B bituminous rank, though some may be high-volatile A. The coal in the lower bench is superior in quality to that in the upper bench. Ash content averages more than 10 percent, and sulfur content, more than 2 percent. No analyses of heating value are available for Waynesburg coal from the Washington area, but two analyses made on this coal from outside the Washington area (Wallace and others, 1955), indicated heating values of 12,460 Btu and 12,090 Btu.

SANDSTONE

Sandstone from the Washington area was formerly quarried and used locally for building stone and as flags for sidewalks. The lower sandstone of the middle member, Washington Formation, was quarried near the southwest corner of the Washington West quadrangle (pl. 1) for building stone used in Washington and is reported to have been used to construct the train terminal in Wheeling, W. Va. Flags used to pave sidewalks in Washington came from a quarry in the lower member of the Uniontown Formation at the northeast edge of Washington. According to Clapp (1907b, p. 129), a sandstone about 130 feet above the base of the Greene Formation was quarried about 1 mile east of Washington for building and curbing stone. As far as could be determined, most of the commercial sandstone came from these rock units, but other sandstones doubtlessly have been used locally. These sandstones have not been used as a commercial building stone in the Washington area for the past 50 years, mainly because they are too friable and they weather too rapidly.

In recent years, sandstone from the quarry near the southwest corner of the Washington area has been used in highway construction. The base course for a 10-mile stretch of Interstate Highway 70, extending westward from Washington, came from that quarry.

LIMESTONE

Limestone has been used more extensively than sandstone in the Washington area and was used rather widely in previous years as a building stone. Clapp (1907b, p. 118) reported that limestone from the thick sequence in the Sewickley Member was used for making cement. In addition to building stone, limestone from the upper limestone member of the Washington Formation was used extensively by farmers for making agricultural lime. Recently, limestone from the upper limestone member was taken from the quarry at Vance, Washington East quadrangle (pl. 1), for use as the base course for a stretch of Interstate Highway 70 east of Washington.

In quantity, limestone is an abundant resource in the Washington area. The quality, however, is relatively lower than that of limestone currently used for commercial purposes. The $CaCO_3$ content of most is less than 65 percent, though the $CaCO_3$ content of the uppermost beds of the upper limestone member, Washington Formation, locally is more than 90 percent.

The limestones of the Washington area will have commercial value when resources of purer limestones elsewhere become scarce. The widespread upper limestone member of the Washington Formation seems most promising for future use, as it can be stripped at the surface over large parts of the area. The thick limestone in the Sewickley Member is a potential source for cement, but the amount of clay and silt impurities varies from place to place, and the product would require special preparation.

MUDSTONE AND CLAYSTONE

Mudstone is an abundant resource in the Washington area. Several units in the Greene Formation are widespread and thick. The mudstone unit in the upper part of the middle member, Washington Formation, and associated claystone and siltstone, is quarried for making brick at two localities in the Washington East quadrangle—in the east part of Washington and at Vance (pl. 1). The mudstone commonly contains thin beds of siltstone. Claystone is not abundant and units are lenticular. The general stratigraphic and geographic location and distribution of mudstone are shown on plates 3 and 4.

Samples of two mudstone units and a claystone were collected by B. J. O'Neill, Jr., of the Pennsylvania Bureau of Topographic and Geologic Survey, for a series of analyses and tests to determine the commercial potential. The units sampled, their location, and the evaluation of the material on the basis of the tests are summarized as follows:

Description of unit	Sample location	Evaluation
Claystone 8 ft thick; 100 ft above base of Greene Formation.	Washington West quadrangle, north side of Interstate Highway 70, 6 miles southwest of Washington and 0.35 mile north of Highland School.	Has long firing range and probably would make an excellent lightweight aggregate by the rotary kiln process.
Mudstone and siltstone 14 ft thick; lower part of middle member, Washington Formation.	Washington West quadrangle, on hill slope 0.4 mile west of Reservoir 1 and 0.4 mile south of Elwood Park.	Potential use for brick, floor tile, and sintered aggregate.
Mudstone and siltstone 6½ ft thick; upper part of middle member, Washington Formation.	Donley Brick Co. quarry, north side of U.S. Highway 40, eastern part of Washington.	Potential use as brick and floor tile and possibly for sintered aggregate.

Detailed data obtained from the tests are given in O'Neill and others (1965, p. 337–350).

ENGINEERING GEOLOGY

Washington County is one of six counties in southwestern Pennsylvania that are a part of or adjacent to the greater Pittsburgh metropolitan complex. These counties are economically interdependent and, for purposes of regional planning, have formed the Southwestern Pennsylvania Regional Planning Commission, whose functions include studies of present and future land use.

Washington and environs constitute the largest population center in Washington County. As population grows in future years, much of the remaining agricultural land in the Washington area will be converted to residential, industrial, commercial, and recreational uses. Efficient use of land is as important an aspect of economic development as the extraction of mineral resources.

Knowledge of the bedrock and its relation to topography can be a valuable aid in land-use planning. In the Washington area, recognition of the lithologic diversity and complexity of the overall rock sequence is of fundamental importance. The rocks vary greatly as to bearing strength and stability, which are dependent in part on the degree of weathering. Because weathering is influenced by the manner in which ground water will percolate through a rock, it is important to know the porosity and permeability of the particular body of rock and its thickness and relation to topography (ridgetop, slope, or valley).

No attempt is made to interpret the data from an engineering standpoint nor to evaluate specific sites. The intent is to present the geologic data in a manner that will enable the engineer, the builder, the city planner, or the conservationist to select, from the maps, favorable sites for further investigation in the detail dictated by the intended use of the land. The descriptions of both the physical properties of the rocks and their stratigraphic relations in preceding sections of this report and the lithofacies and discrete sandstone maps (pls. 3–7) are complementary to the descriptions of engineering properties in this section, and the data from the two parts of the publication should be used together.

The report describes the bedrock. A report on the engineering properties of the soils above the bedrock in the more heavily urbanized parts of Washington County was prepared by the U.S. Department of Agriculture, Soil Conservation Service (1966). The distribution of the several types of bedrock in the Washington area and a brief explanation of the economic potential and engineering properties are shown on the lithologic maps (pls. 1, 2).

ENGINEERING PROPERTIES OF THE ROCKS

Sandstone and siltstone.—Total porosity, permeability, and compressive-strength tests were made on surface samples from four sandstone bodies (table 4).

The sandstones sampled have relatively low permeability, but both porosity and permeability vary not only from one sandstone body to another but also within a single body because of variations in grain size, thickness of beds, and internal sedimentary structures. Some indication of the amount of this variability is shown by the test data for samples 63PA1 and 63PA2 (table 4). Sample 63PA1 is fine grained, and its porosity and permeability are very low; sample 63PA2 is coarser grained, and the porosity and permeability are higher. The tests, however, do not take into account major bedding planes

TABLE 4.—*Physical and hydrologic properties of sandstone*

[Analysts: compressibility strength tests by T. C. Nichols, G. S. Erickson, and J. C. Thomas; hydrologic-properties and specific-gravity tests by R. P. Moston and A. H. Ludwig.]

Field No.	Lab. No.	Location and formation	Specific gravity	Dry unit weight (g per cu cm)	Centrifuge moisture equivalent (in percent)	Total porosity (in percent)	Specific yield (in percent)	Permeability (gpd per sq ft)	Compressive strength (lbs per sq in)
63PA1	(3–443)	NW¼, Washington East quadrangle, Pittsburgh Formation.	2.68	2.35	3.6	12.3	3.8	0.001	13,800
63PA2	(3–553)	NW¼, Washington East quadrangle, Uniontown Formation.	2.68	2.20	4.4	17.9	8.2	.03	11,900
63PA3	(3–552)	Central part of Amity quadrangle, Waynesburg Formation.	2.69	2.31	3.8	14.1	5.3	.002	12,400
63PA4		SW¼, Washington West quadrangle, Washington Formation.	2.68	2.28	3.4	14.9	7.1	.02	10,200

TABLE 5.—*Atterberg limits, pH, and potential volume change for representative samples of mudstone, claystone, and landslide material*

[Analysts: T. C. Nichols, G. S. Erickson, and J. C. Thomas, U.S. Geological Survey, Denver, Colo.]

Laboratory No.	Sediment	Atterberg limits			pH	Potential volume change (P.V.C.)	
		Liquid limit (L.L.)	Plastic limit (P.L.)	Plasticity index (L.L.-P.L.)		Swell Index (psf)	Rating[1]
D-800294	Silty mudstone	27	24	3	7.51	1,700	2, marginal.
D-800296	Mudstone	24	20	4	7.80	1,100	1.2, noncritical.
D-800295	Claystone	30	20	10	7.70	2,000	2.4, marginal.
D-800297	do	33	24	9	7.50	2,350	2.5, marginal.
D-800298	Landslide material	27	15	12	5.12	425	.3, noncritical.
D-800299	do	36	26	10	4.61	1,000	1.1, noncritical.

[1] Rating according to specifications of Federal Housing Administration as contained in manual by Lambe (1960). Scale of rating: 0–2, noncritical; 2–4, marginal; 4–6, critical; 6–12, very critical.

and joints or fractures within the sandstone that would permit passage of water through the body at a greater rate than that indicated by the permeability tests.

Jointing, where developed extensively, substantially increases the permeability of a sandstone body. Joints were noted in many of the outcrops of sandstone. (See fig. 4*D*, which shows joints in the sandstone in the upper part of the photograph.) Although no systemic study of jointing was made, jointing is believed to be sufficiently extensive to increase the movement of subsurface water in most sandstone bodies.

Siltstone, which is finer grained than sandstone, generally has less porosity and permeability. No tests were made on siltstone, but, just as in sandstone, the bedding planes and joints at a given locality would greatly influence permeability.

Mudstone and claystone.—Swell-index, plasticity-index, and weathering and abrasion tests were made on mudstone and claystone samples (table 5). Similar tests were made on samples of intermixed mudstone and claystone from two landslides, and the results are included in table 5 for comparison with undisturbed mudstone and claystone.

Weathering and abrasion tests were made on eight samples of mudstone and claystone. Results of these tests for one sample (D-800294; table 5) are shown by the series of profiles in figure 24; the results of the tests on the other seven samples were so similar that they need not be illustrated separately. The tests demonstrate the effect of compactive forces and of repeated wetting and drying cycles upon the disaggregation of particles in unconsolidated material. Comparison of profiles 3, 4, and 5 in figure 24 shows that the effect of the single compactive force is almost equivalent to four cycles of wetting and drying.

The porosity and permeability of mudstone and claystone are very low; claystone has almost no permeability. The permeability of mudstone may be increased by joints, but any fractures in claystones are ephemeral because of the plastic nature of claystone when wet.

Limestone.—Specific-gravity and compressive-strength tests were made on samples of limestone from three stratigraphic units (table 6). The characteristics of samples 3–550 and 3–548 are believed to be typical of most limestones in the Washington area. Sample 3–549 is from the limestone of the Sewickley Member, which is relatively higher in clay and silt impurities than most of the other limestones and has noticeably less bearing strength.

Porosity and permeability tests were not made. The permeability of individual limestone beds is relatively high becouse of numerous joints. (Fig. 4*D* shows the many joints in the limestone beds in the lower part of the picture.) However, the vertical movement of water through the limestone bodies is greatly impeded by the claystone layers that separate the beds of limestone. Some of the major springs are at or near the top of limestone bodies that underlie sandstone.

The impermeability of both limestone and mudstone has implications concerning residential development. Homes built beyond municipal sewage service require a cistern. If the near-surface bedrock is a thick limestone or mudstone body, no natural capacity exists for dispersing the discharged waste. In such places the reservoir from which sewage water is to be dispersed should be of larger than normal size to allow an adequate fill of crushed, permeable material. Furthermore, dispersal reservoirs placed in a thin sandstone that overlies a limestone-clay sequence will disperse the waste, but the discharged water may percolate downward to the limestone and

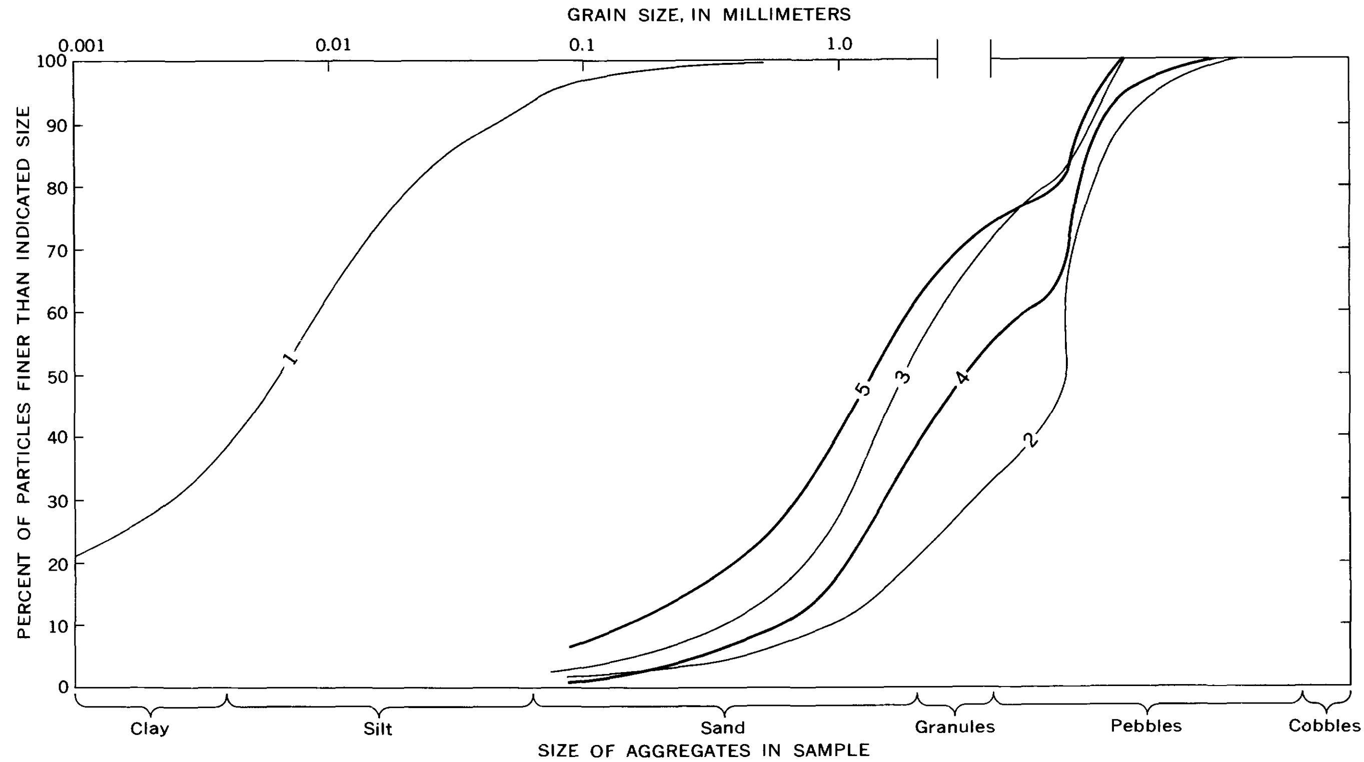


FIGURE 24.—Results of weathering and compaction tests on a sample of silty mudstone. Data are in cumulative percent. Profile 1, Grain-size distribution of disaggregated sample after sieving. Profile 2, Distributed size of aggregates as dug from outcrop. Profile 3, Distributed size of aggregates after hammer test (equivalent to theoretical effect of a single passage of a bulldozer weighing 30 tons). Profile 4, Distributed size of aggregates after one wetting-and-drying cycle. Profile 5, Distributed size of aggregates after four cycles of wetting and drying.

then move laterally to form a seepage of contaminated water along hillsides.

Landslide material.—Much unconsolidated debris that exists on hill slopes in the Washington area has been moved by slumping and sliding. The locations of many of these landslides are shown on plates 1 and 2. The clay content of the material is high, and the mass is characterized by relatively high porosity and low permeability. The capacity of the material to absorb large amounts of water that cannot pass with ease through it causes slumping or sliding during prolonged wet periods or following heavy rains because of the increased weight and pore pressure caused by the accumulated water. Landslides emit water for long periods following saturation and are sites for seepage. The roadbeds of dirt roads that cross landslide material are usually soft and muddy, particularly during the winter months and after heavy rains. Where roads are paved, the prolonged seepage eventually may induce pumping of the pavement which will cause cracking and failure of the pavement because of the soft, plastic base beneath it.

TABLE 6.—*Physical properties of limestone*

[Analysts: T. C. Nichols, G. S. Erickson, and J. C. Thomas]

Lab. No.	Stratigraphic unit	Specific gravity	Compressive strength (psi)
3-550	Fishpot Member, Pittsburgh Formation	2.68	33,000
3-548	Upper limestone member, Washington Formation	2.66	28,200
3-549	Sewickley Member, Pittsburgh Formation	2.66	9,330

The thickness of the numerous landslides was not measured but probably is in the range of 5–10 feet; a few may be thicker. Material from two landslides was tested for swell and plasticity index and for potential-volume-control rating (table 5).

MOVEMENT OF GROUND WATER

The close association of different types of rock in the overall sequence exposed in the Washington area affects to a marked degree the direction of movement of ground water. Relatively permeable and impermeable rocks are interlayered throughout the sequence. Sandstones are reservoirs and permit the passage of water; limestones and associated claystone, underclay beneath coal beds, and mudstones do not transmit water readily. No quantitative field tests were made of the relative flow of water from the various types of rock. However, sufficient observations were made to form an empirical basis for a few general statements.

Typically, water from the ground surface that is not carried away as initial runoff percolates through the sandstones until it reaches an impermeable layer or body which diverts the water laterally near the contact between the permeable rock above and the impermeable below. The amount of water diverted and the direction it moves depend upon the direction of inclination or dip of the impermeable layer, the position of the permeable layer at the surface relative to the topography, and to some extent upon the joints within the permeable layer. The effect of topography and type of rock on ground-water movement are shown schematically in figure 25. An example of lateral movement of water as a result of a difference in permeability between rock units can be seen in both the north and south banks of Interstate Highway 70 in the deep cut 0.15 mile southeast of Lincoln Hill, Washington West quadrangle. The water moves downward through the siltstone in the upper part of the middle member, Washington Formation, and is emitted from the carbonaceous mudstone and the underlying Washington "A" coal bed. The coal bed lies on an impermeable claystone unit that is 7.7 feet thick.

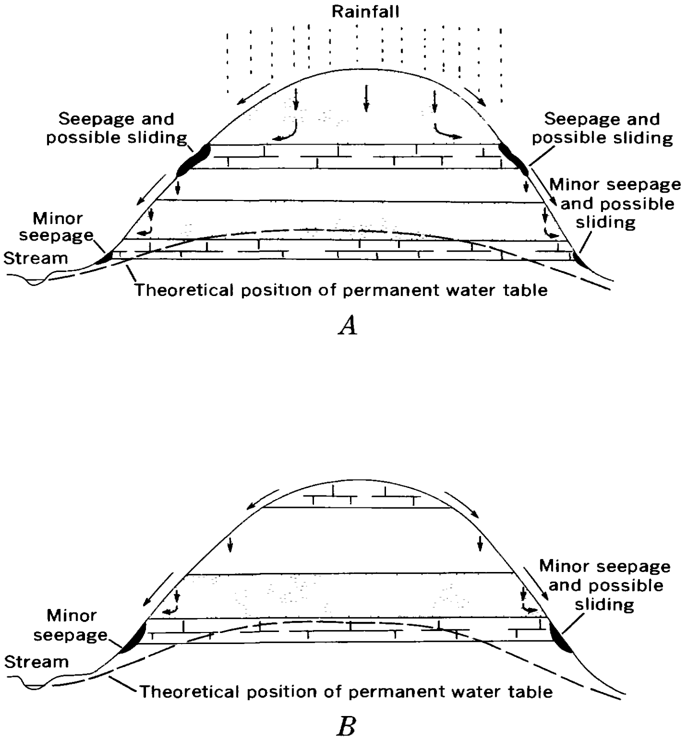


FIGURE 25.—Schematic cross sections of ridges showing generalized movement of water in the subsurface relative to type of rock and topographic position of permeable (stippled) and impermeable (block pattern) layers. Arrows indicate directions of water movement. Arrows outside the ridge profiles indicate surface runoff. *A*, Relatively porous permeable sandstone and siltstone underlie upper part of ridge. *B*, Impermeable limestone and claystone underlie upper part of ridge. If a slight dip is assumed, the amount of seepage would be larger on the downdip side of the ridge.

Because the impermeable layers cause much of the water to move laterally, the outcrops of the top of some of these layers along ridge slopes are lines of seepage. The amount of seepage is influenced by the factors shown in figure 25. As shown in figure 25, water typically seeps from the surface at or near the contact of limestone bodies and overlying sandstone and siltstone, particularly where the clastic rocks underlie the entire upper part of the ridge. The position of the outcrop of the upper limestone member of the Washington Formation is the site of the majority of landslides; its position at the surface over much of the Washington area is similar to that illustrated in figure 25*A*. The principal factors that cause the upper limestone member to slide probably are dissolution of the limestone in the shallow subsurface, lubrication by wet interbedded claystone, and exceeded angle of repose along the hill slopes.

Areas of seepage cause problems both in residential and industrial construction and in cuts for highways. Basements or parts of buildings beneath the surface at or slightly downhill from seepage will frequently be wet unless precautionary measures are taken during construction. Seepage in deep highway cuts, if of large volume, will cause almost continual slumping during, and for some time after, wet periods. In highway planning adequate drainage should be provided where impermeable units will cause seepage, whether in cuts or along the roadbed. Potential lines of seepage can be anticipated if the lithology and distribution of the several types of rock are known.

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