Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin

GEOLOGICAL SURVEY PROFESSIONAL PAPER 259

Geology of the Bedford Shale and Berea Sandstone in the Appalachian Basin

By JAMES F. PEPPER, WALLACE DE WITT, JR., *and* DAVID F. DEMAREST

GEOLOGICAL SURVEY PROFESSIONAL PAPER 259

A study of the stratigraphy, sedimentation and paleogeography of rocks of Bedford and Berea age in Ohio and adjacent States

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1954

UNITED STATES DEPARTMENT OF THE INTERIOR

Douglas McKay, *Secretary*

GEOLOGICAL SURVEY

W. E. Wrather, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C. - Price $4.25 (paper cover)

CONTENTS

ILLUSTRATIONS

[Pls. 1–12, 14 in pocket; pl. 13*A–I* follows p. 106]

GEOLOGY OF THE BEDFORD SHALE AND BEREA SANDSTONE IN THE APPALACHIAN BASIN

By JAMES F. PEPPER, WALLACE DE WITT, JR., and DAVID F. DEMAREST

ABSTRACT

The Berea sand of eastern Ohio, western Pennsylvania, western West Virginia, and eastern Kentucky has long been an important producer of gas and oil. Although many thousand wells have been drilled into and through this sand, few studies have been made showing the variation in the thickness of the sand from place to place or the relationship of accumulation of oil and gas to the variations in sand thickness. Studies of the Berea sand were begun in 1943 by the Geological Survey as a part of an expanded program of oil and gas investigations, and by 1946 nine preliminary maps and one preliminary chart had been published on the results of these studies. The present paper is a compilation and an evaluation of the large amount of data accumulated in the preparation of the preliminary maps.

The Berea sandstone, the surface equivalent of the Berea sand, and the genetically related underlying Bedford shale form a wedge of sedimentary rocks lying between two black shales, the Ohio below and the Sunbury above. The Bedford shale was deposited in part subaerially upon a delta and in part subaqueously as offshore beds along the delta front. The Berea sandstone was deposited above the Bedford shale, at first subaerially as a delta and later as a marine pavement that formed as the sea inundated this delta. The Bedford and Berea formations, therefore, represent a cycle of deposition during an oscillation of the land and sea between two periods of quiescence.

Correlation of the surface exposures of the Bedford and Berea rocks of northern Ohio and the Corry sandstone of northwestern Pennsylvania has long been a matter of controversy. Although the Corry sandstone is a close temporal equivalent of the Berea sandstone, it is not an eastern siltstone phase of Berea sedimentation. The Berea sandstone is a single sandstone throughout its extent and is not a threefold or tripartite formation representing, as some authors have stated, the northern Ohio equivalent of the Corry sandstone, Cussewago shale, and Cussewago sandstone of northwestern Pennsylvania. Also the Cussewago sandstone is a separate sand body unrelated in source of sediments to either the Bedford and Berea or the Corry. Subsurface data confirm the surface correlations showing that the Cussewago sandstone, which is the surface equivalent of the Murrysville gas sand, had a southeastern source whereas the Berea and Bedford had several sources, principally northern and eastern.

The writers believe that some of the rocks near the base of the Pocono sandstone in eastern West Virginia may be the temporal equivalent of the Berea sandstone of Ohio. However, the Berea sandstone of northern Ohio cannot be traced either on the surface or in the subsurface into the sandstones of central Pennsylvania and eastern West Virginia that have been named Berea. The surface exposures of these beds cannot be traced around the Appalachian basin, and the wells drilled for gas or oil are not sufficiently close to the eastern outcrops to permit satisfactory correlation.

Examination of the mineral constituents, sedimentary structures, grain size, sand thickness, and other data from many outcrops and well samples gives conclusive evidence that the sediments representing the depositional cycle of the Bedford and Berea were derived from several widely separate sources, and during transportation into the basin of deposition the sediments coalesced to form the wedge of Bedford and Berea. A northern source area in eastern Canada and an eastern source area in West Virginia and Virginia have been recognized, and a less well substantiated source lay in the area of the present North Carolina Piedmont region.

The Bedford and Berea sediments from the northern source were deposited as a great delta fan across central and eastern Ohio. Evidence of the deposition of these sediments in shallow water is the presence of the Second Berea barrier bar on the eastern side of a delta of red sediment here called the Red Bedford Delta and the prevalence of oscillation-type ripple marks in both the Bedford shale and the Berea sandstone in surface exposures. Parts of the courses of the streams which carried the sediment that built the Berea Delta may be seen along the outcrop in northern Ohio as thick channel sandstones, some of which are now the sites of large sandstone quarries. Parts of a braided and meandering Bedford stream system have been traced by means of the records of wells drilled through the Berea sand, from Medina County southward about 100 miles along the center of the Red Bedford Delta.

The Berea sediments from an eastern source were carried into the Appalachian basin through two or more river channels. A petrographic examination of well cuttings from the longer of the channels, here called the Gay-Fink Channel, shows that much of the sand came from an eastern source beyond the eastern limit of the area covered in this report. Also, the Gay-Fink Channel contains some sand reworked from a preexisting delta of probable Cussewago (Murrysville) age into which the eastern end of the channel was incised in Berea time. The second and shorter channel, here called the Cabin Creek Channel, is known only from wells drilled in the western part of its course, but the petrography of the sand and pebble filling shows that the source area of the sediment lay to the east.

The paleogeography of Bedford and Berea time was influenced by small upwarps of the land and oscillations of the sea level. At the close of the Devonian period the Ohio Bay, a small shallow arm of the epicontinental sea, covered central Ohio and western West Virginia. The widespread flooding during earliest Mississippian time was followed by a long period of slow delta growth that reached its maximum in middle Bedford time when the Ohio Bay was nearly completely divided by the Red Bedford Delta. Flooding of the basin area followed in late Bedford time, and upwarp partly drained the Ohio Bay in earliest Berea time. Small oscillations of the shore line followed until late Berea time when the sea again encroached widely upon the land nearly to the extent of the flooding in earliest Mississippian time. The black mud which comprises the Sunbury shale was then deposited.

INTRODUCTION

PURPOSE OF THE STUDY

The Berea sand in the Appalachian basin has long been a prolific producer of oil and gas. Although thousands of wells have been drilled into and through this sand in the search for oil and gas, no regional and few local studies have been published that show the variation in thickness and lithologic character of the sand from place to place or the relationship of accumulation of oil and gas to these variations.

The great demand for petroleum and its products consequent to the military and industrial operations required by World War II drew heavily upon our national resources of petroleum. The need for expanded geologic investigations to provide the basic data upon which could be based a renewed search for new sources of supply of petroleum was recognized by leaders of the petroleum industry, by Government officials, and by Congress. As a result a greatly expanded program of oil and gas investigations by the United States Geological Survey was authorized by Congress beginning July 1, 1943. As one phase of these investigations, a study was begun of the Berea sand in the Appalachian basin, which comprises parts of New York, Pennsylvania, Ohio, West Virginia, and Kentucky. (See fig. 1.) Results of the study were released promptly in a series of preliminary maps and charts accompanied by brief texts, which were published as individual sheets in the United States Geological Survey's Oil and Gas Investigations series of preliminary maps and charts. A list of these maps and charts follows:

1944, Pepper, J. F., and others, Map of the Second Berea sand in Gallia, Meigs, Athens, Morgan, and Muskingum Counties, Ohio: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 5.

1944, Pepper, J. F., and others, Map of the First Berea sand in southeastern Ohio and western West Virginia: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 9.

1945, Pepper, J. F., and others, Map of the Berea sand of southeastern Ohio, northern West Virginia, and southwestern Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 29.

1945, Pepper, J. F., and others, Map of the Berea sand of northern Ohio: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 39.

1946, Demarest, D. F., Map of the Berea and Murrysville sands of northeastern Ohio, western Pennsylvania, and northernmost West Virginia: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 49.

1946, de Witt, Wallace, Jr., The stratigraphic relationship of the Berea, Corry, and Cussewago sandstones in northeastern Ohio and northwestern Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Chart 21.

1946, Rittenhouse, Gordon, Map showing distribution of several types of Berea sand in West Virginia, eastern Ohio, and western Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 58.

1946, Merrels, C. W., 2d, Map of the Berea sand of southern West Virginia: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 59.

1946, Pepper, J. F., and others, Map of the Berea sand of southern Ohio, eastern Kentucky, and southwestern West Virginia: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 69.

1947, Pepper, J. F., and others, (revised by de Witt, Wallace, Jr., and Demarest, D. F.), Map of the First and Second Berea sands of southeastern Ohio and western West Virginia: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 79. [Revision of maps nos. 5 and 9.]

1948, Pepper, J. F., and others, (revised by Demarest, D. F., and de Witt, Wallace, Jr.), Map of sands of Berea and Murrysville age in southeastern Ohio, northern West Virginia, and southwestern Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 89. [Revision of map no. 29.]

1949, de Witt, Wallace, Jr., Map of the Berea sand of northern Ohio: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 99. [Revision of map no. 39.]

From the outset of the study, however, it was realized that the large volume of data necessarily accumulated would yield, when subjected to critical scrutiny and

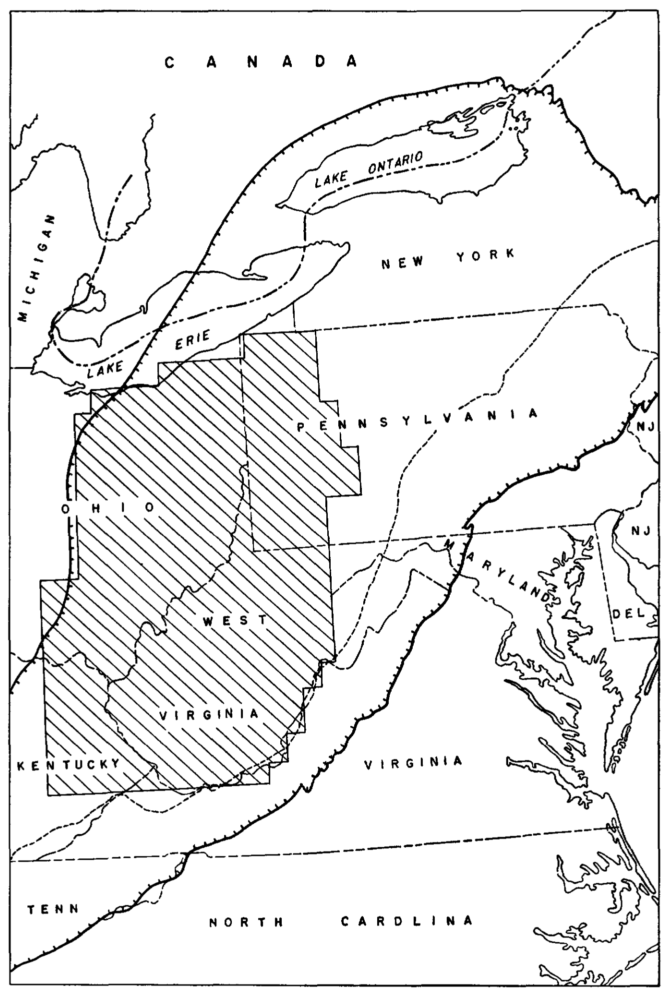


FIGURE 1.—Sketch map showing the northern part of the Appalachian basin of the oil and gas geologist. The boundaries of the basin are shown by the hachured line, and the location of the structural front is shown by the dashed line. The area covered by this report is shaded.

review, a picture of the history and environment of sedimentation and the paleogeography of the region and would ultimately give some clues as to the relationship of these factors to the accumulation of oil and gas. Since the end of the war it has been possible to devote the time required for the preparation of this more comprehensive report on the sedimentary and paleogeographic history of the Berea sandstone in the entire region of its occurrence in the Appalachian basin. It is hoped that eventually a general review of the occurrence of oil and gas in the sand and of the geologic factors that have controlled it can be prepared.

The primary purpose of this program was a search for likely areas in which to drill for oil or gas. A secondary purpose was the regional paleogeographic study in the Appalachian basin, to ascertain the manner in which the Berea sand was deposited and the probable relationship of the accumulation of oil or gas to the sand.

The Berea sandstone, together with the underlying shale and siltstones of the Bedford shale, forms a distinct cycle of deposition. The position of the Berea and Bedford between two distinctive black shales that are present over a large part of the area aids in the recognition and correlation of the Berea and Bedford on the outcrop and in the records of wells, thus making the two formations particularly suitable for intensive study. (See fig. 2.)

The isopach map (pl. 1) shows primarily the thickness and extent of all contiguous sand and silt bodies of Berea age, or of Berea and Bedford age where differentiation is impossible. Secondarily, the map shows the Corry sand, which is lithologically distinct from the Berea though of similar age, as well as the Cussewago (Murrysville) and other older sands that have an important bearing on the interpretation of problems of correlation and paleogeography related to the investigation.

ACKNOWLEDGMENTS

The writers wish to acknowledge the kind cooperation of the State Geological Surveys of the several States in the Appalachian basin and of the Divisions of Mines of Ohio and West Virginia. The Geological Survey of Ohio, the Pennsylvania Topographic and Geologic Survey, the State Department of Mines and Minerals of Kentucky, and the West Virginia Geological Survey furnished well locations and records in their respective States. The West Virginia Geological Survey kindly granted laboratory space and equipment for petrographic studies of the Berea sand. The Division of Mines of Ohio at Columbus and the Department of Mines of West Virginia at Charleston graciously made available thousands of well locations and records in their files.

The individuals and companies to whom the writers are indebted for well records and information would constitute a directory of the oil and gas producers in the Appalachian basin. All who have freely contributed material for the preliminary maps have been listed in the texts accompanying these maps, which are the basis for the present report. To many individuals and companies the writers owe a deep debt of appreciation, and to them the writers wish to express sincere thanks for their interest, cooperation, and kind support.

The geological societies in the Appalachian basin have been an unfailing source of encouragement to the writers. To the Pittsburgh Geological Society, Pittsburgh, Pa.; the Appalachian Geological Society, Charleston, W. Va.; the geology section of the Ohio Academy of Science; and the Kentucky Geological Society the writers express their sincere thanks.

It is a pleasure to acknowledge the fact that this study could not have been carried to completion without the indefatigable and loyal assistance of members of the United States Geological Survey who were associated with us for various periods of time: R. D. Holt, 1943–45; C. H. Summerson, 1943–44; C. W. Merrels 2d, 1943–45; H. H. Gray, 1943–44; H. H. Mead, 1943–44; J. M. Gorman, 2 weeks, 1943; D. K. Cook, 2 weeks, 1944; Gail M. Everhart; Violet M. Massarelli; Mary E. Galpin; M. Elaine Cather; Sarah B. Guckenheimer; G. E. Saam; and L. E. Miller. To Gordon Rittenhouse the writers wish to acknowledge their appreciation for his unfailing cooperation and assistance in the accumulation and interpretation of much petrographic and sedimentary data, to which reference is made in this report, and further, for a critical reading of the manuscript.

To Wilbert Hass of the Paleontology and Stratigraphy Branch, U. S. Geological Survey, the writers wish to express their appreciation for his interpretation of the results of his intensive collecting of the conodont assemblage from the Ohio shale and the Sunbury shale in Ohio and Kentucky, from the Orangeville shale in Ohio and Pennsylvania, and from the Chattanooga shale in Kentucky and Tennessee. His conclusions regarding the age and correlation of these strata have been incorporated in this report.

The writers are much indebted to C. H. Dane, former chief of the Fuels Branch, and W. H. Monroe for their helpful suggestions and critical reading of the text. Mr. Monroe has devoted much effort to the improvement of this report, and his criticism is gratefully acknowledged. Lastly, the writers can express in only a small measure their gratitude to H. D. Miser, who instigated and encouraged this project when he was chief of the Fuels Section, for his advice and interest in all matters pertaining to these studies and for his critical reading of this report.

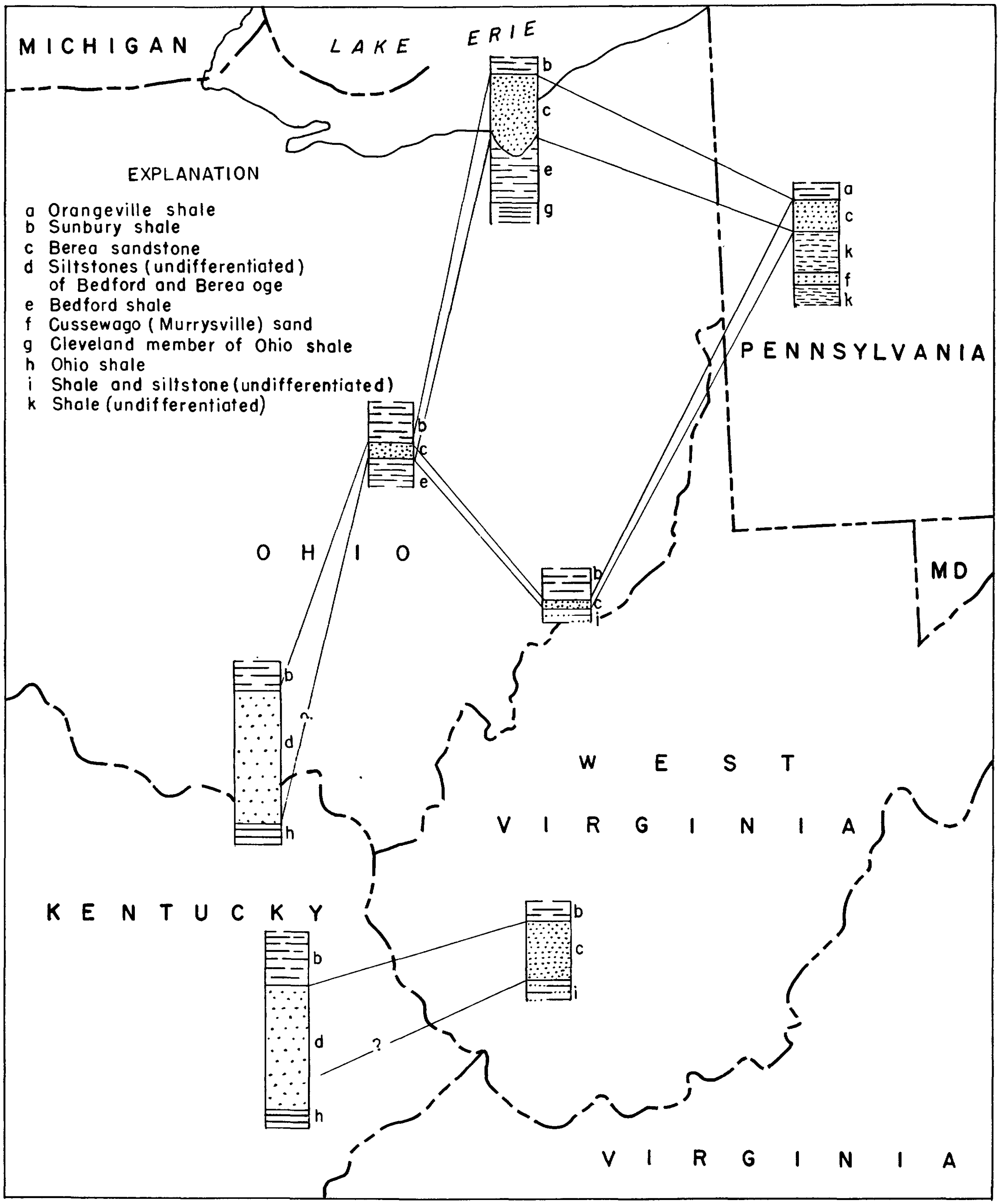


FIGURE 2.—Representative sections of the lower Mississippian and Upper Devonian rocks in the area mapped. The lines limit the sand and silt unit of which the thickness has been mapped in the study of the Bedford shale and Berea sandstone.

CHARACTER AND EXTENT OF THE BEREA SANDSTONE

The Berea is a medium- to fine-grained sandstone in the vicinity of the type locality at Berea, Ohio, where it was first described and named by Newberry (1870a). As shown by plate 3, the Berea crops out southward from Berea, Ohio, to the vicinity of Irvine, Ky., and eastward from Berea, Ohio, into northwestern Pennsylvania to the vicinity of Meadville.

From well records the writers traced the Berea sand into western Pennsylvania, western West Virginia, and northeastern Kentucky. The greater part of the sand and silt of the Berea was deposited upon silt and shale which are thought to be of earliest Mississippian age. The Berea is capped by black shale, which in some places, as in West Virginia, extends eastward beyond the Berea.

The Berea was known as "grit" to the quarryman of northern Ohio, to early geologists, particularly Newberry (1870a), who first described this rock, and to Orton (1888a, p. 35–36; 1888b, p. 311–409), who applied the name Berea grit throughout the outcrop belt and to its continuation underground as the search for oil progressed in eastern Ohio. Later geologists, such as Cushing (Cushing, Leverett, and Van Horn, 1931, p. 45–46) described the Berea as a coarse to medium-coarse sandstone. To the well driller, however, the Berea sandstone when cut by the bit and bailed from the well appears as finely broken fragments or "sand."

None of these descriptive terms can be applied uniformly to the Berea over its entire area. According to Rittenhouse (1946), "Locally, the Berea may be a pebbly, coarse-grained sandstone, but in most of Ohio and West Virginia it varies from a fine-grained sandstone to a medium-grained siltstone." The customary usage, in the Appalachian basin, is to apply the term "sandstone" to outcrops and the term "sand" to areas where information has been obtained from well records. This usage has been followed in this report except where the Berea has been more precisely described from petrographic data in the laboratory or from an examination of outcrops.

The outcrop and laboratory examinations made during this study showed that the grain size of the Berea described by early workers as coarse to medium is misleading. The textures as described in this report are referred to the Wentworth (1922) classification of grain size in sediments, in which sedimentary particles whose diameters range from ½ to ¼ mm are medium sand; ¼ to ⅛ mm are fine sand; ⅛ to $\frac{1}{16}$ mm are very fine sand; $\frac{1}{16}$ to $\frac{1}{256}$ mm are silt; and below $\frac{1}{256}$ mm are clay.

Because the precise measurements for checking grain size according to the Wentworth scale are more readily made in the laboratory than in reconnaissance field examination of the sandstone, a rapid method of obtaining approximate grain classification was devised. By this method, if the unaided eye was incapable of recognizing the constituent grains, but the grains were visible under a 10-power hand lens, the rock was classified as a siltstone. This rough method was checked by comparison of the specimen with a slide containing a series of textural standard samples as described by Rittenhouse (1945). By occasional reference to the easily carried slide, the rocks were classified by the field geologist with considerable accuracy.

However, in many of the outcrops, the sandstone or siltstone of the Berea does not disintegrate into single grains, but owing to differential solution of the cement, small aggregates of grains weather out. The rock then appears to be composed of much coarser grains than are actually present. Probably this type of differential solution of the cementing material and the resulting aggregates of grains of coarse silt size or very fine sand size led Bownocker (1915, p. 75) and others to conclude that the Berea sandstone was a coarse-grained rock rather than a medium- to fine-grained sandstone or a coarse-grained siltstone.

The investigation of the Berea sandstone included three related studies carried on simultaneously:

1. Mapping of the surface outcrops of a part of the Berea sandstone of Ohio and also some of the rocks above and below the Berea.
2. Subsurface studies of numerous drillers' logs of wells drilled into and through the Berea sand and of such sample logs as were available, for the purpose of correlation and determination of thickness of the sand.
3. Petrographic studies of samples of sand to develop criteria to determine the source or sources of the sand; direction of the movement of the sand into the Appalachian basin; and the variations in texture of the sand in relation to the pools producing oil or gas.

Figure 3 shows the parts of the outcrop of the Bedford shale and Berea sandstone mapped by different geologists.

Many surface exposures of the Berea sandstone were examined by Wallace de Witt, Jr., who was assisted by D. F. Demarest and C. W. Merrels 2d, during part of the field mapping. The exposures were plotted on topographic quadrangle sheets of the United States Geological Survey; the sections were measured by hand level or aneroid with the exception of nine sections in northeastern Ohio and northwestern Pennsylvania, which were measured by plane-table methods to establish correlation in areas of complex stratigraphy. The surface trace of part 3 of the outcrop was taken from manuscript maps of R. E. Lamborn of the State Geological Survey of Ohio which were kindly made available by W. F. Stout, former State Geologist of Ohio.

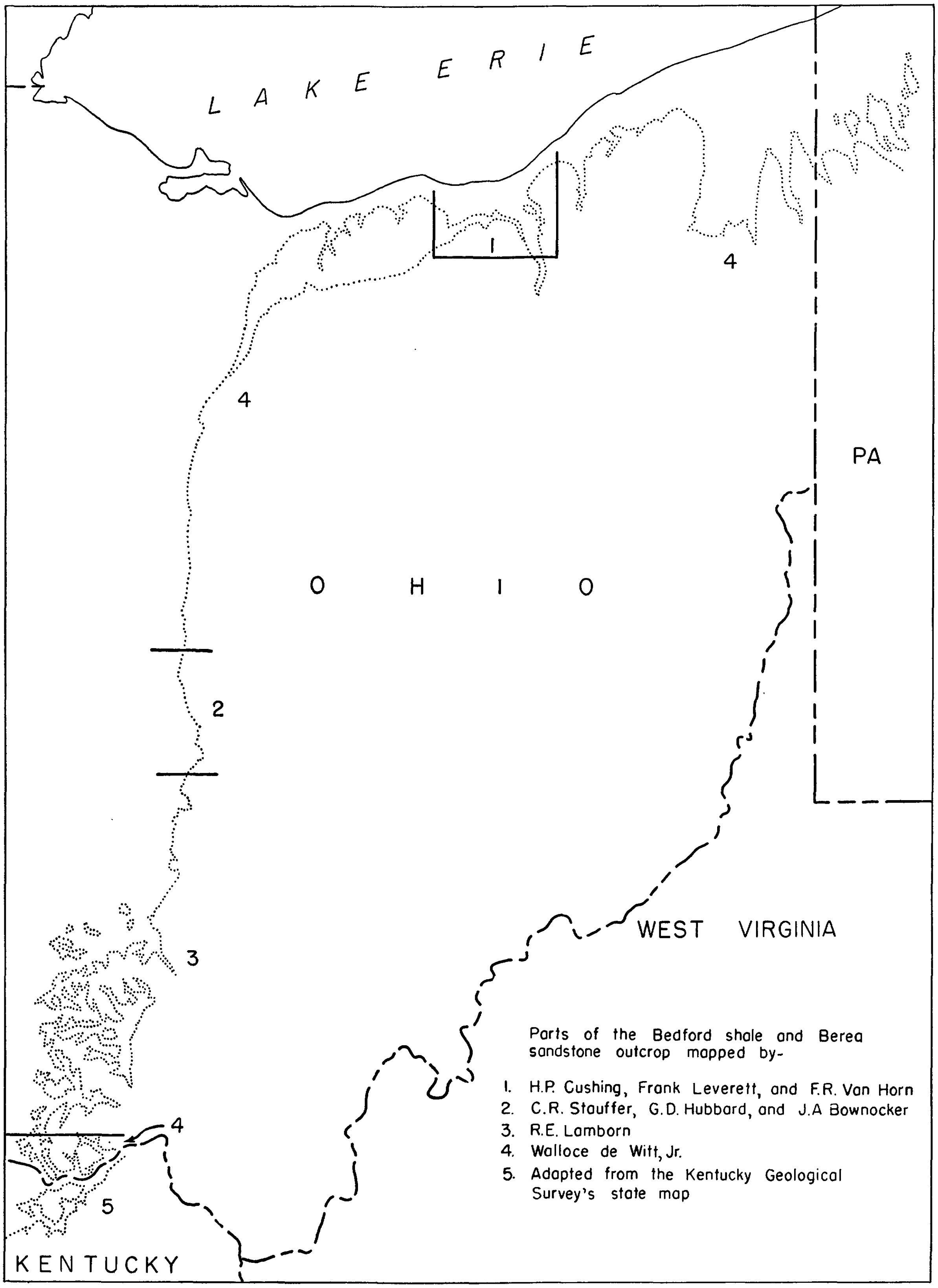


FIGURE 3.—Sketch map which shows the parts of the outcrop of the Bedford shale and Berea sandstone mapped by different geologists.

Part 2 of the outcrop was taken from the areal geology map that accompanied Bulletin 14 of the Ohio Geological Survey (Stauffer, Hubbard, and Bownocker, 1913, areal geology map). The area between Columbus and Cleveland was mapped by de Witt, except in the vicinity of Cleveland, where the outcrop trace was taken from the published map by Cushing and others (Cushing, Leverett, and Van Horn, 1931, pl. 20). From Cleveland eastward into Pennsylvania the Berea sandstone and Corry sandstone were mapped by de Witt (1946). Much information was taken from the early reports of Prosser (1912a) and White (1881) and from an unpublished manuscript report on the Berea and Corry sandstones in northwestern Pennsylvania by S. H. Cathcart (manuscript report in files of Pennsylvania Topog. and Geol. Survey).

The map showing the extent and thickness of Berea and related sands in the Appalachian basin (pl. 1) on a scale of 1:500,000, includes the data from Preliminary Maps 9, 29, 39, 49, 59, 69, 79, 89, and 99, which were published on a scale of 3 miles to the inch. Forty-three thousand well records were used in this study. The well locations were plotted on topographic sheets, and in areas where the wells were closely spaced they were located also on farm-ownership maps on a scale of 4 inches to the mile.

METHOD OF INVESTIGATION

All detailed well records were plotted on log strips as an aid in identifying the Berea sand in areas in which other sands were present near the stratigraphic position of the Berea. From these plotted log strips, 107 cross sections of the Mississippian formations were made across the Appalachian basin. The cross sections were plotted on a scale of 100 feet to the inch vertically and 2 inches to the mile horizontally, or a ratio of about 26:1. As the vertical scale of the cross sections was the same as the vertical scale of the plotted log strips, a direct comparison could be made between the record of any well and the nearest section. The thickness of the Berea sand, as determined by the correlation for each well, was put on a base map in its proper location, and the map was contoured by lines drawn through points of equal thickness. As an aid in determining the regional pattern of the sedimentation, and incidentally as an aid in contouring the thickness of the sand, a colored dot was placed at each well location on the preliminary map base, distinctive colors being arbitrarily assigned to every 20-foot increase in sand thickness. A sheet of tracing paper was placed over this pattern of differently colored dots, and lines were then drawn delimiting each color. As colors are more easily differentiated by the eye than sand-thickness figures, the color pattern with its contoured overlay showed roughly the regional sand pattern. The same procedure was followed for all the preliminary maps, each of which covered about 40 quadrangles. The final contouring was done on a scale of 1 inch to the mile on tracing sheets. Using the regional overlay tracing as a guide, the writers worked out the pattern in detail. The quadrangle tracings were then reduced by pantograph to a base map, which was further reduced to a scale of 3 miles to the inch for publication in the series of preliminary maps. The map (pl. 1) comprising the six preliminary maps which accompanies this report has been further reduced to a scale of 1:500,000, or approximately 8 miles to the inch.

Petrographic studies of sand samples were made by Gordon Rittenhouse. The method of study, which included a microscopic examination and description of the samples, was chiefly concerned, however, with heavy-mineral analyses—in particular, the determination, by percentages, of roundness in tourmalines, the color variations in zircons and in tourmalines, and the relative percentages of quartz grains containing vermicular chlorite. His methods are further described, on pages 91–95. The suites of heavy minerals in the Berea and in older sands in the Appalachian basin contain few varieties of minerals, and these minerals are among the most resistant to erosion. The data derived from the petrographic studies added an effective means of confirming or correcting paleogeological interpretations of the isopach map of the Berea derived from a study of the drillers' logs. As Rittenhouse (1946) states:

> On the basis of mineralogy and grain characteristics the Berea sand may be divided into four main areal units, * * *.
>
> The differences in mineralogy and grain characteristics in these units reflect differences in sources from which the Berea sand was derived. Together with the data on thickness and areal extent, they aid in interpreting the geologic history and paleogeography, and thus help to delineate the areal extent, shape, and trends of areas favorable for oil and gas exploration.

WELL RECORDS

Thousands of wells have been drilled to shallow and deep sands in the Appalachian basin since the completion of the Drake well near Titusville, Pa., in 1859. During the period 1859 to 1900 few records of the formations encountered were kept by companies or individuals. A notable exception, however, was John F. Carll of the Pennsylvania Geological Survey, who in the eighties was an indefatigable collector of well logs and other well data in northwestern Pennsylvania. If others had recognized the value of well records and followed the methods of this astute observer, a wealth of information would now be on hand for the use of the petroleum geologist. The usefulness of well records became apparent to many companies after 1900, and much detailed information has been accumulated since that time by companies and State organizations. During the early 1930's the States of West Virginia and Ohio passed laws that required all companies or operators to file logs and locations at the several bureaus of mines.

The usefulness of a well log to the subsurface geologist depends upon the reliability and accuracy of the driller, who records the footage drilled each day during his tour of duty and describes the character of the formations drilled. Many drillers show a keen interest in the local variation of the sand bodies and the nature of the "pay" within the sand, but much of this information never finds its way into their written records. The well records are most accurate near a "pay" sand or in any formation which is used as a casing seat. For example, in eastern Ohio where many productive wells have been drilled to the Berea sand, the driller carefully logs the thickness of the Berea sand. In central Ohio where the Clinton sand (Silurian) of the drillers, 1,000 feet below the Berea, is productive and where the Berea sand is shallow and close to its outcrop, the upper sand is often less accurately measured.

A subsurface map of a formation in the Appalachian basin is essentially an interpretation of what the drillers recorded. Occasionally, well records are obviously in error. But for any questionable record there are usually many others in the vicinity which are in general agreement. In regional studies the mass effect of hundreds or thousands of well records in an area tends to minimize the effect of a few well records of doubtful accuracy.

A DESCRIPTION OF SOME OF THE MORE COMMON TERMS USED BY THE OIL- AND GAS-WELL DRILLERS IN THE APPALACHIAN BASIN

In the Appalachian basin the well drillers keep a daily record of the rocks encountered in drilling a well. This record includes a very generalized description of the kind, color, and hardness of the rocks being drilled; the depth to and the thickness of these rocks; and the way in which the drill bit is blunted or dulled by cutting them.

In many places the drillers also give colloquial names to some of the rock units that they recognize. Unfortunately, the same name may be given to two or more stratigraphically different units in widely separate areas, or several names may be applied to the same unit in one area. The name "Big Lime" has been applied to two different stratigraphic units. As used by the drillers in northern and central Ohio, Big Lime refers to the sequence of limestone, dolomite, anhydrite, and salt of Silurian and Devonian age that occurs in the interval between the top of the Onondaga limestone and the base of the Lockport dolomite. The same name, "Big Lime", is used by the drillers in West Virginia and eastern Kentucky for the Greenbrier limestone of Mississippian age; in fact, over a wide area in eastern Ohio, northern West Virginia, and northeastern Kentucky, where the Greenbrier overlies the dolomite and limestone sequence of Silurian and Devonian age, the drillers give the name "Big Lime" almost exclusively to the Greenbrier. A limestone of eastern Ohio is an example of a single formation that has been given several local names by the drillers. In Muskingum County this limestone, which is a western equivalent of some part of the Greenbrier, is called Maxville, Fultonham, or Newtonville limestone, or jingle rock.

However, the confusion which may arise from the naming of rocks by the well drillers can be removed if the geologist who is examining the well logs will plot the well records on log strips and correlate them.

Of more concern to the geologist are the terms that drillers use in trying to describe certain types of lithologic character. Because the geologist's subsurface study is actually an interpretation of the sedimentary conditions as reported by a group of well drillers, the geologist must be familiar with these local terms. A few of them are discussed below. Some of the conclusions of Martens (1940), who examined many sets of drill cuttings and compared the cuttings with the drillers' records, have been incorporated in this discussion.

SAND

The rocks described by the drillers as "sand" are usually composed of grains, aggregates of grains, or chips of quartzose conglomerate, sandstone, coarse siltstone, or granular dolomite. The driller determines the presence of sand in the well from the appearance of the drill cuttings, the slow rate of penetration of the drill, the rapid dulling of the bit, and the scratched and roughened surface of the bit which results from drilling through the hard and abrasive rock. Drill cuttings from a productive reservoir rock may be called "sand" by the driller, although the rock consists almost exclusively of limestone, dolomite, or granular chert. For example, the drillers' Newburg sand of northern and central Ohio is at many places a porous saccharoidal dolomite containing no quartz fragments, yet it is consistently called a sand by the driller.

SETTLING SAND

Locally a poorly consolidated, water-filled sandstone may crumble, and large amounts of it will fall into the drilling well. If the sand grains tend to settle around the drill and lodge it in the well, the drillers will record the sandstone as a "settling sand." The lodged or stuck bit is an added hazard to the driller because the drill may be stuck so tight that the well must be abandoned. Because of the danger arising from drilling through settling sands, the driller generally records their presence in the well.

LIME

Any fine-textured hard rock that is difficult to drill will probably be called "lime" by the driller, although the rock may be composed of limestone, dolomite, anhydrite, or fine quartz silt. Because siltstones tend to dull the bit without producing the scratched surface characteristically cut by the coarser quartzose rocks, they are more often identified by the driller as lime than as sand or siltstone. If a rock is cut very slowly by the bit it is usually called "lime" by the driller.

SHELL

The term "shell" is used by the drillers to indicate a bed that is harder than the surrounding rock. The term is applied to sandstone, limestone, dolomite, chert, siltstone, or hard silty shale. Some drillers use a qualifying rock name, such as "lime shell," but this does not guarantee that the rock is a limestone. Generally, a "shell" is a unit ranging from 1 to 25 feet in thickness. However, some well logs record a shell that is more than 100 feet thick.

SHELLS, SHALE AND SHELLS, SLATE AND SHELLS, SAND SHELLS, OR LIME SHELLS

Drillers use the term "shells" to denote a series of alternating beds of hard and soft rocks where none of the beds have a lithologic character sufficiently distinctive to warrant individual description. In general, the term "shale and shells" refers to a series of intercalated siltstones and shale which would on the outcrop be described as flagstones and interbedded shales. In the Upper Ordovician beds, however, the "shells" or "lime shells" are thin-bedded platy limestones which are separated by thin beds of shale or mudstone. At many places in the Appalachian basin, the rocks are part of a near-shore facies which consists of thin interfingering beds of siltstone and shale. The sediments which made up these rocks were deposited in the transition zone between the sands of the littoral zone and the muds of the epicontinental sea. Upon lithification, the sediments of the near-shore facies become the driller's "shale and shells."

CAVE, PENCIL CAVE, AND MULES EAR CAVE

The term "cave" is given by the drillers to that part of a shale and mudstone section which will slump or fall into the drilling well unless supported by casing. Both poor or incomplete induration and closely spaced vertical jointing appear to cause caving of shale into the drill hole. The soft, poorly bedded red mudstones of the Conemaugh formation of southeastern Ohio, which are called the "big red cave" by the drillers, are noted for their characteristic tendency to cave upon drilling.

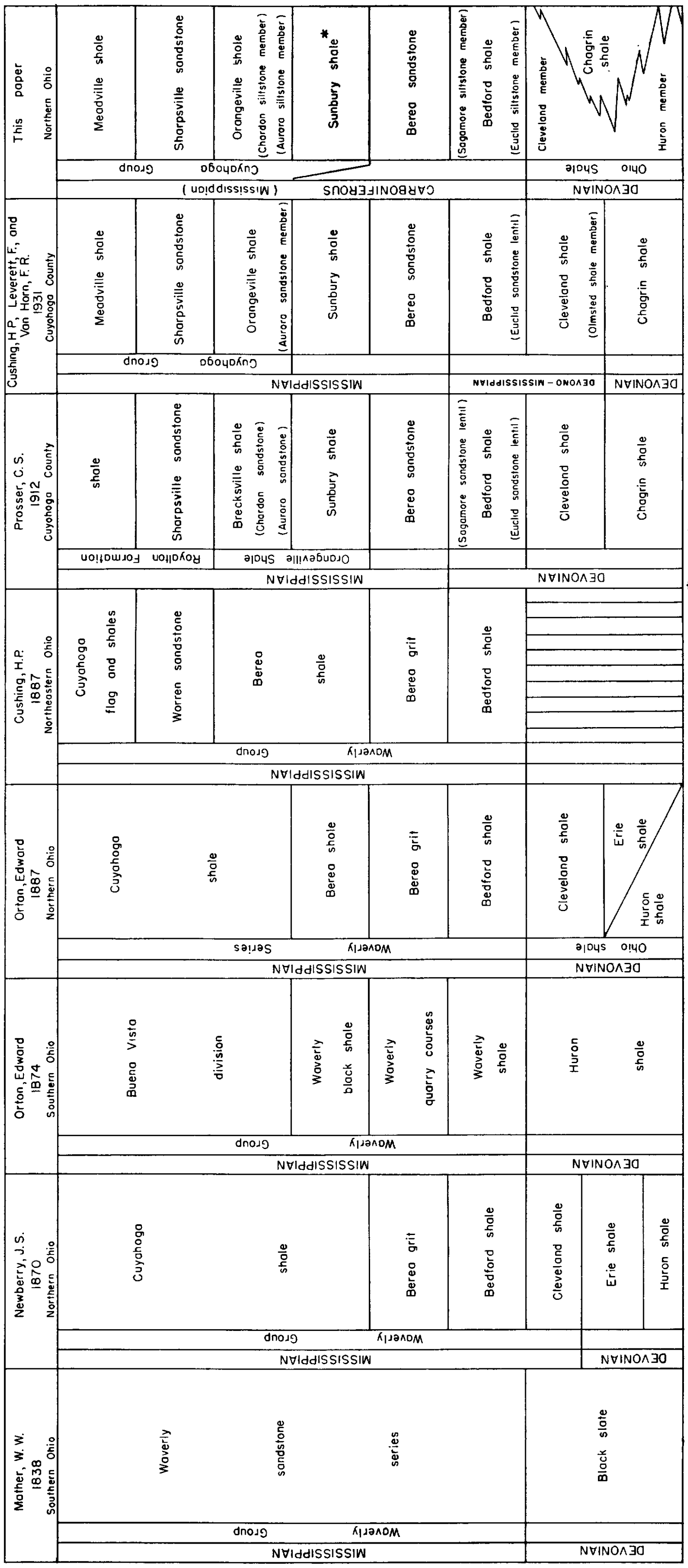
Some of the shales in the Appalachian basin tend to break up into long flat splinters resembling the rectangular marking pencils used by carpenters. Because of the resemblance of these shale fragments to pencils, the drillers refer to the shales as "pencil caves." One of the most widespread of the so-called pencil caves is the shale which overlies the Greenbrier limestone throughout much of West Virginia. In a similar way, the fancied resemblance of some shale splinters to mules' ears gave rise to the term "mules ear cave," which is sometimes applied by drillers to some of the shales of the lower Silurian in central Ohio.

RED ROCK

Because the prevailing color of the rocks in the Appalachian basin is a shade of gray, the drillers usually note any marked change of color in the drill cuttings. Distinctive colors are often extremely useful in making correlations both in adjacent wells and in regional studies. However, if the driller records "red rock," the correlator must use the record with due caution, for the red rock of the driller may be a red sandstone, siltstone, shale, limestone, dolomite, or an iron ore. When used for rocks of Mississippian, Pennsylvanian, or Permian age the driller's term "red rock" generally refers to a soft red shale or mudstone, especially when the term is used for beds in the Mauch Chunk shale of Pennsylvania, the Conemaugh formation of southeastern Ohio, the Dunkard group of southeastern Ohio and West Virginia, or the Bedford shale of northern Ohio. Elsewhere, the red rock may be a red siltstone, as for example the red beds below the Greenbrier limestone in southern West Virginia and southeastern Kentucky. When used for rocks of Devonian age, the driller's red rock may be a shale, siltstone, or sandstone, and for rocks of Silurian age in Ohio it may be siltstone, shale, sandstone, limestone, or an iron ore. The red Queenston shale of Ordovician age is generally sufficiently homogeneous and widespread to be recorded as a red shale, but it too may be called a red rock.

COFFEE SHALE

Because the drill cuttings are wet when bailed from the drilling well, the drillers usually record the color of gray shales as black. Consequently, black shale is recorded more often by the driller than in careful microscopic examination of the washed and dried drill cuttings. However, the driller will also record as black some shales which are unmistakably black on the outcrop. The Sunbury and Ohio shales are typical



* East of Berea, Ohio the Sunbury shale is treated as the basal member of the Orangeville shale and the Cuyahoga group rests on the Berea sandstone

FIGURE 4.—Chart showing the stratigraphic names which have been applied to some of the Upper Devonian and lower Mississippian rocks in Ohio.

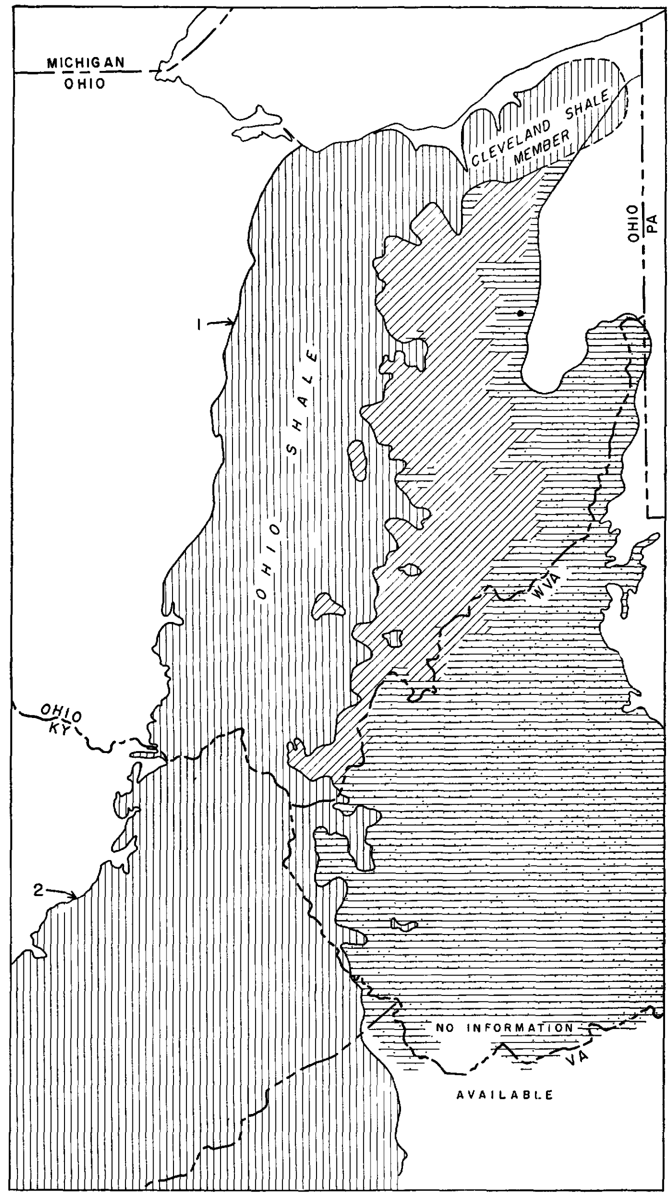
of such shales. Drilling breaks down some shale into a dark-brown mud filled with small black chips that resemble coffee grounds. Because of this resemblance, the Sunbury shale is often called the "coffee" shale and recorded as such by the drillers.

HISTORICAL SUMMARY OF THE STRATIGRAPHIC NOMENCLATURE

Some of the stratigraphic units discussed in this report were named many years ago, and the nomenclature and correlation of these units have long been controversial. Some of the controversies arising from the naming of the Upper Devonian and lower Mississippian units were well summarized by Prosser (1912a, p. 14–24, 509–529) and later by Schuchert (1943, p. 564–570).

As shown in figure 4, the Bedford and Berea rocks in southern Ohio are included in Mather's Waverly sandstone series (1838, p. 356). His Waverly is underlain by 200 to 300 feet of grayish-black shale which was named Ohio by Andrews in 1870 (p. 62). As defined, the Ohio shale included at the base 30 feet of shale which is lighter in color and different in contained fauna than the main mass of bituminous black shale. In 1874 Winchell (p. 243, 287) made the basal part of Andrews' Ohio shale a separate formation, calling it the Olentangy shale. In central northern Ohio, the black Huron shale and the black Cleveland shale are the equivalents of the upper part of the Ohio shale of central Ohio (Cooper and others, 1942, pl. 1, facing p. 1788). The black Huron shale, named by Newberry (1870b, p. 18), has its type locality on the Huron River in Erie and Huron Counties north of Norwalk, Ohio. According to Prosser (1912a, p. 514–515), the black Huron shale is a western facies of the Chagrin shale. The name Chagrin was given by Prosser (1903, p. 521) to the gray shales and siltstones which Newberry (1870b, p. 20) had named Erie, because the name Erie was preoccupied. The black Cleveland shale, named by Newberry (1870b, p. 19–21), overlaps the Chagrin in part and grades into the uppermost beds of the Chagrin in northeastern Ohio. In the vicinity of Olmsted Falls in western Cuyahoga County, Cushing (1912, p. 583) named the lower part of the Cleveland shale the Olmsted shale member. The Olmsted member of Cushing contains many beds of blue shale and some thin gray siltstones in addition to typical black bituminous shales.

The Huron, Chagrin, and Cleveland shales were originally considered to be Devonian in age, but Ulrich (1911) placed them in the Mississippian. Most geologists now believe, however, that the formations are of Devonian age. According to Cooper and others (1942, p. 1752), the Chagrin shale represents westward facies of the Conewango stage including most of the Chadakoin of New York and Pennsylvania. In northwestern Pennsylvania the beds that correlate with the upper part of the Chagrin shale of eastern Ohio were named Riceville by White in 1880 (White, 1881, p. 97–98). Figure 5 shows the types of rocks that directly underlie the Bedford shale of Ohio, the siltstones



1 Line of outcrop of base of Ohio shale from Ohio geologic map
2 Line of outcrop of the base of the Ohio shale or the Chattanooga shale generalized from the Kentucky geologic map

EXPLANATION

Black shale — Gray shale — Shale and shells

FIGURE 5.—Sketch map showing lithologic character of the Upper Devonian rocks upon which the Bedford and Berea sediments were deposited.

and shales of the Bedford and Berea in Kentucky, and the Berea sand of West Virginia.

The lower Mississippian rocks of southern and central Ohio were originally grouped together as the Waverly sandstone series by Briggs (1838, p. 79). The series included all the rocks from the base of the Bedford shale to the base of the Sharon conglomerate. These rocks are mainly unfossiliferous, and according to Schuchert (1943, p. 568) the term Waverly should be restricted to the Mississippian rocks that crop out in the southern part of Ohio. The northern equivalent of the Waverly, the Cuyahoga group, named by Newberry (1873, p. 171–222), is more fossiliferous; this group of rocks was elevated to the rank of system and named Waverlyan by Ulrich (1911). The Waverlyan system of Ulrich included the Cleveland shale, Bedford shale, Berea sandstone, Sunbury shale, and Cuyahoga shale. However, this system is not recognized by the United States Geological Survey, and the base of the Cuyahoga group is placed at the base of the Sunbury shale east of Cleveland and at the top of the Sunbury west of Cleveland.

In Crawford County, Pa., White (1881, p. 94–96) applied the name Cussewago to a coarse-grained sandstone, a local limestone, and a silty shale.

The Bedford shale, named by Newberry (1870b, p. 21), was considered to be of Devonian age by Girty (1912) from the fossil content and the marked unconformity between the Bedford shale and the overlying Berea sandstone. Burroughs (1911), Prosser (1912a, p. 511–512), Kindle (1912), and others have agreed, but Cushing (Cushing, Leverett, and Van Horn, 1931, p. 38–40) indicated that the break between the Cleveland shale and the Chagrin shale is the more significant. The writers, from their observations in the field, from the examination of thousands of well logs and many well samples, and from their interpretation of the paleogeography, have concluded that the base of the Bedford shale is the most marked break between the Devonian and the Mississippian. The Bedford shale correspondingly makes the most logical choice of formations for the basal unit of the Mississippian in Ohio. D. H. Dunkle (oral communication) finds the most significant hiatus in the vertebrate fossils occurs at the end of Cleveland time or in earliest Bedford time. These findings are in agreement with those of Orton (1882, p. 174), who stated in reference to the Waverly group:

> I submit that this boundary [the Devonian-Mississippian boundary] ought to remain undisturbed where it has been fixed by unbroken use in the section [southern] of the state where the name originated, viz., at the base of the Bedford shale. Any other base, it is impracticable to establish.

The Bedford shale contains two massive siltstones in northern Ohio; the lower was named Euclid sandstone lentil by Morse and Foerste (1909, p. 166) and the upper was named Sagamore sandstone lentil by Prosser (1912a, p. 87–88). Each is a local siltstone extending only a short distance on the outcrop. These lentils are siltstone rather than sandstone, and for that reason the Euclid and Sagamore are here redesignated the Euclid siltstone member and Sagamore siltstone member.

In southeastern Ohio in the subsurface, the Bedford shale contains a lens of siltstone which is approximately 80 miles long and 6 to 10 miles wide. It ranges in thickness from a few inches to as much as 30 feet. This siltstone, which has generally been called the Second Berea sand by the drillers, is a correlative of the Euclid siltstone member of the Bedford shale.

The Second Berea sand was first encountered in wells drilled in the vicinity of McConnelsville in central Morgan County, Ohio, where this siltstone produced gas. Here as much as 30 feet of gray shale separates the Second Berea from the Berea sand. During the development of the McConnelsville gas pool the Second Berea sand was called the stray gas sand. Later, however, the well drillers called this siltstone the Second Berea sand. In accordance with well-established usage, the name "Second Berea" as used in this report refers only to this elongate siltstone in southeastern Ohio.

The Berea sandstone, first named the Berea grit by Newberry (1870b, p. 21–29), is a medium- to fine-grained sandstone which in northern Ohio was deposited in deep erosion channels as noted by Cushing. (Cushing, Leverett, and Van Horn, 1931, p. 47–48). In central Ohio, Prosser (1912b) found the sandstone resting upon the gently undulatory upper surface of the Bedford shale. In southern Ohio, Carman (1947) reports that the contact between the Bedford and Berea must be arbitrarily chosen, for there is no suggestion of a lithologic break between them. In the vicinity of the Ohio River in western Scioto County, the Bedford and the Berea are composed largely of siltstones and interbedded silty shale. Similar sections were observed in the adjacent part of Kentucky by Butts (1922, p. 18) and others.

The Corry sandstone, named by White (1881, p. 92–94, 230), is a yellowish-white to gray very fine grained sandstone or siltstone which was quarried at Colegrove quarries south of Corry in Concord Township, Erie County, Pa. The Corry sandstone is not found in northern Ohio, but it is a temporal equivalent of the Berea sandstone.

The Sunbury shale, which has been called the Berea shale by Orton (1879, p. 594), and Cushing (1888), was named by Hicks (1878, p. 216, 220) for exposures of the black shale on Rattlesnake Creek near Sunbury in

Delaware County, Ohio. In central Kentucky the Sunbury shale rests on the Ohio shale by overlap.

A group of dark-brown shales containing some brown siltstones and many ironstone concretions which lies above the Sunbury shale and below the Sharpsville sandstone in northern Ohio and western Pennsylvania was named Orangeville shale by White (1880, p. 63) In northern Ohio the Orangeville shale is considered a formation of the Cuyahoga group. At some places, because he was unable to separate the Sunbury and Orangeville shales, Prosser (1912a, p. 486) included the Sunbury shale as the basal unit of the Orangeville shale. Locally, however, a siltstone, the Aurora sandstone member of the Orangeville (Prosser, 1912a, p. 123, 209, 211), which is here designated the Aurora siltstone member of the Orangeville shale, separates the Sunbury from the main part of the Orangeville shale. Because of the difficulty of separating the Sunbury from the Orangeville at places where the Aurora siltstone member is not present, the writers treat the Sunbury as a member of the Orangeville shale east of the Cuyahoga River and draw the base of the Cuyahoga group in this area at the top of the Berea. In the vicinity of Chardon in western Geauga County, Prosser (1912a, p. 219–220, 229) found a siltstone in the middle of the Orangeville shale, and named it the Chardon sandstone member. In this paper it is designated as the Chardon siltstone member.

The Sharpsville sandstone was named by White (1880, p. 61–62) for exposures near Sharpsville, Pa. The sandstones and flaggy siltstones of the Sharpsville overlie the Orangeville shale throughout northeastern Ohio and a part of northwestern Pennsylvania.

THE AGE RELATION OF THE BEDFORD SHALE AND BEREA SANDSTONE

The placement of the plane dividing the Devonian system from the Mississippian series in the sequence of rocks between the base of the Ohio shale and the top of the Sunbury shale has become a time-honored controversy. As this problem is well summarized by Schuchert (1943, p. 567–570), the writers make no attempt in this paper to reexamine the paleontological evidence for the several opinions.

In southern Ohio the rocks of the Bedford and Berea form a gradational cycle of deposition beginning at the close of deposition of the black Ohio shale. This cycle of deposition shows a gradually increasing amount of coarser clastic material upward from the basal shale of the Bedford through the shales and siltstones of the Bedford into the basal siltstones and sandstones of the Berea. The beginning of the next cycle of deposition is marked by the deposition of another black shale, the Sunbury. The unconformity between the Bedford and the Berea, plainly visible in northern Ohio, is not present in southern Ohio.

Mainly on lithologic grounds, the writers, following the usage established by Orton, place the base of the Mississippian series at the bottom of the Bedford shale. Because sedimentation at the beginning of Bedford time began a new cycle of deposition in which the sediments for the most part came from a source different from the beds below, the writers feel that the base of the Bedford is the logical base of the Mississippian series in Ohio except where the Bedford shale overlaps the Cussewago (Murrysville) sandstone. The Bedford and the Berea are so intimately related genetically that they must be considered a genetic unit regardless of the position of the Devonian and Mississippian boundary as determined paleontologically.

The fauna from the basal part of the Bedford shale in the vicinity of Cleveland, Ohio, is very closely allied to the fauna of the Glen Park limestone of the Mississippi River valley (Cooper and others, 1942, p. 1746, 1762). The Glen Park limestone is classified as lower Mississippian (Kinderhook) by Weller (Weller and others, 1948). Therefore the Bedford shale is probably Kinderhook in age, and the rocks of the Bedford and Berea genetic unit are lower Mississippian.

CORRELATIONS AND STRATIGRAPHY

In discussing the formations of Late Devonian and early Mississippian age in the western part of the Appalachian basin, the writers divide the outcrop arbitrarily into two parts (pl. 3). The first part extends from the type locality of the Berea sandstone at Berea, Cuyahoga County, in northern Ohio, west to Norwalk, Huron County; south to the Ohio River at Buena Vista in western Scioto County; and S. 30° W. to Irvine, in Estill County, central Kentucky. In this area of outcrop the correlations are clearly indicated. Because the exposed lower Mississippian rocks represent a section along the long axis of a deltaic deposit and show a single depositional cycle, the horizontal lithologic changes are gradual over relatively long distances. The other part of the area of outcrop to be described extends from Berea, Ohio, eastward across northeastern Ohio and into northwestern Pennsylvania to Corry in eastern Erie County. The correlations in this area of the outcrop are complicated, for the exposures cut across several delta-fan deposits, and marked lithologic changes occur in short distances.

UPPER DEVONIAN ROCKS

The Upper Devonian rocks upon which the early Mississippian sediments were deposited consist of a thick mass of black shale that at some places merges into thin gray shales and platy siltstones. These

Upper Devonian rocks have been assigned different names in different parts of the outcrop, but as they grade laterally into one another, exact dividing lines cannot be drawn between the several named formations.

OHIO SHALE

The Ohio shale represents essentially continuous deposition of black mud throughout much of Late Devonian time. It crops out in a wide belt from Cuyahoga County, in northern Ohio, to Pulaski County, in southern Kentucky. In northern Ohio this black shale can be divided into two shale units, the Cleveland and the Huron. The separation of the Cleveland from the Huron has been a problem that has elicited much debate from the geologists who have worked in the area. As shown in figure 6, it is proposed in this paper to treat the Cleveland and the Huron as members of the Ohio shale, to which they are genetically related, rather than as separate formations as has been done in the past, because in the vicinity of Norwalk, Huron County, Ohio, the separation of these two black-shale units is impossible except by paleontological evidence. In western Lorain County, between Cuyahoga and Huron Counties, the Cleveland and Huron members of the

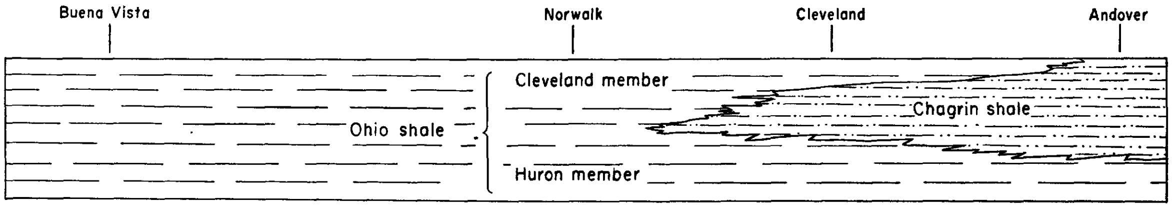


FIGURE 6.—Schematic cross section between Buena Vista and Andover, Ohio, showing the relation of the Cleveland and Huron members of the Ohio shale to the Chagrin shale.

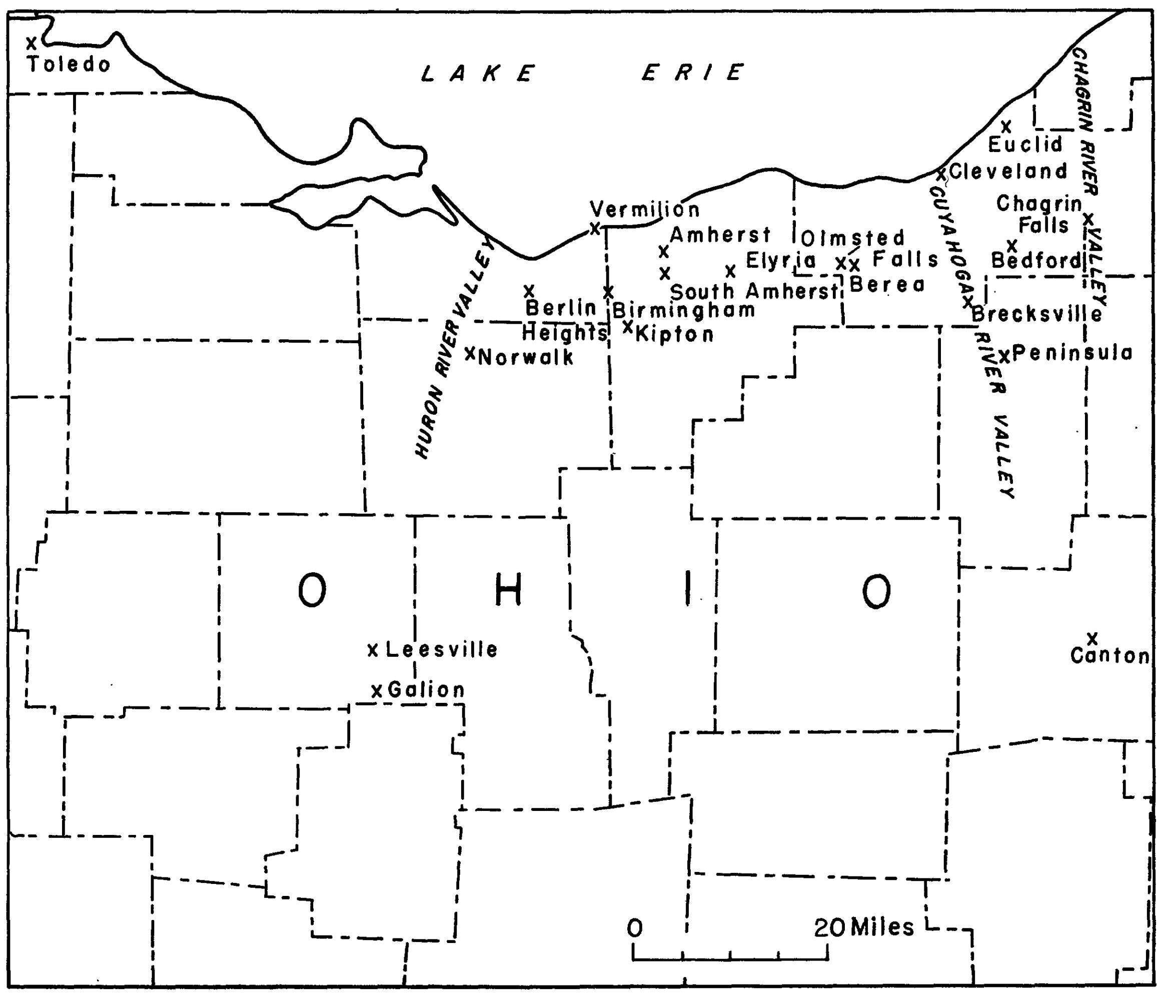


FIGURE 7.—Sketch map showing some of the places in northern Ohio mentioned in this paper.

Ohio shale are separated by the western edge of the Chagrin shale.

Southward from Norwalk, Ohio (figs. 7, 8), the tough bituminous Ohio shale contains many large concretions similar to those found in the Huron member near Norwalk. The Ohio shale, which is more than 500 feet thick in southern Huron County, Ohio, decreases in thickness to the south. It is 376 feet thick west of Chillicothe in Ross County, southern Ohio (Carman, 1947), 250 feet thick near Vanceburg in northern Lewis County, northern Kentucky (Morse and Foerste, 1912,

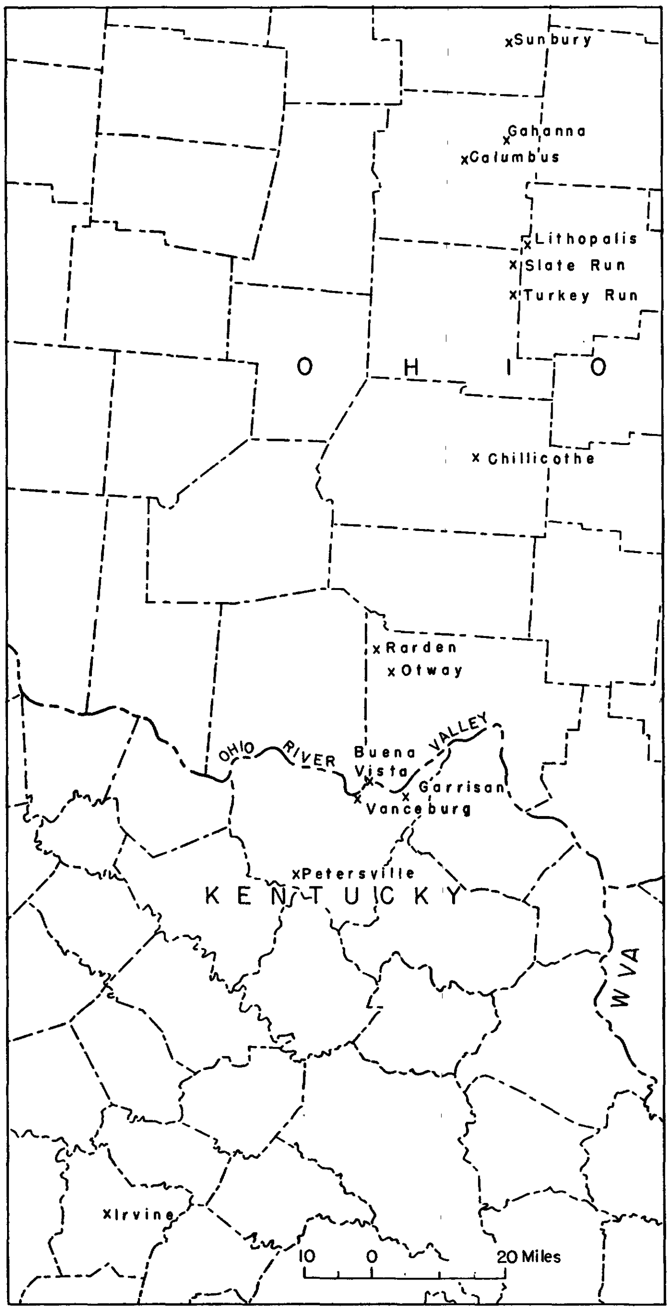


FIGURE 8.—Sketch map showing some of the places in southern Ohio and eastern Kentucky mentioned in this paper.

p. 17), and 95 feet thick near Irvine in Estill County, east-central Kentucky (Butts, 1922, p. 6). In the vicinity of Irvine, the Ohio shale merges with the black Sunbury shale of Mississippian age at the southern limit of the Bedford and Berea rocks. Thus the black shale in south-central Kentucky is of Devonian and Mississippian age.

Because much of the area between Norwalk, in northern Ohio, and Chillicothe, in south-central Ohio, is mantled by glacial drift, bedrock can be found cropping out only along the larger streams. South of the glaciated area, however, in Ross County and southward, in central southern Ohio and the adjacent part of Kentucky, the topography is rougher; as a result, the Ohio shale is well exposed in many imposing cliffs along the valley sides. Much of the thin soil that at one time covered these black shales has been eroded, and at some places stream gullying has cut small areas of badlands in the exposed black shale. In southern Ohio and the adjacent part of Kentucky, the black shale forms the base and lower part of the knobs that lie along the western edge of the Allegheny Plateau. The width of the outcrop of the Ohio shale decreases in Kentucky as the black shale thins toward the south.

The contact of the Ohio shale with the overlying Bedford shale is generally well defined from Berea, Ohio, to Irvine, Ky. In some places a transition zone ranging from a few inches to 4.2 feet in thickness separates the black shale of Devonian age from the succeeding red or gray shales of the Bedford. In northern Ohio, D. H. Dunkle (oral communication) has found near the base of the transition zone a bone bed containing fish fossils of Devonian age. Invertebrate fossils assigned to the Bedford shale are present in the upper part of this transition zone at many places in Ohio and northeastern Kentucky. In southern Ohio and northeastern Kentucky the contact at the top of the Ohio shale is distinct, and the gray shales and siltstones of the Bedford lie directly upon the Ohio shale.

HURON MEMBER

To the west of Berea, Ohio, is a thick mass of grayish-black shale, which contains large septarian concretions in the lower part and thin beds of cone-in-cone limestone in the upper part. The black shale was named Huron by Newberry (1870b, p. 18), and the bluffs of the Huron River north of Norwalk, Ohio, were designated the type locality. Characteristically the Huron member contains many large concretions and septarian nodules ranging from 1 to 6 feet in diameter. The Cleveland and Huron members are essentially identical in lithologic character, and in Erie and Lorain Counties the contact between these two black shales is drawn arbitrarily below the lowest cone-in-cone layer and above the uppermost zone containing the large concretions.

From Berea west to Norwalk, the black shale of the Huron member forms cliffs from 5 to 70 feet high along many of the streams and along the shore of Lake Erie. The black shale, which is more resistant to erosion than the gray clay shales of the Chagrin, underlies a broad terrace which slopes westward from an elevation of 790 feet in the vicinity of Berea to the level of Lake Erie in western Lorain County.

CLEVELAND MEMBER

In outcrops along the Rocky River north of Berea, Ohio, the Cleveland member has a thickness of 100 feet (Prosser, 1912a, p. 475). The upper part is typically a hard dull grayish-black shale which weathers to thin chips that are generally stained a rusty reddish brown by iron oxide. The lower part of the Cleveland member, which was called the Olmsted member by Cushing (Cushing, Leverett, and Van Horn, 1931, p. 36), contains in addition to black shale, many beds of bluish-gray or gray clay shale that range in thickness from an inch to several feet; some thin gray to brown siltstones; many small nodules and lumps of pyrite; and several thin siliceous limestones that are characterized by cone-in-cone structure. The conodont fauna found in the upper 25 feet of Cushing's Olmsted member is identical with the conodont fauna of the Cleveland (Hass, 1947). The writers interpret the beds of alternating black and gray shales as minor interfingering of the black shales of the Ohio and the gray shales of the Chagrin prior to the main eastward transgression of the sea which deposited the main mass of the Cleveland member. This interfingering of black and gray shale in the lower part of the Cleveland has been observed by the writers as far west as Chappel Creek in Vermilion Township, Erie County, Ohio.

Lithologically the Cleveland member east of Berea, Ohio, is identical with the tough grayish-black shale exposed along Rocky River north of Berea. The thickness of the Cleveland member, which is about 60 feet in the southern part of the city of Cleveland, decreases as the outcrop is traced southward along the Cuyahoga River Valley, and on Slipper Run near Peninsula (Prosser, 1912a, p. 149) the thickness is about 6 feet. Surface and subsurface data in northern Ohio indicate that in the vicinity of Cleveland this black shale was deposited in a shallow linear basin whose long axis trends about east-west. As shown by figure 5, the shale disappears abruptly from the section to the south. Traced eastward across Cuyahoga, Lake, and Geauga Counties, the Cleveland retains its characteristic color but decreases in thickness to 20 feet. The black shale forms steep cliffs and flume gullies throughout much of its outcrop, especially along the edges of the plateau of Geauga County. The Cleveland contains very few macrofossils east of Cleveland, and the thin limy cone-in-cone layers which are characteristic of the member west of the type locality are generally wanting to the east.

The Cleveland member is 30 feet thick at outcrop 1 in eastern Cuyahoga County (see pl. 4), 26 feet thick at outcrop 13 in northwestern Geauga County, and 18 feet thick at outcrop 24 in western Ashtabula County (Prosser, 1912a, p. 195–196, 225–226, 316). In the outcrops along the west side of the Grand River valley the shale loses some of its typical grayish-black color, and much gray silt occurs as thin stringers or admixed in the blackish shales. In outcrop 21 in western Ashtabula County, only 11 feet of the grayish-black silty Cleveland shale is exposed. The basal contact of the Cleveland, which is generally sharply defined in much of the outcrop east of Cleveland, becomes difficult to delineate along the western side of the Grand River valley, and as shown in outcrop 24 the Cleveland appears to grade laterally into the upper beds of the Chagrin shale. (See pl. 5.) In exposures examined along the eastern side of the Grand River valley black shale was not observed, and it is the opinion of the writers that the Cleveland grades laterally into the upper beds of the Chagrin shale under the drift cover in the Grand River valley. A well drilled at Andover, in eastern Ashtabula County, is reported to have penetrated, at a depth of about 48 feet, some black shale resting on a massive sandstone (Prosser, 1912a, p. 389). The writers believe that this black shale is the eastern feather-edge of the Cleveland member, because the sandstone in the well, when projected on the regional dip, correlates with the massive siltstones in the upper part of the Chagrin shale that are exposed on Pymatuning Lake 2 miles to the east. In this well quicksand was reported above the black shale. Most probably part or all of the quicksand is the Cussewago sandstone, which is water bearing and very friable. The record of this well suggests that the Cussewago sandstone occurs stratigraphically above the Cleveland member of the Ohio shale.

CHATTANOOGA SHALE

A thin black shale, the Chattanooga (Hayes, 1891, p. 143), has been traced from its type locality at Chattanooga, Tenn., into the black shale of both Devonian and Mississippian age in Estill County, Ky., which lies at the southern end of the wedge of rocks of Bedford and Berea age. The age relation of the Chattanooga shale has long been the subject of much controversy. However, the work of Morse and Foerste (1912, p. 46–49), Butts (1922, p. 6), and others shows that in the vicinity of Irvine, Ky., the black-shale unit includes rocks of both Devonian and Mississippian age.

CHAGRIN SHALE

West of Berea the Chagrin shale is composed of thin gray siltstones, silty gray shale, soft gray clay shale, and a few beds of grayish-black shale. The Chagrin shale as shown on the map of the Berea quadrangle by Cushing, Leverett, and Van Horn (1931, pl. 20) is confined largely to the cliffs bordering Lake Erie, and the general dip of the rocks to the west carries the uppermost beds of the Chagrin below lake level within a short distance.

East of Berea, to the type locality on the Chagrin River, the Chagrin shale consists of a series of gray slightly silty shales and some thin gray siltstones. The top of the Chagrin rises above the level of Lake Erie in western Cuyahoga County, and the outcrop widens to the east as the dip brings more of the shale above lake level. The Chagrin forms many of the high cliffs along the stream valleys in Cuyahoga, Geauga, and Lake Counties. The siltstones in the upper part of the shale form many small parallel ledges on the precipitous slopes. In eastern Ohio the Chagrin reaches a maximum thickness of about 1,200 feet (Cushing, Leverett, and Van Horn, 1931, p. 35), although the base of the shale lies below lake level. Eastward through northern Ohio the siltstones in the Chagrin increase both in thickness and number so that at many places they form zones up to 50 feet thick of intercalated massive siltstones and thin silty gray shales which are separated by thicker zones of relatively siltstone-free shales. From the vicinity of Andover, Ashtabula County, Ohio, eastward, the upper beds of the Chagrin are massive fossiliferous siltstones which are traceable over a large area in northwestern Pennsylvania and northeastern Ohio. In most outcrops in the vicinity of the State line, the upper beds of the Chagrin or the equivalent beds which in Pennsylvania were named Riceville by White (1881, p. 97–98) are overlain by the Cussewago sandstone. In some places, however, the Cussewago sandstone is absent, and stratigraphically higher beds are found lying on the Chagrin or Riceville shale. The Chagrin shale is very fossiliferous in many places, and although it has been studied by a considerable number of geologists, the fauna of the Chagrin has never been completely described.

RICEVILLE SHALE

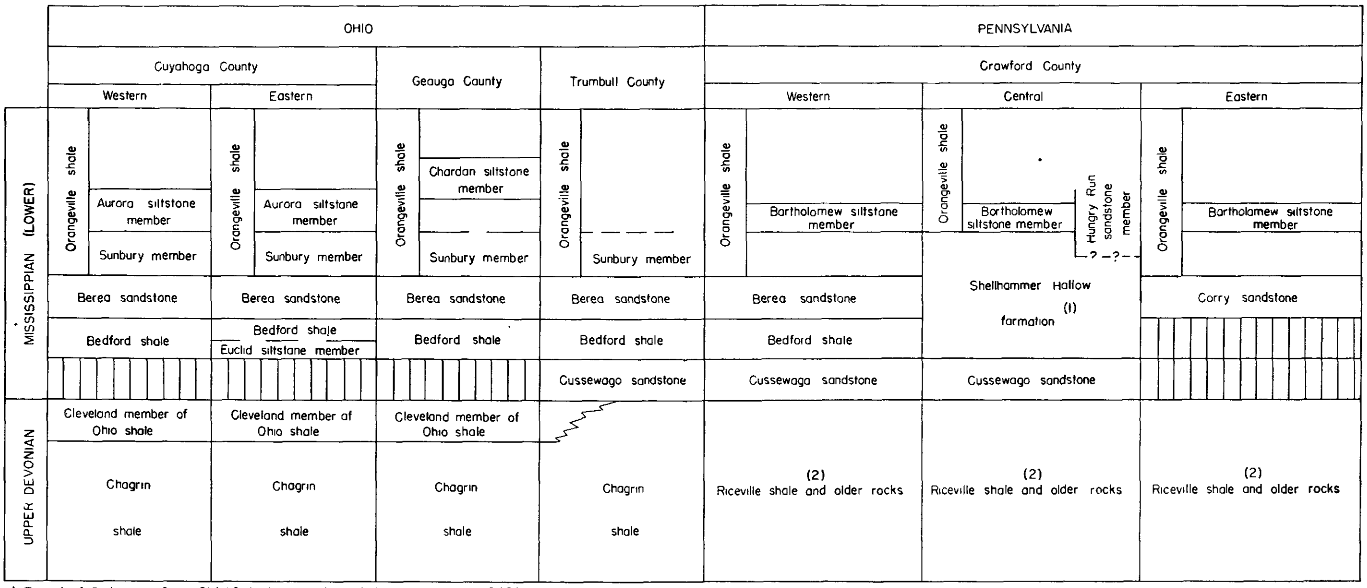
The Riceville shale, which consists of white, light-gray, tan, and light-brown fossiliferous siltstones and intercalated ash-gray silty shales and mudstones, is well exposed in outcrops in Hayfield Township and at the type locality (outcrop 94, pl. 4) near Riceville (White, 1881, p. 97), in Athens Township, Crawford County, Pa. According to White's definition, the limits of the Riceville are "Beneath the Cussewago sandstone and down to the First Oil sand of the Venango group, a distance of say 80 feet * * *." Because of the slightly irregular surface of the upper part of the Riceville shale, the thickness of the Riceville ranges as much as 15 feet from the thickness ascribed to it by White. The Cussewago sandstone was deposited on this irregular surface. The Riceville shale has been redefined and restricted by Caster (1933, p. 203) and Chadwick (1933, p. 195, 197) on the basis of paleontological evidence, but for the purpose of field mapping and for this report White's original definition of Riceville shale is used. From outcrop 50 eastward to outcrop 92 (pl. 4) the Cussewago sandstone rests on the upper part of the Riceville shale, and east of outcrop 92 where the Cussewago sandstone is absent the Corry sandstone lies on the upper beds of the Riceville shale.

MISSISSIPPIAN ROCKS

SURFACE CORRELATION

The relations of the lower Mississippian rocks of northeastern Ohio and northwestern Pennsylvania were studied by Read (1873) in Ohio and White (1881, p. 91–92) in Pennsylvania. Alternative correlations have been proposed by later geologists—Cushing (1888); Girty (1905, p. 5–7); Butts (1910, p. 36–37, 57–58); Prosser (1912a); Ver Wiebe (1916; 1917); Chadwick (1923; 1925; 1933, p. 280–281); Caster (1934); and others. Figure 9 shows generalized sections at various places along the outcrop and the correlation of the lower Mississippian beds according to the findings and interpretations of the present writers.

Because the outcrop of the lower Mississippian rocks between Berea, Ohio, and Corry, Pa., trends across parts of three overlapping delta fans of probable early Mississippian age, as shown by figure 25, the lateral variations in lithologic character are abrupt, even within one formation. In mapping the area between outcrop 28 at North Bristol, Ohio, and outcrop 104 at Corry, Pa. (pl. 4), every outcrop was examined and the rock units were correlated with adjacent sections even where the exposures were within a few hundred feet of each other. This examination was necessary because of the abrupt feathering out or lateral gradation in some of the thinner units in the section and because of the great similarity of the siltstones in this area. About one gully in four contained sufficient outcrops for purposes of correlation. Thus, exposure-to-exposure field tracing was absolutely necessary to avoid confusing the stratigraphic units and making erroneous correlations. Many of the errors and miscorrelations in the literature are due to attempted long-



1 Zone A of Preliminary Chart 21 (U S Geol Survey Oil and Gas Investigations, 1946)
2 As originally defined by I C White (Pennsylvania 2d Geol Survey Rept QQQQ, p 97, 1881)

Figure 9.—Correlation chart of some of the stratigraphic units present along the outcrop between Berea, Ohio, and Corry, Pa.

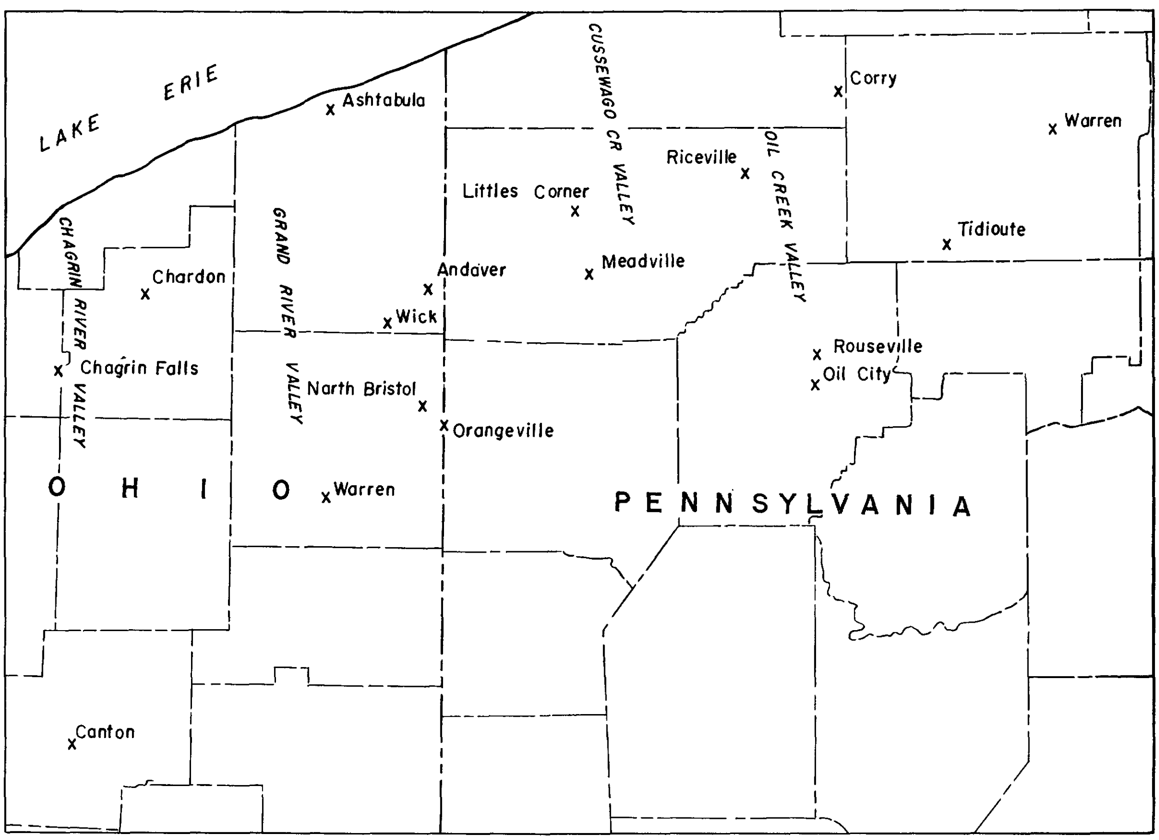


Figure 10.—Sketch map showing some of the places in northeastern Ohio and northwestern Pennsylvania mentioned in this paper.

range correlation of widely spaced sections without adequate study of the intervening exposures.

In 1880 White (1881) made a reconnaissance study of Erie and Crawford Counties, Pa., that was excellent considering the lack of adequate maps and the small number of outcrops from which the structure might be determined. Somewhat later, Prosser (1912a) and his assistants made many reliable stratigraphic observations in northeastern Ohio, but they did not compile a map showing the outcrop of the Berea sandstone in this area although topographic maps were available. However, since this early work there has been a tendency among other geologists to attempt long-range all-inclusive correlations based upon the examination of a few widely scattered sections. Consequently, many conflicting correlations have been proposed by various geologists.

SUBSURFACE CORRELATIONS

Before any valid conclusions could be drawn regarding the subsurface extent, thickness, composition, or mode of origin of the lower Mississippian rocks in the Appalachian basin, it was first necessary to make detailed well-to-well correlations, so that the equivalence of recognizable stratigraphic units from one part of the basin to other parts could be established.

The drilling of wells in the Appalachian basin proceeded independently for many years in a number of isolated areas, with the inevitable result that different names were applied locally to the same formation. Conversely, drillers moving from one field to another often erroneously applied names familiar to them in other fields where they had worked. The result was confusion, producing conflicts of opinion that could not be reconciled until formations could be studied regionally. One of the first objectives, then, of the present investigation became the subsurface correlation of the lower Mississippian rocks, and the consequent determination of recognizable stratigraphic horizons throughout the Appalachian basin. This was done mainly by the study of plotted well logs and detailed cross sections to ascertain the full extent and stratigraphic relationships of the Berea sand and the Bedford shale.

During the course of the investigation it was found convenient for purposes of description to construct two maps. One represents the several areas for which the Bedford shale and its approximate equivalents are described (fig. 11). The other represents the several areas for which the Berea sand and its near equivalents are described (fig. 35). The several areas are designated by letters, and a few of the units described have no other adequate names than these letters. Areas F and C (fig. 11), for example, contain recognizable units in the subsurface, but the rock facies in these areas are not known to crop out. The drillers never distinguished them as distinct units, and hence never assigned distinctive names to them.

On the other hand, some units restricted to the subsurface have been named previously by drillers and by geologists. Nevertheless, these units also are assigned letters for the sake of uniformity and to limit the units more sharply. For example, the unit named the Second Berea sand by the drillers is given the letter "E" in figure 11 to indicate the area of "true" Second Berea sand as defined and described by the authors. Similarly letter designations O and P are applied to the Berea sand in the Gay-Fink and Cabin Creek Channels in figure 35. These units are parts of the Berea sand having previous local designations, but are equal in rank to other parts of the Berea sand that had not been distinguished before the present work. The writers believed that it was best to preserve valid local names where possible, allowing the letter-designations on the maps to indicate the unnamed units and to supplement the names already in use.

These letter-designations are restricted to the sandy or silty rocks of Bedford and Berea strata. Other subsurface units are referred to by their common names. For example, mention is made occasionally of the Catskill redbeds (fig. 13). The use of the name Catskill is not to be interpreted as having any other meaning than to designate a group of Upper Devonian rocks, largely red, that have been known by that name in the literature for many years.

CUSSEWAGO SANDSTONE

GENERAL FEATURES

The Cussewago sandstone is part of the sequence of rocks named the Cussewago limestone, shale, and sandstone by White (1881, p. 94–96) for exposures along Cussewago Creek valley in western Crawford County, Pa. It is composed of fine to coarse, angular to subangular quartz grains that are normally coated by iron oxides. The sandstone is characteristically poorly cemented; in color it is dull greenish-yellow. In many places small discoidal or ellipsoidal pebbles as much as one-quarter of an inch in diameter occur either scattered through or in small lenses in the lower part of the Cussewago sandstone. The Cussewago sandstone appears to be unfossiliferous except for a few bits of plant tissue.

Because the name Cussewago was applied by White to a shale and a local limestone as well as to the sandstone, later geologists have restricted the name to the sandstone, but they have also extended the name beyond the limits of the sandstone. Recent work by the present writers has shown that the shale named

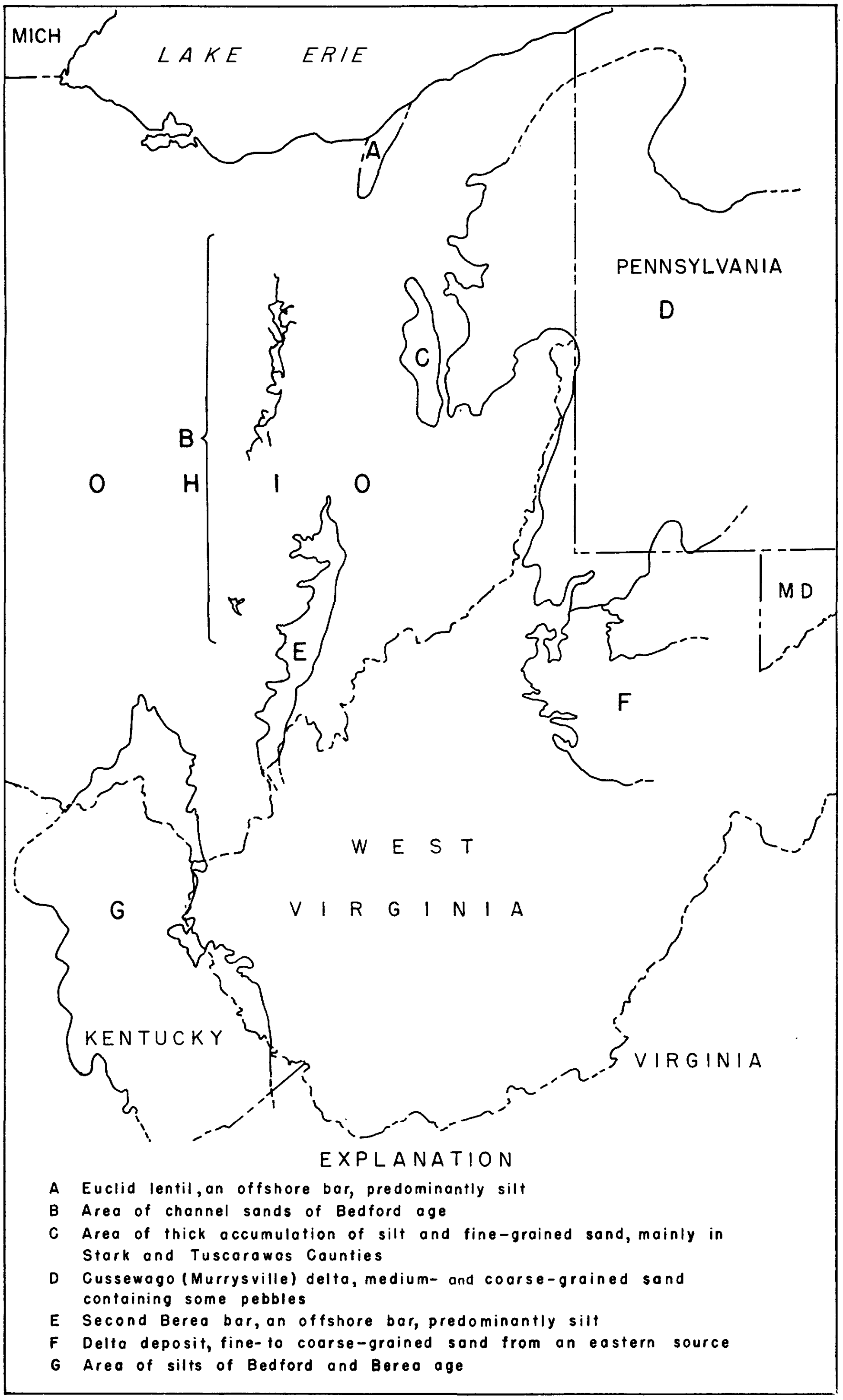


Figure 11.—Sketch map showing the different areas of silt and sand deposition in latest Devonian or earliest Mississippian time as described in this paper.

Cussewago by White is the eastern part of the Bedford shale of northern Ohio, and that White's Cussewago limestone at its type locality is a local limy bed in the base of the siltstones of the Berea sandstone. The name Cussewago, therefore, is best used only to apply to the sandstone. Because White's type locality of his Cussewago rocks is somewhat indefinite, the Cussewago sandstone was defined (de Witt, 1946) as the typical friable greenish-yellow to greenish-brown quartz sandstone found below the Bedford shale in outcrop 59 (pl. 4), which is Bartholomew's section of White (1881, p. 204). In this outcrop 8 miles northwest of Meadville, Pa., the Cussewago sandstone lies 37 feet below the top of the Bartholomew siltstone member of the Orangeville shale and 29 feet below the top of the Berea sandstone. The section occurs on a tributary of Cussewago Creek on the west side of the Cussewago valley, which is in the general type area designated by White (1881, p. 95–96).

The Cussewago sandstone crops out from outcrop 29 at North Bristol, Trumbull County, Ohio, eastward across northeastern Ohio and northwestern Pennsylvania to outcrop 92 about 4 miles west of Riceville, in Athens Township, Crawford County. East of this point the Cussewago disappears, for it is not present in outcrop 94 at Riceville, Pa. The base of the sandstone is not exposed in Ohio, although 30 feet of the Cussewago sandstone crops out in a section, outcrop 34, at Wick, Ohio. In Pennsylvania the full thickness of the Cussewago sandstone can be seen at many places. Apparently owing to an irregular base the sandstone ranges from 9 to 35 feet in thickness. Because the lithologic character of the Cussewago sandstone is constant throughout its extent, the sandstone forms one of the most easily recognizable formations in the area.

At outcrop 59 a siliceous limestone 1 foot thick is present 12 feet below the top of the Cussewago sandstone. It is very hard and weathers to form large slabs characteristically having rounded corners. This limestone and similar lenses of siliceous limestone are local in geographic extent and cannot be traced from outcrop to outcrop. In the past much mention has been made of these siliceous limestones, but the present writers found these local limestones useless as stratigraphic markers because of their erratic occurrence in the Cussewago, Berea, and Corry sandstones.

RELATION OF THE CUSSEWAGO SANDSTONE TO CASTER'S COBHAM CONGLOMERATE MEMBER OF THE KNAPP FORMATION

The Cussewago sandstone together with the overlying shale and the limy layer in the base of the siltstones of the Berea at outcrop 59 has been designated by Caster (1934, p. 52–53, 112–115) as the western extension of the Knapp formation of Warren, Pa. The Cussewago sandstone has been considered by him as the western part of his Cobham conglomerate member of the Knapp formation. Caster (1934, p. 113) states:

> West of Warren the [Cobham] member is usually very loosely cemented. The angular pebbled rock ("millet grained" texture) is known as the Cussewago sandstone in Erie and Crawford Counties and eastern Ohio.
>
> * * * * *
>
> So far as field evidence would indicate, the Cobham retains the Cussewago lithology westward through Crawford County and beyond the Ohio line.

As has been pointed out by the writers, the Cussewago sandstone disappears from the section between outcrop 92 and outcrop 94 west of Riceville, Pa., and the sandstone is not present in the outcrops between Corry and Oil City, Pa. The Cussewago sandstone is separated laterally from Caster's Cobham conglomerate member of the Knapp formation by a belt of shale and therefore is not the western part of the Cobham.

SUBSURFACE FEATURES (MURRYSVILLE SAND)

The Murrysville sand of the subsurface has been traced to its outcrop in Ohio and in Crawford County, Pa., and is there identical with the Cussewago sandstone. Because the name Murrysville is widely used by the drillers, in this paper the present writers have used the name Cussewago (Murrysville) to designate the sand which is the Cussewago sandstone on the outcrop and the Murrysville sand in the subsurface. Traced southeastward in the subsurface from the outcrop the Cussewago (Murrysville) has been known by various names: the Homeworth or "Second Berea" sand in the eastern tier of counties in Ohio; the combined Gas and Salt sands in Lawrence and Beaver Counties, Pa.; the Butler Gas sand in Butler County, Pa.; and the Murrysville sand in southern Clarion County, eastern Allegheny County, and Armstrong, Indiana, and Westmoreland Counties, Pa. The Murrysville sand was named from the village of Murrysville, in Westmoreland County, Pa., where early wells produced large quantities of gas from this sand. In Mercer County and in the northern part of Lawrence and Butler Counties, Pa., this sand is sometimes called Berea, Second Berea, or Gas sand; less frequently other names are applied.

The detailed correlation of these rock units is discussed in the section on the Berea sand, pages 34–36.

BEDFORD SHALE

EXPOSURES WEST AND SOUTH OF BEREA, OHIO

In northern Ohio, the Bedford shale consists predominantly of soft red clay shale which near the base grades into grayish-black shale and a few intercalated ripple-marked siltstones as much as 3 inches thick.

At some places the upper part of the Bedford shale may contain a few thin layers of siltstone. In many exposures the basal siltstones of the Bedford appear greatly deformed and rolled into cylindrical shapes (Pepper and others, 1945b). The present writers have named these distorted siltstones flow rolls and the zone of deformation the flow-roll zone. The thickness of the Bedford shale in northern Ohio is very irregular because the Berea sandstone was deposited in channels that had been scoured into or through the Bedford shale. In western Lorain County the Bedford attains a maximum thickness of 150 feet, and in Huron County, where channeling cut deeply into the Bedford, the Bearea sandstone rests either directly on or in close proximity to the upper part of the black Ohio shale. Outcrops of the Bedford shale are very poor in this part of northern Ohio. Only along the steep valleys of the larger streams does the shale crop out, and because the red shale weathers rapidly to a soft sticky red mud most of these outcrops are soon obscured by slumping and soil creep.

The amount of red shale in the Bedford and the intensity of color decrease from northern Ohio southward. In sections near Lithopolis about 10 miles southeast of Columbus, only a few feet of reddish- or chocolate-brown shale occurs near the middle of the gray and gray-blue soft clay shales which comprise the Bedford in central Ohio. In some sections in central Ohio calcareous siltstones ranging from 2 to 4 inches in thickness occur in the upper 8 feet of the Bedford shale, and in the basal part of the shale some thin gray silty mudstones are present.

Siltstones increase in number and thickness in the upper part of the Bedford shale south of Columbus, so that in sections in Ross County south of Chillicothe the upper third of the Bedford contains a great many thin platy siltstones and layers of hard silty shale. Most of the siltstones show fucoid casts and many well-formed oscillation-type ripple marks on their upper surfaces. Some small nodules of pyrite, marcasite, and calcium carbonate occur in thin layers in the upper part of the Bedford shale in southern Ohio. At a few places along its western outcrop, some small collections of invertebrate fossils have been made from the basal part of the Bedford shale. In Ross and Pike Counties, the Bedford shale grades from soft clay shale in the lower part to thin siltstones and intercalated gray silty shales in the uppermost part of the formation (fig. 55). The outcrops of the Bedford shale south of Norwalk, Ohio, are very poorly exposed, for glacial drift blankets much of the area. However, along some of the south-flowing streams in central Ohio, the Bedford shale crops out in low cliffs. The shale is well exposed at many places along Big Walnut Creek and some of its tributaries between Sunbury and Columbus. The Bedford is 90 feet thick along Big Walnut Creek near Columbus (Stauffer and others, 1913, p. 220) and is 85 feet thick in sections near Chillicothe (Hyde, 1921, p. 36, 86, 104).

The transition zone at the base of the Bedford shale in northern Ohio is missing along most of the western outcrop, and only at a few places are thin stringers of black shale found in the basal part of the Bedford. The disconformity at the top of the Bedford, which is so marked in northern Ohio at places where the Berea sandstone fills channels cut completely through the Bedford, becomes less marked southward along the outcrop. In sections near Columbus, the channeled surface at the top of the Bedford has a maximum relief of about 5 feet (Prosser, 1912b), and south of Lithopolis the Bedford shale and the Berea sandstone are essentially conformable. In the vicinity of Chillicothe the exact contact between the two formations cannot be drawn with certainty, for the basal siltstones of the Berea intergrade into the siltstones of the upper part of the Bedford shale. Carman (1947, p. 52) notes the absence of a lithologic break between the Bedford and the Berea formations in a drill core taken from a test boring about 3 miles southwest of Chillicothe. Hyde (1911, p. 257) has suggested that in southern Ohio the Berea is a phase of the Bedford, because of the apparent impossibility of separating the two formations. South of Chillicothe in Pike and Scioto Counties the Bedford shows a marked change. The siltstones increase to such an extent that in the vicinity of Buena Vista in western Scioto County the Bedford is composed largely of siltstone. Butts (1922, p. 18) reports a section near Garrison, Ky., in northern Lewis County, in which the Bedford seems to be made up completely of siltstone. The siltstones of the Bedford cannot be separated from those of the Berea south of Buena Vista, Ohio, and in that area the two are discussed as a single unit.

The shale partings that separate the siltstones of the Bedford from those of the Berea increase in thickness from Buena Vista, Ohio, to the south and west, and at Alum Rock near Vanceburg, Ky., about 40 feet of silty shale separates the siltstones of the Bedford from the siltstones of the Berea (Morse and Foerste, 1912, p. 16–17). The siltstones are not present in the section in southern Lewis County, Ky., their place being taken by soft bluish-gray shale. Morse and Foerste (1912, p. 24–25) proposed the name Petersville shale for the 46 feet of shale of the Bedford and Berea sequence in the vicinity of Petersville, Ky., about 18 miles south of Vanceburg. They report that only a few thin siltstones are present in this shale. South of Petersville, the combined Bedford and Berea strata are composed of bluish-gray to gray clay shales and some gray silty shale. The thickness of the Bedford and Berea strata, which measures 125 feet at the Ohio River, decreases to a few inches in the vicinity of Hargett and Irvine in Estill County, Ky.

The upper contact of the Bedford and Berea unit is sharply defined where the fissile black Sunbury shale lies with apparent conformity upon siltstones. In sections near Irvine, Ky., the basal beds of the Sunbury shale come in contact with the upper beds of the Ohio shale by the disappearance of the intervening Bedford and Berea rocks from the section.

EXPOSURES EAST OF BEREA, OHIO

The Bedford shale is composed predominantly of soft red shale in the area west of Berea, Ohio, but undergoes a marked lithologic change a short distance to the northeast in the vicinity of Cleveland. Along the west bank of the Cuyahoga River in Independence Township, Cuyahoga County, the Bedford shale contains about equal parts of red and gray shale and in the basal part a 12-foot thickness of the Euclid siltstone member. At its type locality at Bedford, along Tinkers Creek on the east side of the Cuyahoga River opposite the town of Independence, no red shale is found in the entire thickness of the formation. At this locality it is composed of about 85 feet of gray and bluish-gray shales, nodular light-gray mudstones, and brownish-gray to gray irregularly bedded siltstones. The 12 feet of massive siltstone in the base of the Bedford along the west bank of the Cuyahoga River is probably represented by some thin gray siltstones in the basal part of the Bedford at the type locality.

In the vicinity of Cleveland two zones of massive siltstone occur in the Bedford shale. The Sagamore siltstone member is found in the lower third of the Bedford on Sagamore Creek in southeastern Cuyahoga County, and the Euclid siltstone member of greater areal extent crops out from Independence Township, Cuyahoga County, to Willoughby Township, Lake County. (See fig. 53.) The Euclid siltstone member has a maximum thickness of about 20 feet; the Sagamore siltstone member may reach a maximum thickness of 20 feet. The Euclid siltstone occurs at the same stratigraphic level as the Second Berea sand of Athens, Gallia, Meigs, Morgan, and Muskingum Counties.

In some outcrops in the vicinity of Cleveland the lower several feet of the Bedford shale contains many invertebrate fossils. These fossils have been discussed by Cushing (Cushing, Leverett, and Van Horn, 1931, p. 43–45) and Prosser (1912a).

The writers easily traced the Bedford shale eastward across Cuyahoga, Lake, and Geauga Counties, where it forms cliffs beneath the more resistant Berea sandstone. The upper contact of the Bedford shale is extremely irregular, for the Berea sandstone was deposited in channels that had been scoured into the Bedford shale by erosion prior to the deposition of the Berea. The lower strata of the Bedford in many places appear to be gradational into the Cleveland. The silt content of the Bedford increases toward the east so that in outcrops along the west bank of the Grand River valley in western Ashatbula and Trumbull Counties the Bedford is composed largely of silty gray shales, hard silty gray mudstone, and thin platy gray siltstones. The Bedford, thinning eastward, is 85 feet thick at Bedford and 45 feet thick at outcrop 24 in southwestern Ashtabula County (pl. 4).

CORRELATION OF THE BEDFORD SHALE

Attempts to correlate the Bedford shale in northeastern Ohio and northwestern Pennsylvania have created much discussion and resulted in the suggestion of several ingenious stratigraphic interpretations. Read (1873) traced the Bedford shale eastward across Geauga, Lake, Ashtabula, and Trumbull Counties to the State line; and White (1881, p. 91–92 and fig. 11*b*, p. 82) correlated his Cussewago strata with the Bedford shale of eastern Cuyahoga County. Although not in agreement with Read's interpretation of the stratigraphic features of the Berea and associated formations in northeastern Ohio, Cushing (1888) correlated the Bedford shale with White's Cussewago shale of northwestern Pennsylvania. Influenced by the idea of a threefold or tripartite Berea sandstone, later geologists, including Prosser (1912a), Chadwick (1925), and Caster (1934), proposed differing correlations.

In discussing the Chagrin shale of Ohio, Chadwick (1925) revised the correlation of the lower Mississippian rocks between Cleveland, Ohio, and Meadville, Pa. He introduced the idea of an unconformity which from Cleveland rises eastward in the section, thus cutting out progressively younger Mississippian ("Waverlyan") beds. Chadwick assumed that as these beds were cut out, progressively younger Upper Devonian ("Bradfordian") rocks were exposed below the plane of the unconformity as it rose to the east. Figure 12 is his schematic diagram showing the unconformable relation of these beds. Chadwick attempted to show that as the Bedford shale was cut out of the section in Ashtabula County, White's Cussewago shale was exposed below the plane of unconformity. Chadwick (1923, p. 69; 1925, p. 463–464) renamed White's Cussewago shale, calling it Hayfield for the township of that name in western Crawford County, Pa. Chadwick applied the name Hayfield also to White's Cussewago limestone, which Chadwick (1925) believed occurred only sporadically in eastern Ohio because it had been removed by erosion at some places.

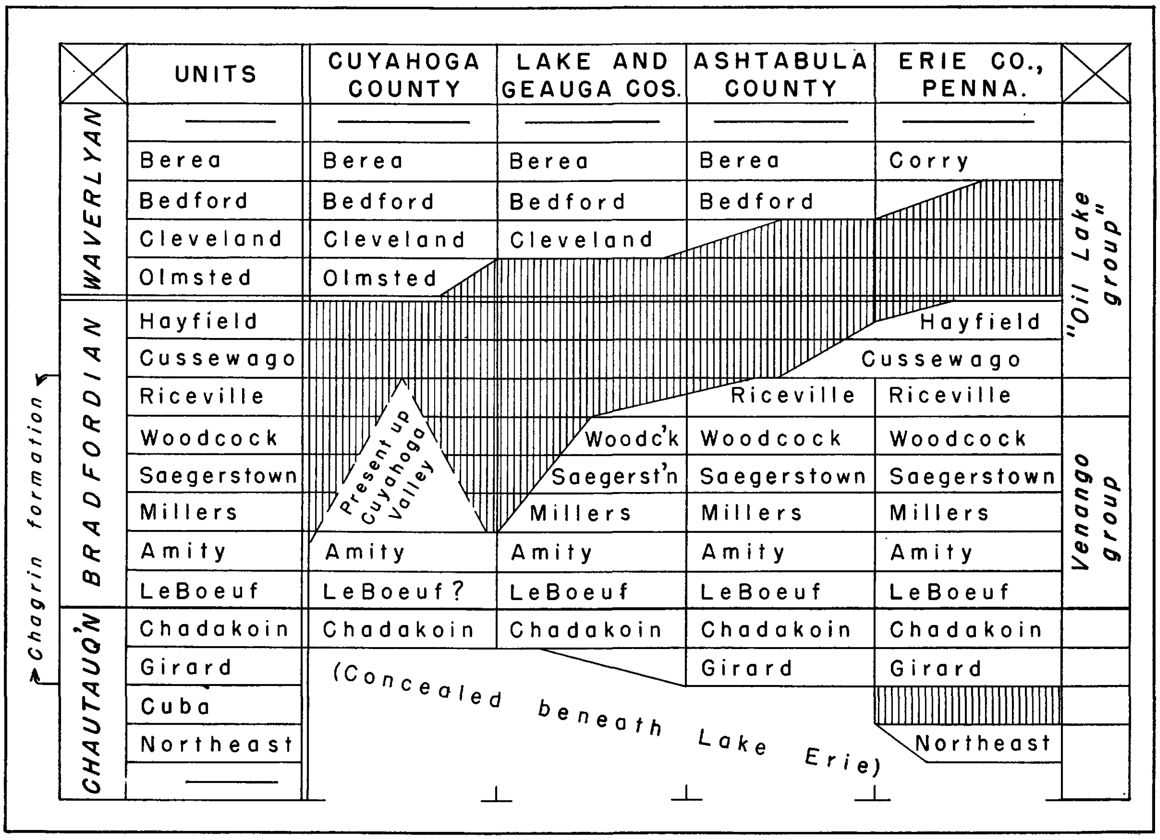


Figure 12.—Correlation of the Chagrin shale and adjacent beds in northern Ohio and northwestern Pennsylvania as proposed by G. H. Chadwick showing diagrammatically the position of his Summit unconformity. After Chadwick (1925, p. 464).

Chadwick also assigned a pre-Bedford age to his Hayfield shale. His correlations (Chadwick, 1933, p. 280–281) are based partly on the painstaking field work of Prosser and Cushing in Ohio and partly on the following assumptions:

1. The Berea sandstone and the Corry sandstone are a single formation.
2. The Cussewago sandstone is a part of the Knapp formation of southwestern New York and northwestern Pennsylvania.
3. A great unconformity is present at the base of the Cleveland shale, but no marked unconformity is known between the Cussewago sandstone and the underlying Chagrin shale.
4. His Hayfield shale, which is of pre-Bedford age, extends eastward into the vicinity of Warren, Pa.

Caster (1934, p. 104–105, 155–164) revised Chadwick's classification of these lower Mississippian rocks. Caster correlated the Bedford shale of Ohio with his Kushequa shale of north-central Pennsylvania on rather tenuous evidence which is based in large part on paleontological data. Caster (1934, p. 116) described his Hayfield "monothem" as

really composed of two parts, seemingly of member rank. The upper is the Hayfield, sensu stricto [Chadwick's Hayfield shale], which includes the Hayfield limestone (here called Littles Corner limestone), and a lower member which enters toward the east and south which is only meagerly developed in the type Hayfield area. This lower member is being termed the Tidioute shale member.

He states also (Caster, 1934, p. 121):

The position of the Littles Corner limestone to the Berea (Corry) is somewhat variable, but it usually occurs from 15 to 20 feet below the Corry base.

The writers have traced the Bedford shale across the Ohio-Pennsylvania State line between outcrop 24 in southwestern Ashtabula County, Ohio, and outcrop 59 in central Crawford County, Pa. Although fossils were observed only at outcrop 39 on Stratton Creek, the Bedford was traced from gully to gully by its characteristic lithologic features. The shale contains many gray and bluish-gray ripple-marked siltstones whose upper surfaces are marked by many fucoids. Pyrite, some mica, and fragments of plant tissue are found scattered through the Bedford shale in eastern Ohio. From outcrop 34 at Wick, Ashtabula County, Ohio, eastward the Bedford rests on typical Cussewago sandstone and is overlain by siltstone of the Berea. The Bedford shale is 44 feet thick at outcrop 34 and decreases to 22 feet at outcrop 59, 8 miles northwest of Meadville, Pa. East of outcrop 59 the Bedford shale thins rapidly and loses its identity as a formation in the vicinity of Meadville, Pa. At outcrop 73, a unit 4.8 feet thick, consisting of silty gray shales and intercalated thin siltstones, which has been named the Shellhammer Hollow formation (de Witt, 1951), contains equivalents of both the Bedford shale and the Berea sandstone. The eastward thinning of these rocks continues and at outcrop 75, 8 miles northeast of Meadville, Pa., the Shellhammer Hollow formation is composed of 4 inches of silty gray shale.

A few thin siliceous limestones occur in the upper or lower parts of the Bedford shale in eastern Ohio and northwestern Pennsylvania. Chadwick (1925) applied the name Hayfield limestone to one of these extremely lenticular local limestones which was exposed in Hayfield Township, Crawford County, Pa. These limestones may occur at any stratigraphic horizon from the middle of the Cussewago sandstone to the lower part of the siltstones of the Berea, and they cannot be correlated from one exposure to the next. They certainly do not constitute a formation; in fact no limestone is present in the Bedford shale at outcrop 59, which is the type locality cited for White's Cussewago limestone, renamed the Hayfield limestone by Chadwick. At outcrop 59 a thin siliceous limestone occurs in the base of the Berea sandstone and a similar appearing limestone occurs 12 feet below the top of the Cussewago sandstone, but no widespread limestone occurs in Chadwick's Hayfield shale. In the partly exposed sections between outcrop 59 and outcrop 62, several siliceous limestones were found, but they were found either in the lower part of the Berea or in the Cussewago sandstone rather than in the Bedford shale.

In describing the Tidioute shale member of his Hayfield "monothem," Caster (1934) says:

> The *Tidioute shale member* is so-called for the excellent exposure of the unit along the Allegany River at Tidioute, and especially for the exposures along the State Highway through Dennis Run, one mile southwest of Tidioute. This seems to be the area of maximum development of the member. Here, on Dennis Run it is 23 feet thick. At Meadville the member is about ten feet thick, at Warren the thickness is in excess of fifteen feet, but the total is unknown. At Miller Farm, on Oil Creek the Tidioute member is slightly over 20 feet thick. At Tionesta, on the Allegany River the thickness is approximately the same. On Cussewango Creek, in the type section of the Hayfield shale the Tidioute member is much thinner than at Meadville, being not more than five feet thick in sections studied.

However, the Bedford shale, which was called Hayfield by Chadwick, disappears from the section in the vicinity of Meadville and cannot be recognized as a distinct formation in outcrop 72. Therefore, it seems improbable that Caster's Tidioute shale member extends westward from the vicinity of Tidioute and Warren, Pa., to outcrop 59, Hayfield Township, 8 miles northwest of Meadville. Caster (1934, p. 116) reports the thickness of his Hayfield "monothem" to be 60 feet in the vicinity of Meadville; slightly less than 60 feet on Cussewago Creek; and about 45 feet near Tidioute on the Allegany River. However, the shale between the top of the Cussewago sandstone and the base of the siltstone of the Berea at outcrop 59 is only 22 feet thick; at outcrop 65 it is 7 feet thick; and at outcrop 81 it is 4 feet thick. At outcrop 75 the Shellhammer Hollow formation, which is 4 inches thick, includes the easternmost remnants of the Berea sandstone and the Bedford shale. Therefore, Chadwick's Hayfield shale cannot possibly extend east of Meadville to the Allegany River.

The writers conclude that White's Cussewago shale is synonymous with the Bedford shale and that, because the name Bedford has priority, the names Cussewago shale and Hayfield shale are invalid and may be dropped from the literature. Also, the names Cussewago limestone, Hayfield limestone, or Littles Corner limestone cannot be applied to definite rock units and may also be dropped from the literature.

SUBSURFACE

At its type locality at Bedford, Ohio, along Tinkers Creek, the Bedford shale is composed mainly of gray to bluish-gray shales and thin gray to brown siltstones. Well records do not provide sufficient evidence to trace these shales and siltstones of the Bedford in the subsurface for any appreciable distance, and over a large area the presence of the typical Bedford may be only surmised. The base of the Bedford shale may be recognized in well records only where it rests on the black Cleveland shale. The Chagrin shale, which occurs below the Cleveland shale on the outcrop, can easily be mistaken for the Bedford in the subsurface because of its lithologic similarity. It is thus impossible to draw the boundary between the Chagrin and the Bedford on the basis of well logs alone at places where the black Cleveland shale is absent.

In the area in which both the Cussewago sandstone, known to oil and gas men as the Murrysville sand (area D of figure 11) and the Berea sand are present, the Bedford is presumably the shale that occupies the interval between the base of the Berea sand and the top of the Cussewago (Murrysville) sand. The Berea and Bedford formations, as clearly shown along their outcrop in southern Ohio, are so closely related in depositional history that the Bedford shale is present, at least in part, in almost the entire area containing the Berea sand derived from a northern source (as discussed on p. 73). In a few localities, however, the Bedford is absent. For example, some of the drill cores of the U. S. Army Engineers in Champion Township, Trumbull County, Ohio, show that the Bedford is absent, probably by scour, and that the Berea sand rests directly on the Cussewago (Murrysville) sand. Other cores in the same locality, however, show what appears to be a thin remnant of Bedford. Perhaps the rock between the Berea and Cussewago (Murrysville) sands represents all of the Bedford. It is possible that this interval may represent only the upper Bedford deposition, and that the lower Bedford is in part equivalent in age to some of the Cussewago (Murrysville) sand. If this supposition is true, the lower Bedford was probably not deposited in this area.

A few miles west of its type locality the Bedford shale contains only a small amount of gray to bluish-gray shale. Most of this is present in the basal part, where it merges into grayish-black shale that appears gradational with the black Cleveland shale below. Beds of gray Bedford shale are present also a few feet above the Euclid siltstone member of the Bedford along the outcrop. However, the predominant and characteristic color of the Bedford shale west of the type locality is red, though some gray shale occurs in places along the outcrop, especially in or near the transition belt between the red and gray phases of the formation. In surface exposures in northern Ohio the red Bedford shale is unmistakable, because other red shales are not present in the Mississippian or Upper Devonian rocks of this area.

In the same way in the subsurface the red Bedford shale is easily recognized by its distinctive color. When the drillers record shale colors at all, they almost invariably record the red Bedford shale wherever it is present. A driller is not necessarily accurate in estimating the thickness of the red shale, however; for under the drill it may be churned and mixed with underlying gray shale so that a somewhat greater thickness of red shale is logged than is actually present. The red Bedford shale throughout most of its area is 50 to 150 feet thick. It is true, nevertheless, that many lenses of gray shale, if enclosed by red Bedford shale, would not be noticed by the driller.

The persistence of the red Bedford shale southward is remarkable. The writers traced the red shale from well to well, starting in Lorain and Cuyahoga Counties, Ohio, and reaching due south across the Ohio River into Cabell County, W. Va., at one point, and into Boyd County, Ky., at another. This broad belt (pl. 7) is defined by about 2,000 reliable records that note the presence of red shale at the horizon of the Bedford. Though some of the wells are grouped, as in certain of the Clinton fields, or along the trend of the Second Berea sand, which is area E in figure 11, the rough outline of the full extent of the red Bedford shale is indisputable, because a fair spread of detailed logs is available over the entire area. On the east and south the extent of the red shale is known from wells whose logs show only gray shale at the stratigraphic position of the Bedford. On the west along the outcrop, as well, the red shale thins and grades into gray Bedford shale in Pickaway County, Ohio. Generally, along all the margins of the red phase of the Bedford the red shale thins and grades into gray shale. The Berea sand is recorded above the red shale in nearly every well log in the entire area of deposition of the red Bedford shale. In many places a few feet of gray shale separates the red Bedford shale from the Berea sand.

In the subsurface the red Bedford shale is normally separated from the underlying black Ohio shale by about 15 feet of gray shale, representing the basal part of the Bedford shale. This gray shale appears to thicken markedly east of the red Bedford shale along the northern outcrop, and merges into the 85 feet of gray shale and siltstone at the type locality. Similarly along the western outcrop the basal gray Bedford shale thickens greatly toward the south as the red shale feathers out. The basal gray shale near the eastern border of the red shale lies at the same stratigraphic position as the Second Berea sand (area E, fig. 11), and, indeed, bears the same relationship to the Euclid siltstone member of the Bedford (area A, fig. 11) on the northern outcrop. It appears that the basal gray Bedford shale is a shale facies equivalent of the Second Berea sand and also of the Euclid siltstone member, and that the Second Berea sand and the Euclid siltstone member must have been deposited in early Bedford time.

Conclusive proof that the Second Berea sand is not merely a lower member of the Berea sand is furnished by many logs showing that the red Bedford shale occupies much or most of the 25- to 40-foot interval between the Second Berea and the Berea sand. The Second Berea sand is easily traceable as a single sand body, and is particularly well defined because more than 1,000 wells have been drilled to it in search of natural gas. The Second Berea sand is completely isolated and is stratigraphically lower than other sand bodies that some drillers have called "Second Berea" in Cambridge Township, Guernsey County (cross section A-A′, pl. 10); in Union and Rich Hill Townships, Muskingum County; and in York Township, Morgan County, Ohio. The red shale does not extend east of the Second Berea sand in the subsurface, or east of the Euclid siltstone member of the Bedford along the outcrop. How far the gray Bedford shale extends east of the Second Berea sand is a matter for speculation. The well logs provide inconclusive evidence.

Other sand bodies, which are separated vertically from the Berea by the red Bedford shale, are located in

Ames Township in Athens County, Reading Township in Perry County, and at other places in the area of the Red Bedford Delta. These sands are, of course, within the Bedford shale. Also, an elongate and sinuous sand body lying deeply enclosed in red shale at many places occurs in the main part of area B. This sand body trends north-south, is branched at irregular intervals, and is generally continuous for more than 40 miles. Because of its close association with red shale it is considered a part of the Bedford.

The Bedford shale appears to correlate also with the greater part of the thick mass of siltstone and fine sand, which lies in southern Ohio and eastern Kentucky as shown in figure 11 (area G). Similarly, much of the thick deposit of sand and siltstone generally known as Berea in area J (fig. 35) may also be of Bedford age. The upper 40 feet of the thick sand in this area is Berea, because it is continuous with Berea sand in surrounding areas. The lower 60 feet, however, which is often recorded only as shells or broken sand, is much less uniform and may be stratigraphically equivalent to part of the Bedford shale.

One of the regional problems of correlation of the Bedford is the possible equivalence of the red Bedford shale with the westernmost occurrences of the Catskill redbeds of Late Devonian age. Figure 13 incorporates the results of a survey of thousands of well records examined to determine the probable maximum boundaries of the Catskill redbeds and the red Bedford shale and to discover if at any point they merged or overlapped. No results of such a study have been published for more than half a century; consequently, correlations of these beds have been at best tentative or suppositional.

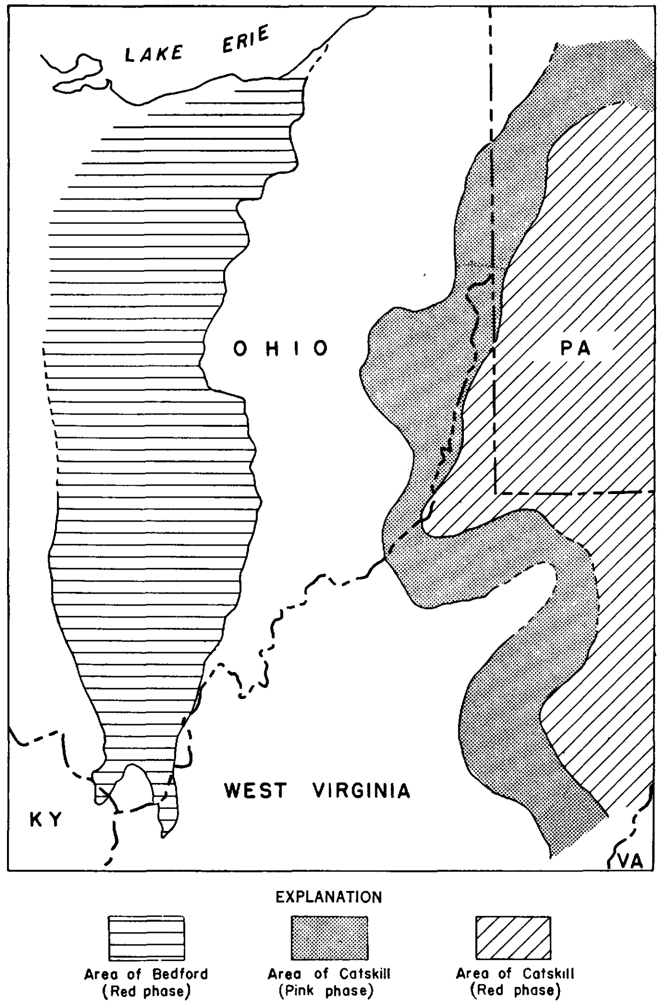


Figure 13.—Sketch map showing the westernmost extent of the upper part of the Catskill redbeds with relation to the red Bedford shale.

John F. Carll (1890, p. 93–104) thought that the red Bedford shale of Ohio could be traced into the upper part of the Catskill redbeds of western Pennsylvania. In his sketch map showing the general outlines of the red shale, Carll was amazingly accurate considering the amount of data he had available. His 16 wells, 15 in Ohio and 1 in Kentucky, coupled with information on outcrops, give a remarkably true picture of the red Bedford shale in Ohio, except for one area. This area, unfortunately, was critical; for Carll based his entire correlation with the redbeds of Pennsylvania on one well that was drilled in 1886 in Canton, Ohio. The record of this well, as quoted by Orton (1888b, p. 359) is certainly open to question. The well log gives 14 feet of red shale below the Berea, but since that well was drilled, hundreds of other wells, including wells from which samples were collected, have been drilled through the Bedford in that area without finding any trace of red Bedford shale. It is clear now, on the basis of abundant well logs, that the red Bedford shale is not traceable across eastern Ohio into the red shales of Late Devonian age in Pennsylvania.

Red shale of definite Late Devonian age is found 50 to 100 feet below the Berea locally in Monroe, Belmont, Jefferson, and Columbiana Counties, Ohio, although it is very erratic in distribution. Unless one keeps in mind the wide belt of rocks in which red shale is not present west of these counties, he can easily misidentify these eastern red shales of Late Devonian age as Bedford shale. Further, red shales in Cabell County, W. Va., and Boyd County, Ky., which were erroneously identified as the Catskill redbeds, are red Bedford shale.

The Michigan Basin is the only other area containing red shale reported to be of Bedford age. Newcombe (1933, p. 79) suggested that the red shale occurring locally below his Berea sandstone of that area is the equivalent of the red shale of the Bedford formation of Ohio. In their study of the Berea sandstone of Michigan, which was based largely on an examination of drill cuttings, Cohee and Underwood (1944) did not find red shale in the Bedford of that area. Their findings suggest that the extent of the red shale in Michigan is much more limited than was at first supposed.

BEREA SANDSTONE

EXPOSURES WEST AND SOUTH OF BEREA, OHIO

The Berea sandstone is a medium- to fine-grained clay-bonded quartz sandstone which can be divided into two parts at some places along the outcrop between Berea and Columbus. The upper 20 to 30 feet of the Berea is thinly bedded, and the upper surfaces of these beds show many well-formed oscillation-type ripple marks. The beds of the lower part of the Berea sandstone are more massive than the upper beds and cross bedding predominates over ripple marks. The thickness of the Berea sandstone varies greatly in this area, for the sandstone was deposited in channels which had been scoured into, and at some places through, the underlying Bedford shale. The Berea averages about 50 feet in thickness between Berea and Norwalk, although the mantling glacial drift makes thickness determinations difficult.

The name "channel sandstone" is used throughout the report for the thick isolated masses of sandstone which are characterized by steep walls, sinuous alinement, and rounded basal profiles. As shown in plate 6, channel sandstones form the lower part of the Berea sandstone in both the surface and subsurface parts of area H (fig. 35).

The channel sandstones range in thickness from a few feet to more than 235 feet, which is the maximum depth of quarrying in the Buckeye quarry at South Amherst, Lorain County. (See figs. 14, 15, 16.) Sandstone as much as 200 feet thick has been reported from core-drilling operations in that vicinity. East and west of South Amherst, the thickness of these channel sandstones decreases. West of South Amherst the amount of thinning cannot be accurately determined because of insufficient exposures in an area mantled by glacial drift and ancient lake deposits. The rate of decrease in thickness of the channel sandstones appears to be less to the west of South Amherst than to the east. The lower part of one of these channel sandstones is exposed on the shore of Lake Erie near Vermilion, Ohio. In this channel the scouring cut through the Bedford shale and most of the Cleveland member of the Ohio shale.

The sandstones of these channels are remarkably free of contaminating materials. A few small lenses of discoidal shale and siltstone pebbles, scattered plant fragments, and a few thin seams of coaly material can be found in the quarries, but this debris makes up much less than 1 percent of the total mass of sediment in the lower phase of the Berea sandstone. The lenses of pebbles are small, ranging in thickness from 1 to 16 inches and in length from 2 to 25 feet. They are most numerous in those channel sandstones which lie farthest to the south in area H (fig. 35). The pebbles range from ⅛ to 1 inch in thickness and from ½ to 3 inches in diameter. Most are discoidal and their edges are well rounded, showing that they had undergone some transportation prior to burial in the sandstone. These pebbles are composed of red, gray, and black shale and fine-grained steel-gray siltstone similar in appearance to the thin siltstone found in the basal part of the Bedford shale. The pebbles are enclosed in a matrix of Berea sandstone. Most of the lenses of pebbles stand out markedly from the enclosing light-gray or tan sandstone because ground water has stained the exterior of the pebbles deep brown or dull pinkish red. Three lenses of pebbles were observed in the Buckeye quarry at South Amherst and 11 in the Nicholl quarry at Kipton.

South of Norwalk the size and depth of the scour channels decrease, and in the vicinity of Columbus the basal contact of the Berea sandstone is a gently undulatory unconformity, which dies out to the south in the drift-covered area. The thickness of the Berea sandstone decreases toward the south. The total thickness of the sandstone is 65 feet at Sunbury (Stauffer, Hubbard, and Bownocker, 1913, p. 223); 39 feet near Gahanna (Stauffer, Hubbard, and Bownocker, 1913, p. 220–221), east of Columbus; 6½ feet at Lithopolis; and about 1 foot on Slate Run (Prosser, 1912b, p. 601–603) in the northeastern corner of Pickaway County, about 14 miles southeast of Columbus. South of Lithopolis the Berea is a siltstone containing only small amounts of very fine sand.

South of Slate Run the siltstone facies of the Berea increases in thickness; it is about 6 feet thick on Turkey Run in section 13, Walnut Township, Pickaway County, Ohio, and about 30 feet thick in southern Ross County, Ohio. (See figs. 18, 19.) In the vicinity of Chillicothe the lower part of the Berea contains many light-gray and buff siltstones which greatly resemble the siltstones that occur in the top of the underlying Bedford shale. Along the Ohio River in western Scioto County, Ohio, the siltstones of the Berea and the siltstones in the Bedford intergrade, and it becomes impossible to separate the mass of siltstones into two formations. Therefore, the Bedford and Berea are mapped together and considered a single unit lying between two black shales.

Throughout most of the area between Berea and Norwalk the Berea underlies a broad gently sloping, drift-mantled terrace. In the stream valleys that trench this surface, the sandstone is well exposed, and many of the smaller streams and runs are choked by large float blocks of Berea sandstone that have fallen

FIGURE 14.—The north wall of the Buckeye quarry, South Amherst, Lorain County, Ohio. About 150 feet of Berea sandstone is exposed in this photograph. Less than 300 feet back from the quarried face, core drilling recorded only red Bedford shale.

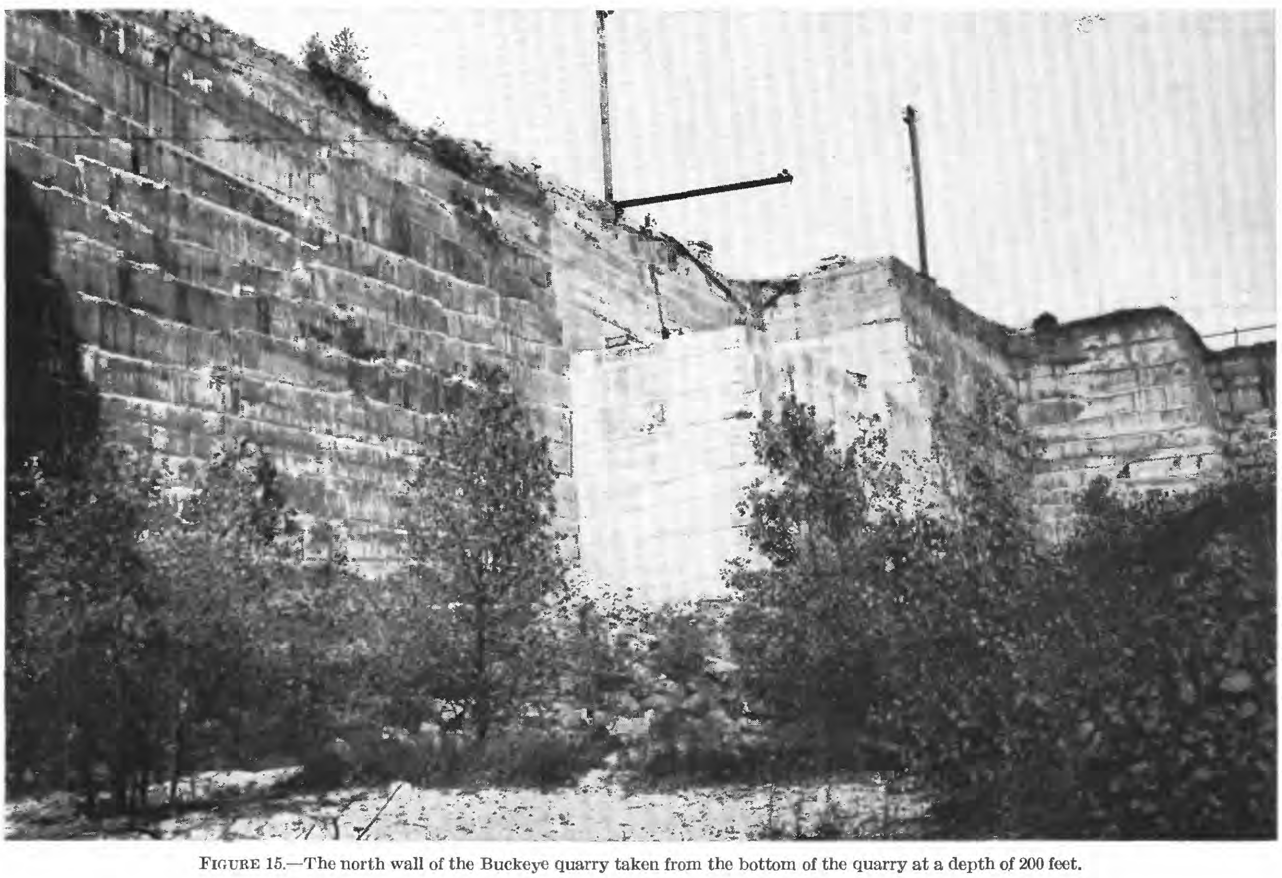


FIGURE 15.—The north wall of the Buckeye quarry taken from the bottom of the quarry at a depth of 200 feet.

FIGURE 16.—Southeast corner of the Nicholl quarry at Kipton, Camden Township, Lorain County, Ohio. View illustrates the steep wall of one of the thicker sandstones of the Berea. The man is seated on Berea sandstone which core-drill records show has a minimum thickness of 100 feet. The red Bedford shale is exposed in the small excavation to his left. A drill-hole core, 20 feet to the man's left, showed only red shale and no sandstone. Figure 39 shows the relative location of the Nicholl and Buckeye quarries.

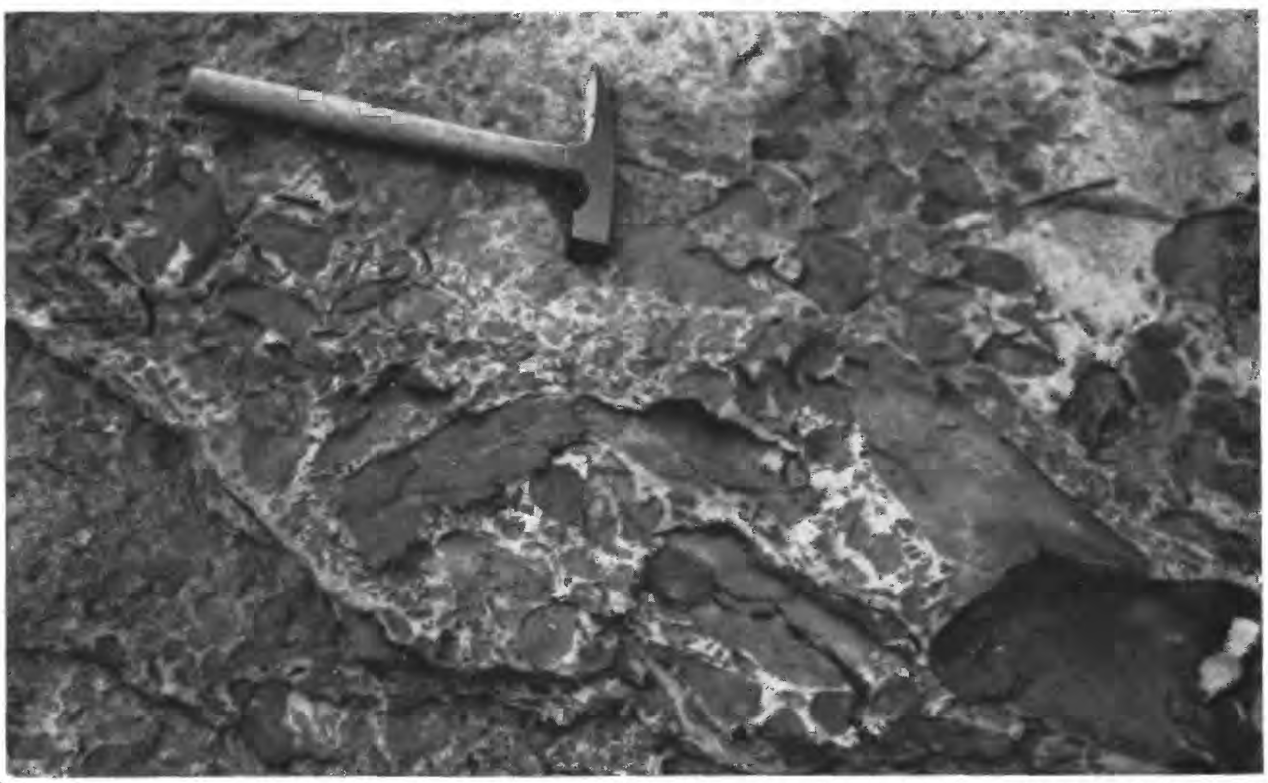


FIGURE 17.—Pebbles of iron-stained siltstone, black shale, and red shale in a block of Berea sandstone from the Nicholl quarry, Kipton, Lorain County, Ohio. Scale shown by hammer.

FIGURE 18.—The hermit's cave in the upper part of the Berea sandstone, on U. S. Highway 23, 5½ miles north of Waverly, Pike County, Ohio, showing the massiveness of the upper siltstones of the Berea in southern Ohio. When William Hewitt, a hermit, occupied this cave, the roof rock extended 25 feet farther to the left, making a much more extensive cave.

FIGURE 19.—Outcrop of the black Sunbury shale (*a*), the Berea sandstone (*b*), and the upper part of the Bedford shale (*c*) on Turkey Run, section 13, Walnut Township, Pickaway County, Ohio. This outcrop is 8 miles northeast of Circleville, Ohio. The geologist's hammer marks the contact of the Berea sandstone and the overlying Sunbury shale. In this exposure the basal part of the Berea sandstone fills a shallow channel in the underlying Bedford shale. The basal 10-inch bed of the Berea contains oil.

into the creek beds because of the removal of the underlying soft red Bedford shale. The Berea caps some of the cliffs along many of the larger stream valleys, and in these exposures the irregular base of the Berea sandstone is clearly exposed. The topography between Norwalk and Columbus is much more subdued, and much of the outcrop is covered by a thick mantle of glacial debris. Small patches of Berea sandstone crop out along some of the major streams, but because of the low degree of dip of the sandstone and the low stream gradient, exposures of the complete thickness of the sandstone are uncommon.

Between Columbus and Chillicothe the outcrop of the sandstone is nearly everywhere covered by drift, and exposures of the Berea are difficult to find. Very little can be determined about the deposition of the Berea sandstone in this part of its outcrop. However, throughout eastern Adams, Pike, Ross, and Scioto Counties, Ohio, the topography is much rougher, and the Berea caps many of the broad, flat-topped hills in those counties. Small streams cascade across outcrops of the Berea, and many exposures of the siltstone can be found except along the river valleys which have been partly filled by alluvium.

EXPOSURES EAST OF BEREA, OHIO

The writers traced the fine- to medium-grained Berea sandstone without difficulty from the type locality at Berea, Ohio, eastward across Cuyahoga, Lake, and Geauga Counties. The sandstone, which averages about 40 feet in thickness, is characteristically rippled-marked in the upper part and cross-bedded in the lower part. Throughout most of these counties and in the outcrops along the west side of the Grand River valley, the Berea sandstone filled channels which were scoured in the Bedford shale. In the vicinity of Berea in western Cuyahoga County the channel sandstones average about 100 to 125 feet thick—about half as thick as those in the vicinity of South Amherst and Amherst, Lorain County. The decrease in depth of the channels was apparently accompanied by an increase in width. The outcrop between the Cuyahoga and Chagrin Rivers contains the thinnest channel sandstones in any part of the Berea outcrop west of the Grand River valley. East of the Chagrin River, the channel sandstones of the Berea are again thicker, and in northern Geauga and southern Lake Counties they are about as thick as those observed in the vicinity of Berea, Ohio. The channels appear to have been cut to a greater depth in northwestern Geauga County than in eastern Cuyahoga or eastern Geauga Counties. The sandstone filling the channels is slightly coarser grained than the sheet sandstone in the upper part of the Berea. At a cut in Granger Road, shown in figures 20, 36, 37, 38, and at Peninsula, south of Cleveland, the lower massively bedded part of the Berea sandstone contains some small discoidal to round pebbles that are largely composed of vein quartz. These pebbles are found along the surfaces of the planes of cross-bedding or in small scour channels in the Berea sandstone.

Throughout much of this area of thick sandstone east of Cleveland, the Berea contains some thin local lenses of gray silty shale similar in appearance to the underlying Bedford shale. These lenses of shale or "breaks" are extremely local and cannot be traced from outcrop to outcrop. At outcrop 18 (pl. 4) on Phelps Creek a shaly zone near the middle of the Berea contains many well-formed sun cracks. Figure 21 shows the occurrence of some of these local lenses of shale in the Berea sandstone in northeastern Ohio.

East of outcrop 26 in northwestern Trumbull County the Berea changes from a fine-grained sandstone to a siltstone containing small amounts of very fine sandstone. Although the exposures between outcrop 28 in southeastern Geauga County and outcrop 31 in central Trumbull County are very poor, the siltstone in the Berea was traced across the southern end of the drift-filled Grand River valley by means of core-drill records furnished by the U. S. Army Engineers. These drill records plus some outcrop data verified the presence of siltstone of the Berea in southeastern Trumbull County. Thinning of the Bedford shale in southern Trumbull County brings the siltstone in the Berea into close proximity to the Cussewago sandstone and thus facilitated the tracing of the Berea across the Grand River valley.

Between outcrop 31 in central Trumbull County, Ohio, and outcrop 59 in central Crawford County, Pa., the Berea is composed of thin- to medium-bedded gray, white, tan, and light-brown siltstone which shows extreme local current cross bedding in some places and massive bedding in others. In some outcrops thin lenses of light bluish-gray or medium-gray siliceous limestone occur in the lower part of or at the base of the Berea. Although much of the bedrock in this area is obscured by glacial drift, the Berea was easily traced from outcrop 31 to the vicinity of outcrop 59. Correlation of units in the exposed rocks of this area is particularly hazardous, for the Sharpsville sandstone which lies about 40 feet above the Berea and the massive siltstones in the upper part of the Chagrin shale which lie about an equal distance below the Berea can easily be mistaken for siltstones of the Berea.

East of outcrop 59 near Littles Corner and west of outcrop 73, 2 miles north of Meadville, the siltstones of the Berea merge into the Shellhammer Hollow formation and cannot be positively identified.

Exposures of the Berea sandstone in northeastern Ohio examined by the writers clearly show that the

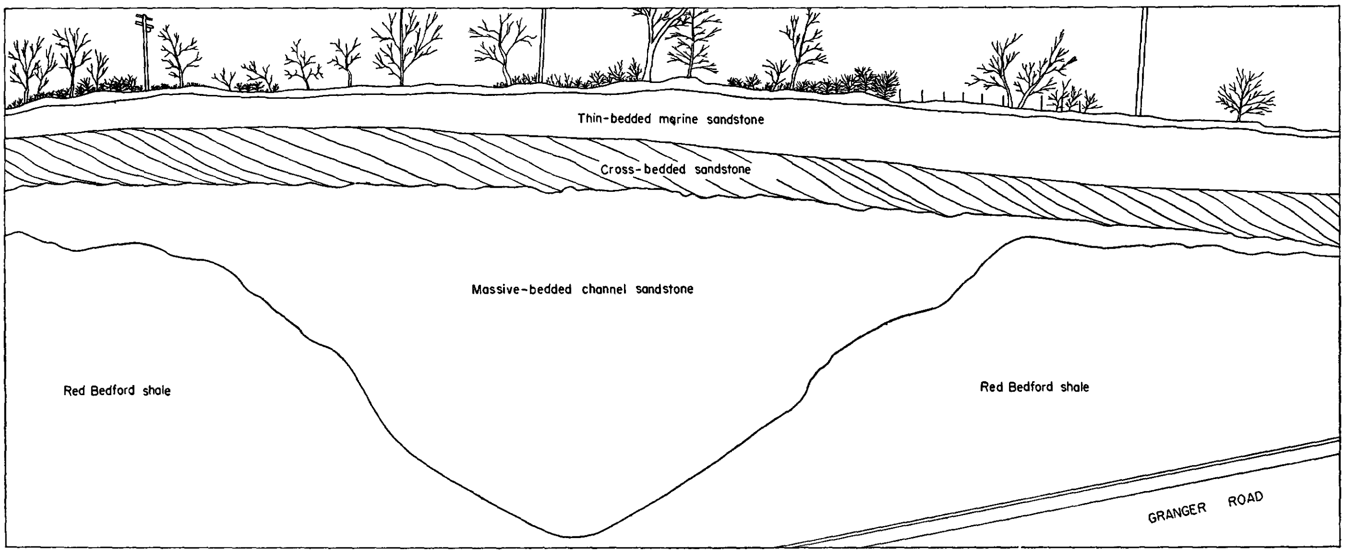


FIGURE 20.—Sketch showing three phases of the Berea sandstone in northern Ohio. Exposure on Granger Road, U. S. 17, Newburg Township, Cuyahoga County, Ohio See figs. 36, 37, 38 for photographs of this outcrop.

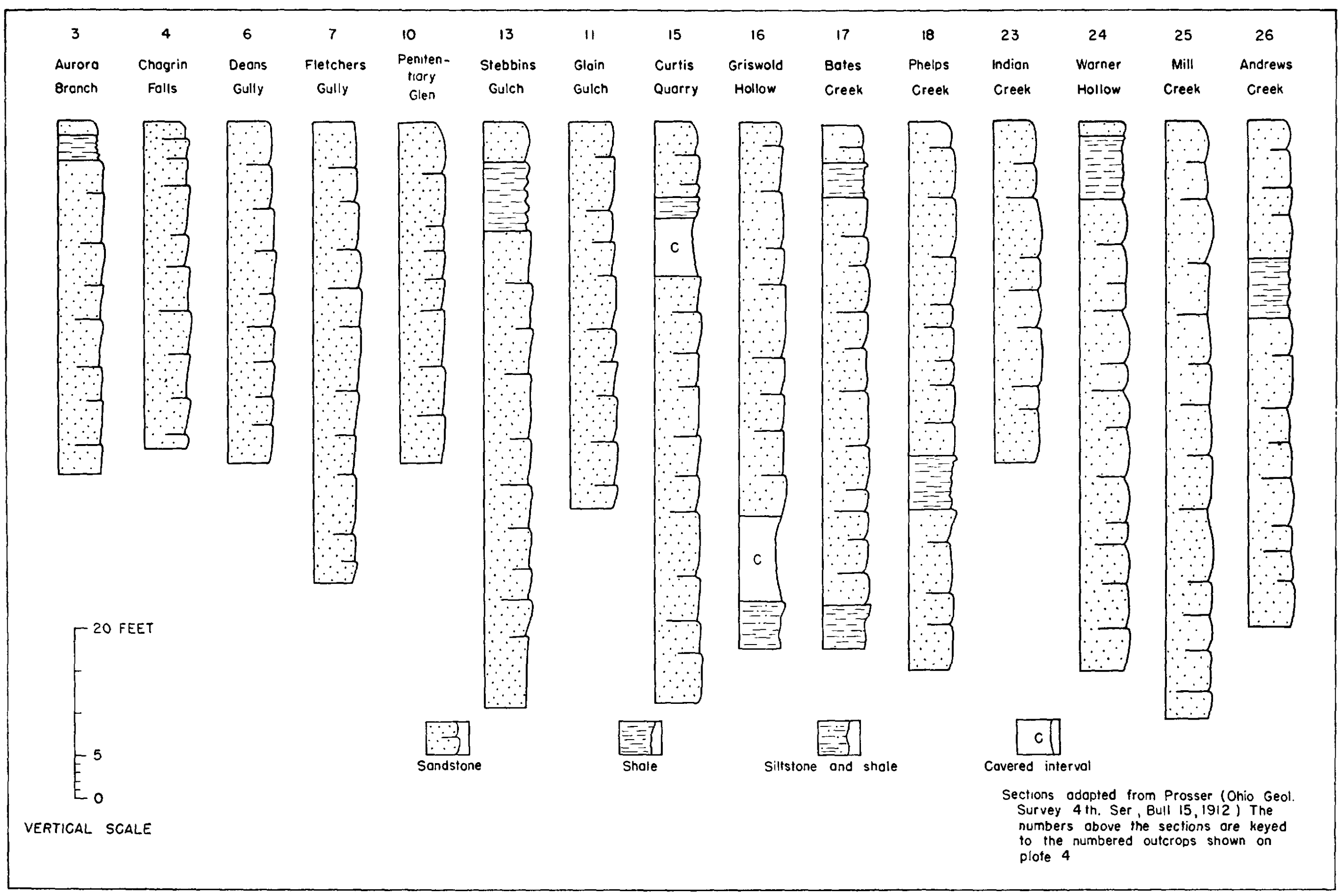


FIGURE 21.—Sections of the Berea sandstone in northeastern Ohio. Shows the irregular occurrence of thin lenses of shale or siltstone and shale in the Berea sandstone in northeastern Ohio.

Berea sandstone is not the threefold or tripartite formation that Caster (1934, p. 47) believed it to be. Thin lenses of shale occur at many horizons, but none of these could be traced beyond a single outcrop. The hypothesis of the tripartite or threefold Berea was evolved to account for the presence of the Cussewago sandstone in northeastern Ohio on the assumption that the Cussewago was genetically a part of the Berea. However, the Cussewago sandstone is a separate formation which was deposited from the southeast and is not related genetically either to the Berea sandstone of Ohio or to the Knapp formation of north-central Pennsylvania.

In studying the outcrops of the sandstone and siltstone of the Berea sandstone in northeastern Ohio and northwestern Pennsylvania, the writers observed invertebrate fossils in the siltstones of the Berea only along the Ohio-Pennsylvania border, especially in outcrop 39 at Stratton Creek near Kinsman, Ohio. The fossils in these siltstones resemble those found in the siltstone of the Corry sandstone in the vicinity of Corry, Pa. With the exception of the outcrops in the vicinity of the State line in eastern Ohio, the Berea sandstone is largely unfossiliferous.

SUBSURFACE

From the type locality at Berea in northern Ohio, the Berea sand may be traced underground by means of numerous well records and is recognizable in the subsurface as an almost continuous sand body over thousands of square miles of eastern Ohio, western Pennsylvania, western West Virginia, and northeastern Kentucky.

Throughout most of Ohio in areas I and J and in most of areas H and K, as shown in figure 35, the Berea maintains a gradual southeasterly regional dip. The black Sunbury, or "coffee", shale lying on the Berea sand serves as a marker, and except in local areas which will be discussed below, no other persistent sands are found near the horizon of the Berea.

South of Chardon, Geauga County, Ohio, and in surrounding areas the black Sunbury shale grades into gray shale in places, and local sands such as the Chardon siltstone member may be present in the lower part of the Orangeville shale. Where the Berea is thin and one or more of these local sands are logged by the driller, proper identification of the Berea sand can be made by checking the interval between the top of the Berea and the top of the "Big Lime" (Devonian). Also, at places in or near Mahoning County, Ohio, the Berea may be absent or reduced in thickness as a result of erosion that cut deep valleys into the Mississippian sediments in the area. Pennsylvanian sands, such as the Sharon conglomerate (member of the Pottsville formation), were deposited in these valleys and so may be found in some places at or near the horizon of the Berea. The localities where erosion has removed part or all of the Berea must be carefully determined so that these valley-fill sands of Pennsylvanian age are not correlated as a part of the Berea.

Although the Berea sand can be traced eastward from Ohio into northwestern Pennsylvania, it has not always been identified there as the Berea. Instead, it is known by a variety of names, each usually, but not exclusively, applied in local areas. Chief among these names are "Amber sand" in Lawrence County and in parts of Mercer and Butler Counties, "St. Patrick sand" in northern Butler County, and "Big Shell" in parts of Mercer County.

The Corry sandstone of eastern Crawford County and Venango County, which has been confused with the Berea in some places, cannot be distinguished from the Berea by its elevation alone; for the top of the Corry and the top of the Berea probably do not differ by more than 10 feet stratigraphically. Nevertheless, the Corry is not an eastern siltstone phase of the Berea, because as shown on plate 1 a definite belt of shale and shells between 5 and 25 miles wide separates the Berea sand laterally from the Corry in the subsurface, making continuous tracing impossible. This belt of shale and shells is present also along the nearby outcrop, where it is named the Shellhammer Hollow formation (de Witt, 1951). Additional evidence presented in the discussion of surface correlations shows that the Berea and Corry are separate formations.

In addition to the Corry, the Cussewago (Murrysville) and 2d Gas sands of Pennsylvania and their various lobes or extensions, which are also known by an assortment of names, have likewise been wrongly identified as Berea or Berea equivalents in various places. Though their stratigraphic positions are very close to that of the Berea, detailed subsurface tracing shows that they are distinct lithologic units.

RELATIONSHIP OF BEREA SAND AND CUSSEWAGO (MURRYSVILLE) SAND IN EASTERN OHIO AND WESTERN PENNSYLVANIA

Wherever both the Berea and Cussewago (Murrysville) are present, the Berea lies above the Cussewago (Murrysville). Locally, in Champion Township, Trumbull County, Ohio, as shown by samples of drill cores of the U. S. Army Engineers, the intervening Bedford shale has apparently been removed by scour, and the Berea sand rests directly on the Cussewago (Murrysville) sand. Northward on the outcrop, however, as much as 44 feet of Bedford shale is present. Well logs generally show a shale "break" of about 20 feet between the Berea and Cussewago (Murrysville) sands, but a very wide range from 2 to 40 feet is not uncommon. The thinnest "breaks" are usually found in Ohio.

The most difficult area for correlations, and the one that holds the key to most of the correlation problems of the lower Mississippian in the northern half of the Appalachian basin, lies in Washington County and eastern Allegheny County, Pa., and extends westward across the West Virginia panhandle into Jefferson County, Ohio. In the central part of this area drillers usually log about 100 feet or more of what they term the "Upper 30-foot shells" or "sand." This unit was called the "Berea-30-foot sand" on the original Preliminary Map 29, and "Upper 30-foot sand" on Preliminary Map 89. (See pl. 14 and fig. 22.) Traced westward, the middle part of the Upper 30-foot shells grades into easily recognized Berea sand, but eastward the middle zone is represented only by shale. Traced westward the basal zone becomes shale, but eastward it is the Cussewago (Murrysville) sand. The topmost zone of the Upper 30-foot shells is continuous both eastward, where it is called the "2d Gas sand", and westward where the name "Stray sand" is used. Confirmation of these correlations is provided by six wells in the Burgettstown quadrangle, including a sample well by Fettke (1941, p. 23–28), the A. T. McBurney No. 1, all of which show three distinct zones of sand in the Upper 30-foot shells, corresponding to the 2d Gas, Berea, and Cussewago (Murrysville) sands. The three units are thus present in the Burgettstown quadrangle, though usually lumped by the drillers into a single large unit. In the Carnegie quadrangle, to the east, the 2d Gas and Cussewago (Murrysville) sands are present, but the Berea is missing, and in the Steubenville quadrangle, to the west, the Stray (2d Gas) and the Berea sands are present, but the Cussewago (Murrysville) is absent. The area in which the name "Upper 30-foot shells" is applied by the drillers corresponds roughly with the southernmost lobe of the Cussewago (Murrysville) sand as shown in figure 22. In the area of this lobe the Berea is probably almost completely absent except along the northwestern border, but the 2d Gas sand, occurring in the upper part of the Upper 30-foot shells, and especially the Cussewago (Murrysville), occurring in the lower part, are generally present. The 2d Gas sand is also present in Fayette County, Pa., and eastern Monongalia County, W. Va., just east of the lobe of Murrysville sand. This area of the occurrence of 2d Gas sand is called "area of Upper Berea sand" on the original Preliminary Map 29. The term Berea is here restricted to deposits genetically related to the type Berea in Ohio, and the name "2d Gas sand" is more suitable for the stratigraphically higher sand.

In western Pennsylvania where the Berea sandstone is absent, the relationship of the Cussewago (Murrysville) sand to other sands is complex. It is advisable,

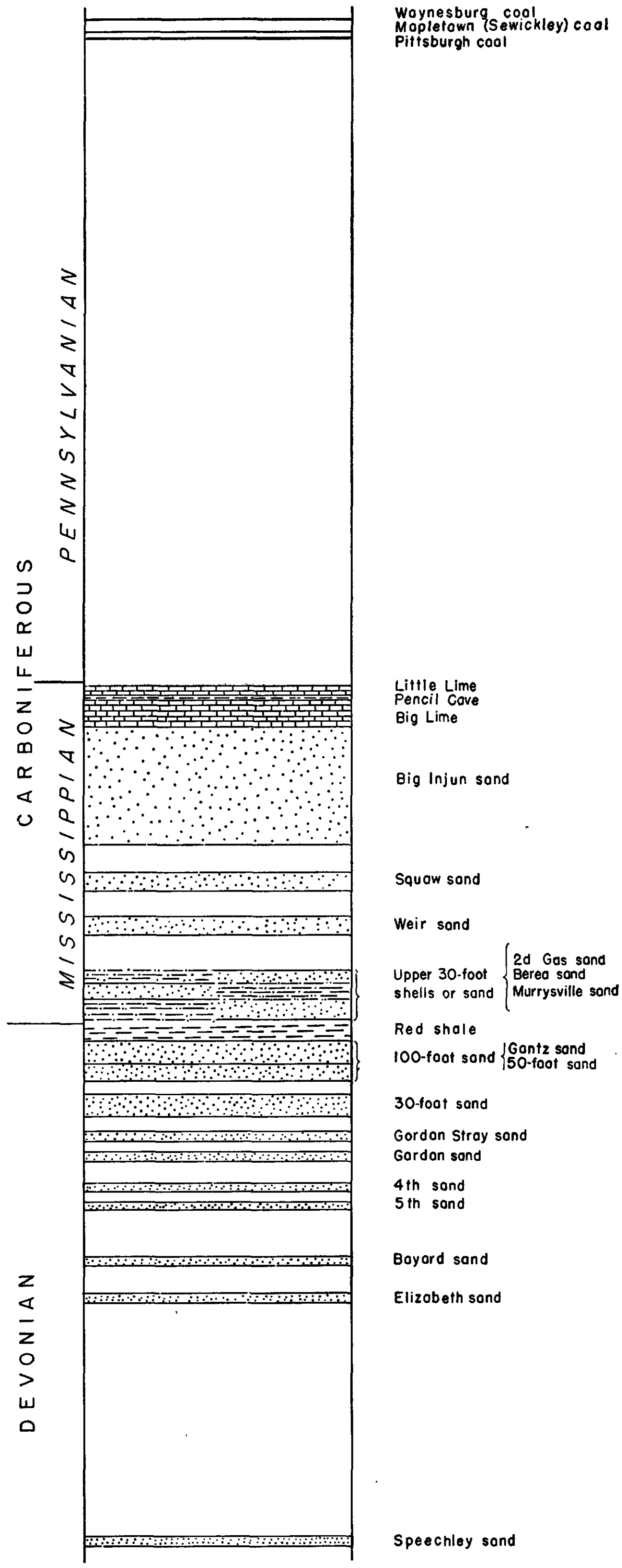


Figure 22.—A generalized columnar section of Washington County, Pa., showing the relative position of some of the drillers' stratigraphic units mentioned in the text. The thickness of the sands has been exaggerated.

282219—55——4

therefore, to discuss the means of determining the approximate stratigraphic position of the Cussewago (Murrysville) sand for any well drilled in this area.

The coals of Pennsylvanian age are the most reliable guides to correlation in the greater part of the area, because they are widespread and are usually accurately logged. The Pittsburgh coal is the most reliable, and its identification can often be checked by the presence of the Mapletown (Sewickley) and Waynesburg coals about 100 and 325 feet above it, respectively. The rough average interval of the Pittsburgh coal above the Cussewago (Murrysville) in this area is about 1,800 feet, but the interval increases somewhat to the southeast, and decreases to the northwest. The Upper Freeport coal, about 1,200 feet above the Cussewago (Murrysville) in the eastern part of the area, is also useful locally as a guide in ascertaining the horizon of the Cussewago (Murrysville). The base of the Injun sand maintains a fairly constant interval of about 350 feet above the Cussewago (Murrysville) in the western part of this area, but the interval thins irregularly to about 250 feet in the eastern part. Although the Injun is of much aid locally, its usefulness cannot always be relied upon, because of the presence in some areas of the underlying Squaw sand.

The parallelism of the numerous Upper Devonian sands and the Cussewago (Murrysville) sand in area D (fig. 11), though marked, is not as striking as it is to the south in area F (fig. 11) of West Virginia. In Pennsylvania especially, these Upper Devonian sands are subject to much lensing or overlapping and are often wrongly identified by the drillers. Shale of the Catskill redbeds is logged by many drillers at about 50 or 100 feet below the Cussewago (Murrysville) sand in the southwestern corner of Pennsylvania, and similarly below the Berea in a few places in the West Virginia panhandle, and in eastern Monroe County and Belmont and Jefferson Counties, Ohio. This red shale provides one of the best indications for separating the Berea and Cussewago (Murrysville) sands from the Upper Devonian Gantz sand and 50-foot sand (100-foot group) below, for in no place in this area is red shale recorded above either the Berea sand or the Cussewago (Murrysville) sand (fig. 22). The best recent discussion of the Upper Devonian sands of this area is to be found in the report by Matteson and Busch (1944).

CORRELATION OF THE BEREA SAND OF SOUTHERN OHIO, WEST VIRGINIA, AND KENTUCKY

The Berea sand of Ohio is usually easily recognized. Below the Berea lies the characteristic red Bedford shale, thus making identification positive in a wide north-south belt extending from Cuyahoga County on Lake Erie to Lawrence County, along the Ohio River in the southernmost part of the State.

In southeastern Ohio, however, approximately along the valley of the Ohio River, the Berea sand thins to shells and finally disappears. The single notable exception occurs where the sand of the Gay-Fink Channel abuts the main area of the Berea. This channel sand provides the only means of correlation of the Berea sand of Ohio with sediments derived from the eastern side of the basin. The Berea can be traced without difficulty from well to well northeastward along the channel to the vicinity of Fink, which lies on the west edge of area F (figs. 11 and 47). In area F the Sunbury shale appears to be absent, and the Upper Devonian sands increase in number and thicken progressively toward the eastern flank of the Appalachian basin. New and erratic sands appear in the lower Mississippian rocks, and structural trends become more marked, adding to the complication of the correlation problem in area F. The results of the correlation study indicate that the Berea sand at Fink lies at the same stratigraphic level as a broad fan-shaped, eastward-thickening sand that has been interpreted on the basis of petrographic and other evidence as a delta fan. The Berea at Fink, and for at least 19 miles eastward, as is more fully explained on pages 75–78, 94–95 and shown on plate 1, appears to have been incised into these slightly older rocks of the delta fan. The sand of this delta fan merges northward at the same stratigraphic level into the southernmost lobe of the Cussewago (Murrysville), and may be considered to be approximately equivalent to Cussewago (Murrysville) in age.

The striking parallelism of the sand of area F delta fan and the other Upper Devonian sands is of great service in determining the stratigraphic position of the delta fan. The intervals between the sand of area F delta fan and the higher Mississippian sands are very irregular and hence less useful. The Upper Devonian sands below the sand of this delta fan most often encountered in the well records of this area are, from top down, Gantz, 50-foot, 30-foot, Gordon Stray, Gordon, Fourth, Fifth, Bayard, Elizabeth, and Speechley. (See pl. 14 and fig. 22.) The intervals between the delta-fan horizon and these deeper sands are surprisingly constant. The Fifth sand is the most useful for correlation, because it is sheetlike, productive, isolated vertically from other sands, and is nearly always logged in area F, though occasionally not correctly named by the drillers. A good rule of thumb is that the top of the delta-fan deposit lies about 500 feet above the top of the Fifth sand. This relationship holds true for more than 90 percent of the wells reaching the Fifth sand in area F. If the Fifth sand is not logged, the deeper Bayard, Elizabeth, or Speechley sands frequently provide good guide horizons. If the wells do not reach the Fifth sand, the next best guide horizons are the Fourth, Gordon, and Gordon Stray sands, particularly if these are productive. Sometimes the 30-foot or 50-foot sands are helpful, but they are seldom diagnostic. The Gantz sand, which often is logged only as the upper part of the 50-foot, is of little use in correlating the delta-fan horizon. Frequently the name "Gantz" is misapplied to the next higher sand, which is actually the area F delta fan, especially when the Gantz and 50-foot are logged in combination as "50-foot." The Upper Devonian redbeds sometimes provide an additional correlation check, but more often are not dependable because of their erratic distribution.

From the top down, the Mississippian units named by the drillers that are most often encountered above the area F delta fan are the Little Lime, Pencil Cave, Big Lime, Big Injun, Squaw, and Weir, but correlations of sand of the delta fan based on any of these units are generally unreliable, except possibly in very local areas. The Weir sand is not logged regularly enough to be used, and the intervals between the sand of area F delta fan and the other higher Mississippian units decrease with marked irregularity southeastward toward the eastern outcrop belt. Although the interval between the base of the Big Injun and the top of the delta fan may be fairly constant locally, the frequent inclusion of the Squaw sand in the Big Injun makes it difficult to recognize the true base with any assurance of accuracy. Because of unequal deposition or by unconformity the upper Mississippian units thicken and thin rapidly, and correlations based on them are doubtful. Because of their extreme lenticularity, Pennsylvania units have been found highly unsatisfactory for correlating any of the lower sands. The Pittsburgh and Mapletown (Sewickley) coals do not appear in most well records in area F, and the coals recorded are not persistent.

In most of area F the delta-fan horizon can be correlated from well to well without difficulty, but in Barbour and Upshur Counties, W. Va., and eastward to the outcrop on the east side of the Appalachian basin, the Upper Devonian and lower Mississippian sands thicken, and the intervening shales thin or disappear. Although the approximate delta-fan horizon may be recognized in Barbour and Upshur Counties and eastward, the determination of the boundaries of this unit is impossible.

The easily recognizable Berea sand of Ohio extends southward through areas N and M shown in figure 35, as far as the southernmost counties in West Virginia. The correlation of the Berea in these areas, as in most of Ohio, is relatively simple because of the absence of the Upper Devonian sands that are present in area F and in parts of western Pennsylvania and because the Sunbury shale is present throughout the area. Almost duplicating the relationship found to the north in the vicinity of the Gay-Fink Channel (area O), the Cabin Creek Channel (area P) provides the only safe means of tracing the Berea east of the main sand body in area N. The sand in area N becomes progressively thinner and more erratic to the east, until in the eastern part of the area the Berea is nearly absent except for the comparatively uniform sand body of the sand of the Cabin Creek Channel. This channel sand is the main aid in determining the horizon of the Berea either to the north, east, or south in south-central West Virginia. Whether a delta fan comparable to the one in area F lying east of the Gay-Fink Channel exists east of Cabin Creek is still a matter of conjecture, because there has been almost no drilling between the Cabin Creek Channel and the Pocono sandstone of the eastern outcrop.

The Berea sand is difficult to trace from area M to area G (see fig. 35) because of abrupt changes in thickness and lithology. As can be seen from the isopach map (pl. 1), the thickness of sand and siltstone increases sharply in area G. The drillers' records generally show a thick section of sand in the interval between the black Sunbury shale above and the black Ohio shale below. Much of this so-called sand may be Bedford in age as is suggested locally by a shale break in the upper part of the sand in Boyd County, Ky. However, in most of area G the age separation cannot be made because of the gradation of the siltstone of the Bedford into siltstone and fine sand of the Berea.

In the western part of area G, the siltstones of Bedford and Berea age grade laterally into a gray shale named Petersville shale by Morse and Foerste (1912, p. 24–25). This gray shale, which separates the Sunbury shale from the Ohio shale, thins to a knife edge. In this area miscorrelations are sometimes made because drillers may fail to record the thin gray Petersville shale of Morse and Foerste. Thus, they record the Sunbury shale, Morse and Foerste's Petersville, and the Ohio shale as a single unit which they recognize only as the Ohio shale. The Weir sand (see fig. 23), which in this area occurs above the Sunbury shale, is then called Berea because it lies above a black shale which the drillers believe is the Ohio shale. The miscorrelation is completed when a dark shale above the Weir is erroneously termed "Sunbury". The result of this miscorrelation has been to extend the name Berea sand westward into an area where the Berea does not exist. The fact cannot be stressed too strongly that in this particular area, and indeed throughout the entire basin, correlation of a great mass of plotted logs is the only safe course to follow if reasonably reliable conclusions are

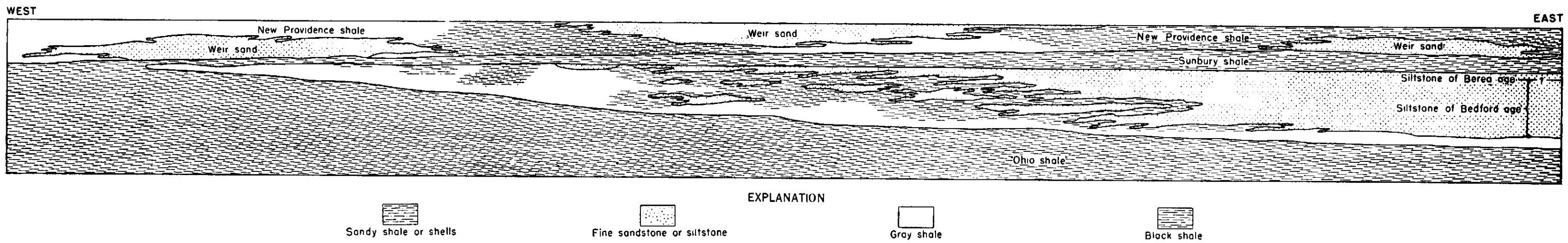


FIGURE 23.—Generalized cross section showing the relation of the siltstones of Bedford and Berea age in the western half of area G in eastern Kentucky.

I. C. WHITE 1881

OHIO	PENNSYLVANIA
Berea grit	Corry sandstone
Bedford shale	Cussewago {limestone, shale, sandstone}
Cleveland shale	

H. P. CUSHING 1887

OHIO	PENNSYLVANIA
Berea grit	Corry sandstone
Bedford shale	Cussewago shale
	Cussewago sandstone

C. S. PROSSER 1912

OHIO	PENNSYLVANIA
Berea sandstone	Corry sandstone
	Cussewago {shale, sandstone}
Bedford shale	

G. H. CHADWICK 1925

OHIO	PENNSYLVANIA
Berea sandstone	Corry sandstone
Bedford shale	
Cleveland shale	
	Hayfield shale
	Cussewago sandstone

K E. CASTER 1934

OHIO	PENNSYLVANIA
Upper Berea sandstone	Corry sandstone
Berea shale	Hayfield shale
Basal Berea sandstone	Cussewago sandstone
Bedford shale	Kushequa shale

K E. CASTER, *ALTERNATE HYPOTHESIS*

OHIO	PENNSYLVANIA
Berea sandstone	Corry sandstone
Bedford shale	Hayfield shale
	Cussewago sandstone

THIS PAPER

OHIO	PENNSYLVANIA (Crawford County) Western	Central	Eastern
Berea sandstone	Berea sandstone	Shellhammer Hollow formation	Corry sandstone
Bedford shale	Bedford shale		
Cussewago sandstone (Murrysville sand in subsurface)	Cussewago sandstone (Murrysville sand in subsurface)		
Clevelond member of the Ohio shale			

FIGURE 24.—Correlations between northeastern Ohio and northwestern Pennsylvania

desired. The use of plotted records of single wells, or typewritten log sheets, or even of isolated sample logs if not used in conjunction with plotted drillers' logs, generally raises more difficulties than it settles. The extra time and trouble required by the use of large numbers of plotted logs are amply rewarded by the greater accuracy in the resulting correlations.

CORRELATION OF BEREA AND CORRY SANDSTONES

Read (1873) traced the Berea sandstone eastward from western Lake County and Geauga County into the broad drift-covered valley of the Grand River in western Ashtabula and Trumbull Counties. (See pl. 4.) Here, because of local lenses of silty gray shale which occur in the Berea sandstone at some places and because of the presence of the Cussewago sandstone which occurs about 35 beet below the Berea sandstone, he assumed that the Berea was made up of two sandstones separated by a shale. Also, in tracing the outcrop of the Berea in eastern Trumbull County, Read apparently misidentified widespread massive siltstones of the Sharpsville sandstone which occur about 40 feet above the Berea for the upper member of his hypothetical threefold Berea sandstone. Somewhat later White (1881) traced the thin but persistent siltstone of the Corry sandstone westward from the type locality at Corry in southeastern Erie County, Pa. He found a similar-appearing siltstone in western Crawford County which he assumed was the western extension of the Corry. He (White, 1881, p. 91–92) correlated this siltstone with the Berea sandstone of Ohio. White applied the name Cussewago to the limestone, shale, and sandstone which occur below his "Corry" in western Crawford County and tentatively correlated them with the Bedford shale of the Cleveland area. Later many geologists, including Chadwick, Caster, Cushing, Prosser, and Ver Wiebe, have discussed the relation of the Berea sandstone to the Corry. The opinion of some of these workers, shown on figure 24, is that the siltstone of the Corry is either an eastern extension of the Berea sandstone, or at least the upper member of Read's hypothetical threefold Berea sandstone of northeastern Ohio. The evidence presented by the present writers on pages 61 to 74 shows that in no part of Ohio is there a threefold or tripartite Berea sandstone, and also that the siltstone of the Corry, although a close temporal equivalent of the Berea sandstone, is not an eastern siltstone facies of the Berea sandstone of northern Ohio.

The object of the surface studies of the lower Mississippian rocks of northeastern Ohio and northwestern Pennsylvania was to determine the relation of the Berea sandstone of Ohio to the Corry sandstone of Pennsylvania and to delineate the extent of outcrop of the two formations.

The Berea of northeastern Ohio extends as a siltstone across the Pennsylvania border to about longitude 80°10′ W. in the vicinity of Meadville. The siltstone of the Corry extends westward from the type locality at Corry, Pa., to about longitude 79°50′ W. near Riceville (see pl. 4). Both formations thin as they approach each other, and grade laterally into the Shellhammer Hollow formation. Therefore, the Corry sandstone represents a temporal equivalent of the Berea but is the result of deposition from a different source and, therefore, should not be considered a siltstone member of the Berea. The siltstone in western Crawford County in the vicinity of Bartholomew's section of White, outcrop 59, which in the past has been called Corry by many geologists, is actually Berea.

In the area between Berea, Ohio, and Corry, Pa., parts of three deltaic deposits of lower Mississippian age are exposed along the outcrop. Figure 25 shows the position of the delta fans and the direction from which the sediments were deposited. Many of the erroneous correlations that have been proposed for these lower Mississippian rocks are the result of attempted long-range correlation of similar-appearing rocks in the different delta fans.

The Knapp formation (Glenn, 1903), which consists of beds of conglomerate, fossiliferous sandstone, and sandy shale in the vicinity of Warren and Tidioute, makes up the northeasternmost of the three deltas shown in figure 25. The age determination of many of the unfossiliferous lower Mississippian rocks in both northwestern Pennsylvania and northeastern Ohio depends upon their correlation with the fossiliferous Knapp formation. The formation thins to the west across Warren County, Pa., as the coarse-grained conglomeratic sandstones grade laterally into less fossiliferous siltstones and shales. In eastern Crawford and Erie Counties the only persistent fossiliferous unit representing the Knapp formation is the siltstone facies of the Corry sandstone. Chadwick (1925) and Caster (1934, p. 52–53, 112–115) assumed on the basis of reconnaissance studies that the Cussewago sandstone of western Crawford County, Pa., represented the western extension of the conglomeratic sandstones of the Knapp. However, as shown in figure 25, the Cussewago (Murrysville) sandstone belongs to the Cussewago (Murrysville) Delta and not to the Knapp Delta. The correlation between these two deltaic deposits appears to have been based upon similar lithologic character because the Cussewago sandstone is unfossiliferous.

The misidentification by White (1881, p. 91–92, 94) of the easternmost siltstone of the Berea as Corry in the area between Andover, Ohio, and Meadville, Pa., was not corrected by later geologists. Chadwick and Caster used this miscorrelation as part of the basis for extending their stratigraphic units of the Knapp formation from the area of Warren, Pa., where they are present into the area of the Ohio-Pennsylvania State boundary where these units are not present.

The presence of the Cussewago sandstone as a separate formation below the Bedford shale in northeastern Ohio was not recognized by many geologists who thus concluded that the Berea sandstone at Berea, Ohio, was the equivalent of two sandstones in eastern Ashtabula County and Trumbull County. In northeastern Ohio

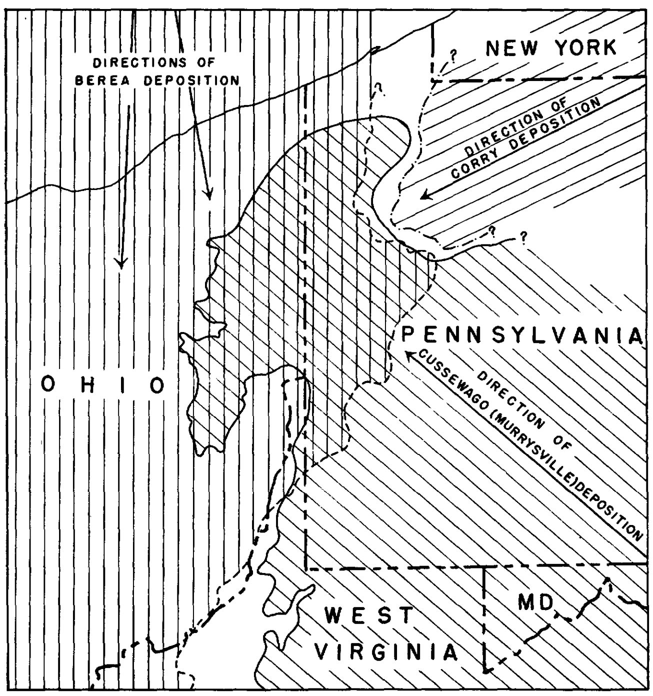


FIGURE 25.—Sketch map showing the relation of the Berea, Cussewago (Murrysville), and Corry sandstones in northwestern Pennsylvania and northeastern Ohio.

a tripartite or threefold Berea formation was used to explain and strengthen the erroneous correlations that had been brought into this area from north-central Pennsylvania in disregard of Cushing's emphatic statement (Cushing, 1888) that only one sandstone in northeastern Ohio was the Berea.

The present interpretation of the stratigraphy of the lower Mississippian rocks takes into consideration not only the formations present on the outcrop but also their extensions into the subsurface and the sedimentary history of the formations including the direction of their deposition and their genetic relation to the adjacent formations.

CORRY SANDSTONE

The Corry sandstone near its type locality, the Colegrove quarry, outcrop 104, 1 mile south of Corry, Pa., consists of about 20 feet of white and gray siltstones and some very fine grained white sandstones. These siltstones and sandstones are irregularly bedded, and the individual beds are lenticular. The base of the Corry is not exposed at its type locality, but it can be seen in sections to the south and west of Corry where considerable amounts of silty gray shale are present intercalated in the basal part of the Corry. The siltstones in the basal parts of the Corry contain many fossils throughout much of their outcrop. The fossils occur as molds in the weathered parts of the siltstones and are not apparent in the freshly exposed rock.

While studying these eastern outcrops, the writers traced the siltstone of the Corry southward from Corry, Pa., down Oil Creek to Oil City and to outcrop 122 a few miles southwest of Oil City where the Corry dips below the Allegheny River. At many places the Corry can be divided into three units: a basal massive siltstone unit which makes up about one-half of the formation; a medial unit of silty shales, thin siltstones, and irregularly bedded mudstones; and an upper unit of hard siltstones (Cathcart, Sherrill, and Matteson, 1938, p. 3; Dickey, 1941, p. 5; Dickey, Sherrill, and Matteson, 1943, p. 20). In many sections along Oil Creek, dark bluish-gray lenticular beds of siliceous limestone as much as 10 inches thick occur at or near the base of the Corry. Although the Corry ranges from 6 to 39 feet in thickness, at most places it is about 20 feet thick. In the outcrops where the Corry reaches its maximum thickness, the medial part of the Corry is made up of medium- to thin-bedded siltstones and contains very little silty shale. The threefold division of the Corry can be seen in the vicinity of Oil City and Rouseville from outcrops 115 to 121 and is best exposed at outcrop 118 north of Rouseville and at outcrop 121 in Oil City. At outcrop 121 on Holiday Street, the New York Central railroad tunnel is cut in the massive siltstones of the Corry, and the Bartholomew siltstone member of the Orangeville shale occurs at the top of the heavy ledge that forms the roof of the tunnel.

The siltstone of the Corry was traced from the type locality of the formation, outcrop 104, westward across eastern Erie and eastern Crawford Counties to the vicinity of Riceville at outcrop 94, where it is 6.1 feet thick. Throughout much of this area the outcrops are poor, but at most places the siltstone of the Corry can be found in the steeper gullies and runs which descend into the larger stream valleys. West of outcrop 94, and east of outcrop 92 about 2 miles west of Riceville, the Corry grades laterally into the Shellhammer Hollow formation and loses its identity as a formation.

SHELLHAMMER HOLLOW FORMATION

Between outcrop 63 near Meadville, Pa., and outcrop 92 near Riceville, Pa. (pl. 4), at the stratigraphic position of the Berea sandstone to the west and the Corry sandstone to the east, a thin sequence of intercalated brown, tan, and gray irregularly bedded siltstones, silty mudstones, and gray silty shale crops out. This sequence of rocks, which is everywhere capped by the Bartholomew siltstone member of the Orangeville shale and underlain by the Cussewago sandstone, has been named the Shellhammer Hollow formation (de Witt, 1951). The type locality of the formation is outcrop 73, 2 miles north of Meadville, Pa., where the road from Meadville to Saegerstown on the east side of French Creek crosses Shellhammer Hollow. The Shellhammer Hollow formation crops out on the north and south sides of the hollow about 20 feet above stream level. The Shellhammer Hollow formation, which was named zone A in Preliminary Chart 21 (de Witt, 1946), ranges in thickness from 5 feet at outcrop 72 on Bennyhoof Run about 1.5 miles north of Meadville to a minimum of 4.0 inches at outcrop 75, 8 miles northeast of Meadville near Blooming Valley, Pa. In the vicinity of Meadville the easternmost recognizable Bedford shale and siltstone of the Berea grade laterally into the Shellhammer Hollow formation, which there is composed of about equal amounts of siltstone and shale. The amount of silt decreases as the Shellhammer Hollow formation thins to the east, and at outcrop 75, where the formation is thinnest along meridian 80° 01′, it is made up predominantly of soft, gray, silty shale. East of this meridian the Shellhammer Hollow formation increases in thickness, and siltstones are again present intercalated in the upper part of the formation. Between outcrops 92 and 94 west of Riceville, Pa., the eastern part of the Shellhammer Hollow formation grades laterally into the westernmost siltstone of the Corry sandstone.

SUNBURY SHALE

The Sunbury shale is a black bituminous shale whose lithologic character is very similar to the Cleveland member of the Ohio shale. From its type locality at Sunbury, in Delaware County, Ohio, south to the vicinity of Irvine, in Estill County, Ky., the Sunbury shale is an easily recognizable formation. Throughout this area the black Sunbury shale is readily separated from the silty gray shale and siltstone of the overlying Cuyahoga formation and from the underlying siltstone of the Berea sandstone or gray Petersville shale of Morse and Foerste. In the area from Sunbury, Ohio, north to Berea, Ohio, only a few outcrops of the Sunbury have been found, and in most of these exposures the upper part of the Sunbury was not seen. At many places from Berea eastward, the Sunbury shale cannot be separated from the overlying Orangeville shale, because the Orangeville contains many beds of black or very dark gray shale similar to the Sunbury.

In many places on the outcrop or in the subsurface a bed of pyrite ranging from 0.01 inch to 2 inches in thickness is present at the contact of the Berea and the Sunbury. The bed of pyrite commonly is sandy in the lower part and contains much grayish-black argillaceous matter in the upper part. Just above this pyritic layer is a zone of small invertebrate fossils which is characterized by *Lingula melie* and *Orbiculoidea herzeri.* This fossil zone, which contains many conodonts, is an excellent stratigraphic marker throughout the outcrop of the Sunbury shale, and it is restricted to the basal 3 inches of the Sunbury.

SOUTH OF SUNBURY, OHIO, TO IRVINE, KY

Good exposures of the Sunbury shale can be studied along Big Walnut Creek and Rattlesnake Creek near Sunbury, Delaware County, Ohio. To the south between Lithopolis, Fairfield County, and Chillicothe, Ross County, the Sunbury is rarely exposed, but south of Chillicothe many good exposures of the black shale can be found in the highlands of Ross, Pike, Adams, and Scioto Counties, Ohio. The Sunbury can be traced from Chillicothe, Ohio, to Irvine, in east-central Kentucky, for throughout the area it forms a widespread stratigraphic marker. In the vicinity of Irvine the black shale of the Sunbury comes in contact with the black shale of the Ohio shale as a result of the feathering out of the Berea and Bedford strata.

NORTH OF SUNBURY, OHIO, TO THE VICINITY OF BEREA, OHIO

Few good outcrops of the Sunbury shale are present in northern Ohio, probably because the Sunbury has been removed from the top of the more resistant Berea sandstone by glacial erosion. Prosser (1912a, p. 485–486) reported as much as 25 feet of black and dark-gray shales above the Berea sandstone at Berea, Ohio, but because of the absence of the Aurora siltstone member of the Orangeville between the Sunbury and his Brecksville shale member of the Orangeville, he included the Sunbury in the Orangeville. However, the basal few inches of this 25 feet of black and dark-gray shale contains the zone of conodonts and the brachiopods *Lingula melie* and *Orbiculoidea herzeri,* which are characteristic of the Sunbury. Thus, at least the basal part of the black shale above the Berea is Sunbury.

FROM BEREA, OHIO, EASTWARD

From Berea, Ohio, eastward to outcrop 39 near Kinsman in eastern Trumbull County, Ohio, the tough black shale of the Sunbury, which contains the characteristic zone of *Lingula melie* and *Orbiculoidea herzeri* in the basal 2 inches, caps the sandstone or siltstone of the Berea. However, because the Sunbury cannot be separated from the overlying Orangeville shale, from Berea eastward to outcrop 39 (pl. 4) near Kinsman in eastern Trumbull County, Ohio, the Sunbury is treated as the basal member of the Orangeville shale.

In central and eastern Ashtabula and Trumbull Counties the Sunbury shale loses its characteristic black color by the admixture of gray silt. Thus the eastern edge of the Sunbury merges into the basal part of the Orangeville shale, and east of outcrop 39 where the zone of typical Sunbury fossils has not been found the Sunbury shale cannot be recognized.

ORANGEVILLE SHALE

The Orangeville shale is composed predominantly of dark-gray mudstone and dark-gray silty shale containing a few thin gray or brown siltstones, many nodular limonitic concretions, and locally in northwestern Pennsylvania a conglomeratic sandstone. Throughout much of its extent, the surface exposures of the Orangeville shale are stained brown, orange, and yellow from the disintegration of the iron minerals.

In the vicinity of Cleveland, Ohio, the Orangeville shale is about 100 to 125 feet thick, including the local siltstones near its base. The shale can be traced eastward across Ohio to its type locality at Orangeville on the Ohio-Pennsylvania State line where it has a thickness of about 75 feet. The Orangeville is only slightly fossiliferous, but in some places a few layers contain a great many fossils.

In Pennsylvania the Orangeville shale thins to the east. It is 40 feet thick at outcrop 73 about 2 miles north of Meadville and 29 feet thick at outcrop 92 near Riceville. (See pl. 4). The thinning of the Orangeville results from the intertonguing of Orangeville shale and basal siltstones of the Sharpsville sandstone at progressively lower stratigraphic positions to the east. East of outcrop 92 near Riceville, Pa., the base of the Sharpsville sandstone cannot be delineated, and the two formations merge into a thick sequence of interbedded brown and gray sandstones, siltstones, silty mudstones, and some silty shale.

The writers have recognized five members of the Orangeville shale: the Sunbury member, which has already been discussed (p. 41); the Aurora siltstone member; the Chardon siltstone member; the Bartholomew siltstone member; and the Hungry Run sandstone member.

AURORA SILTSTONE MEMBER

In eastern Cuyahoga County in the vicinity of Chagrin Falls, a local siltstone in the basal part of the Orangeville shale was named the Aurora sandstone by Prosser (1912a, p. 123). Because this unit is composed predominantly of siltstone and is genetically a part of the Orangeville shale, it was renamed the Aurora siltstone member of the Orangeville shale (de Witt, 1951). In the type locality on the Aurora Branch of the Chagrin River, the Aurora siltstone member lies upon about 12 feet of grayish-black and very dark gray shale of the Orangeville which includes the Sunbury member. The Aurora member, which has a maximum thickness of about 6 feet, is local in areal extent and is well exposed in outcrops 3, 4, and 6 in the vicinity of Chagrin Falls. The member is 5 to 6 feet above the Berea sandstone along the Cuyahoga River south of Cleveland and about 15 feet above the Berea in the western part of Geauga County north of Chagrin Falls.

CHARDON SILTSTONE MEMBER

Prosser (1912a, p. 219–220) gave the name Chardon sandstone to about 8 feet of thin- to thick-bedded light-gray siltstone and intercalated silty shale that occurs in the Orangeville shale about 30 feet above the Berea sandstone in the vicinity of Chardon, Ohio. (See pl. 5.) Because this unit is a part of the Orangeville shale and is composed largely of siltstone, it was renamed the Chardon siltstone member of the Orangeville shale (de Witt, 1951). Rothrock (1949) stated that the names Aurora and Chardon have been applied to different parts of the same stratigraphic unit. Although they were unable to trace the Aurora into the Chardon because of a lack of outcrops, the present writers agree that Rothrock's interpretation is reasonable.

BARTHOLOMEW SILTSTONE MEMBER

A thin bed of brownish-gray to gray siltstone, which was first observed at outcrop 47 in the southwestern corner of Crawford County, Pa., occurs near or at the base of the Orangeville shale in Crawford, Erie, and Venango Counties, Pa. This bed, which averages less than a foot in thickness, is characterized by many short curved markings ranging in thickness from a film to an eighth of an inch and in length from one-quarter to three-quarters of an inch. The markings at most places occur at random in the siltstone but in some places may roughly parallel the bedding laminations. The markings are darker than the matrix of the siltstone in unweathered specimens. On the surface of the siltstone bed weathering produces a fretwork of small semicircular grooves from which the softer material has been etched. Thus, these markings make possible the quick identification of this very useful stratigraphic reference bed in both the weathered and unweathered state.

Because the curved markings resemble cuneiform writing, de Witt (1946) called the siltstone bed the graphic siltstone layer. Later he (de Witt, 1951) named the bed the Bartholomew siltstone member of the Orangeville shale. The type locality of this bed is outcrop 59, which is White's (1881, p. 204) Bartholomew's section 1 mile northwest of Littles Corner on a small run. Here the Bartholomew siltstone member occurs 8 feet above the top of the siltstones of the Berea and 37 feet above the top of the Cussewago sandstone.

The Bartholomew member forms an easily recognizable stratigraphic marker over a wide area in northwestern Pennsylvania. It has been traced by the present writers eastward from outcrop 47 near the State line in Crawford County to outcrop 103 near Corry in Erie County, and down Oil Creek to outcrop 121 at Oil City in Venango County. Preliminary reconnaissance indicates that the Bartholomew member may extend farther to the east in Pennsylvania.

From outcrop 47 east to outcrop 62 on Cussewago Creek near Meadville, the Bartholomew siltstone member rests on the basal beds of the Orangeville shale; from outcrop 62 to outcrop 92 near Riceville, it rests on the Shellhammer Hollow formation; and east of outcrop 92 it may lie directly on the Corry sandstone or be separated from it by a few inches to several feet of silty gray Orangeville shale.

The Bartholomew member is present 15 feet above the siltstones of the Berea at outcrop 47, 8 feet above the top of the Berea at outcrop 59, and 10 inches above the top of the Berea at outcrop 81. The eastward thinning of the interval between the Bartholomew siltstone member and the siltstones of the Berea is apparently due to the nondeposition of the basal part of the Orangeville shale rather than to post-Berea erosion.

The Bartholomew siltstone member is sparingly fossiliferous. At many places a few specimens of *Lingula* cf. *L. melie* have been obtained from it, and at outcrop 68, 4 miles south of Meadville, Pa., two specimens of *Conularia* were found in addition to some crushed specimens of *Lingula*.

HUNGRY RUN SANDSTONE MEMBER

The type locality of the Hungry Run sandstone member of the Orangeville shale (de Witt, 1951) is at outcrop 100 in a small quarry on a headwater of Hungry Run, 1 mile west of the southeastern corner of Union Township, Erie County, Pa., and about 7.5 miles southwest of Corry, Pa. The member is composed of 10 feet of massively bedded iron-stained sandstone and 2 feet of underlying massive siltstone. The medium- to coarse-grained sandstone contains a great deal of iron oxide, which stains some parts of the stone a deep reddish brown. The sandstone is similar in grain size to the coarser-grained beds of the Cussewago sandstone but is less well sorted and contains more secondary cement. The upper 2 feet of the Hungry Run member is conglomeratic, containing many small lenses of flattened discoidal pebbles which range from one-eighth to one-quarter of an inch in thickness and from one-half to two-thirds of an inch in diameter. Most of the pebbles are composed of white or gray vein quartz, although a few pieces of chert, jasper, and igneous rock have been found in the conglomerate. A 5-inch zone of poorly preserved fossils occurs 6 feet below the top of the sandstone, and some small clay galls are present in the fossiliferous layer. The lower 4 feet of the sandstone is less massively bedded and is finer grained than the upper 6 feet.

As shown in figure 26 the Hungry Run member is present in a belt about 5 miles wide and 15 miles long mainly in Union Township, Erie County, and in Bloomfield, Athens, and Steuben Townships, Crawford County, Pa. South of outcrop 91 (pl. 4) the sandstone splays out in a fan-shaped sheet, on the periphery of which are outcrops 87 and 88. Although the sandstone at most localities is not observed in place because of soil creep on the steep hillsides, many of the small valleys are filled by large lichen-covered float blocks of this sandstone. About 8 feet of coarse-grained sandstone, containing some small pebbles in the upper part, is exposed along the north side of the road to Canadohta Lake about 400 feet west of Pages Corners at outcrop 99. As shown at outcrop 94, near Riceville, 2 feet of massive coarse-grained white sandstone of the Hungry Run caps 6 feet of siltstone of the Corry sandstone; and in outcrop 95 about 500 feet to the south, 3½ feet of the member lies on 8 feet of siltstone of the Corry. Although no rocks are present above the Hungry Run sandstone member in the type exposure, beds of the lower part of the Orangeville shale are found capping the member at outcrops 87 and 88 in southeastern Athens and north-central Steuben Townships, Crawford County. Chips of a gray shale, which is probably Orangeville, were dug out of the grass-covered slopes above float blocks of the Hungry Run sandstone at outcrop 91 in eastern Athens Township and at outcrop 93 in southern Bloomfield Township.

The Hungry Run sandstone member is overlain sharply by dark-gray shales of the Orangeville shale and rests either upon the siltstones of the Corry or upon the Cussewago sandstone. In the vicinity of outcrop 87 in southwestern Athens Township, the Shellhammer Hollow formation is absent, and the Hungry Run member lies on the Cussewago sandstone. The contact between the Hungry Run and the Cussewago cannot be determined adequately at these outcrops because of the similar appearance of the sandstones and because some Cussewago sandstone seems to have been reworked into the basal part of the Hungry Run sand-

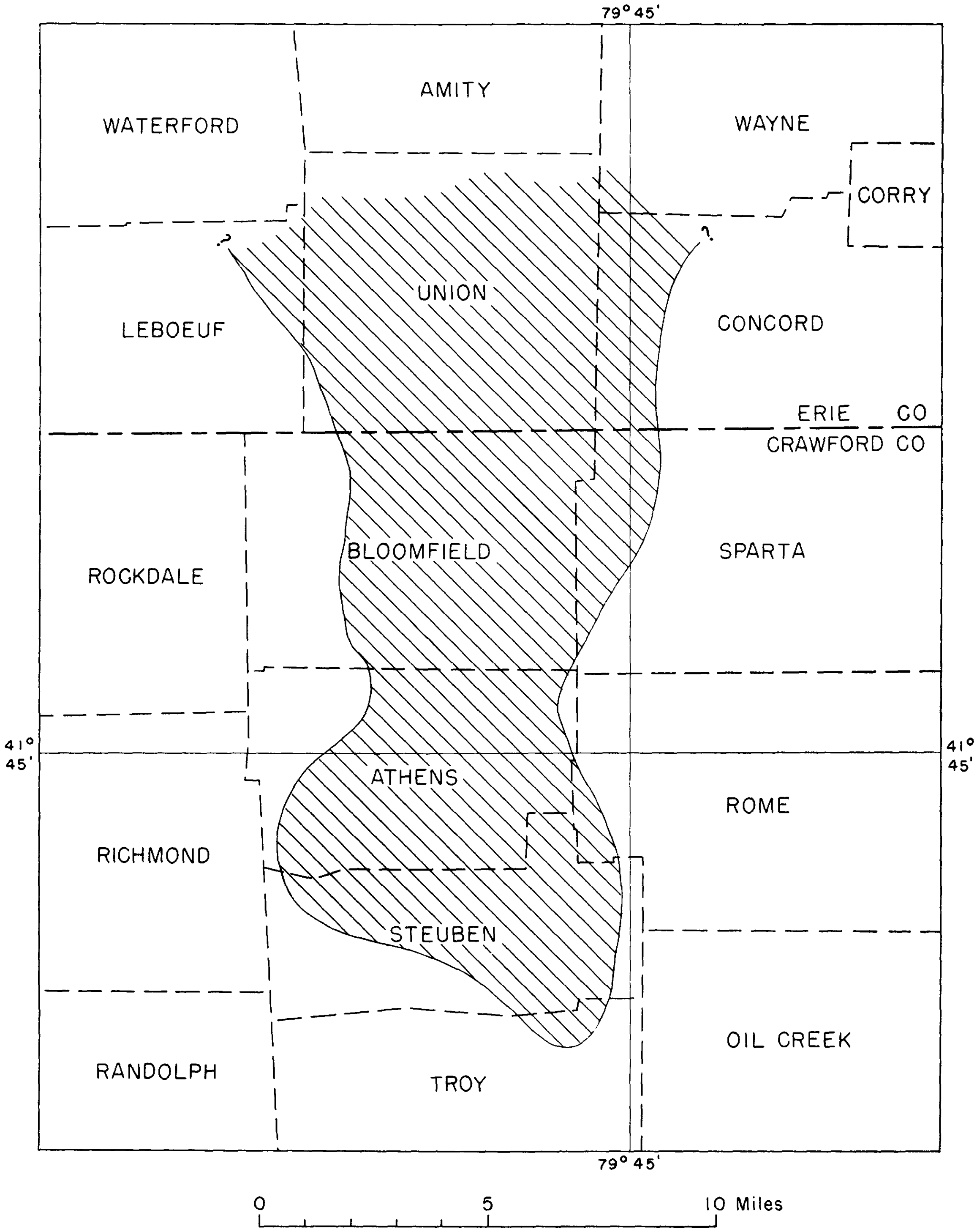


FIGURE 26.—Map showing the area of the Hungry Run sandstone member of the Orangeville shale in Erie and Crawford Counties, Pa.

stone. The Hungry Run sandstone is interpreted as part of a local delta deposit which covered Chautauqua County, N. Y., and parts of Erie and Crawford Counties, Pa. That the source of the sediment lay to the northeast is shown by the increase in thickness of the sandstone, the increase in coarseness of the sand grains, and the increase in the size and number of pebbles in a northeasterly direction. Apparently this local sandstone was deposited at about the same time as the Bartholomew siltstone member of the Orangeville shale.

SHARPSVILLE SANDSTONE

The Sharpsville sandstone is composed of varying amounts of flaggy brown and gray sandstones, brownish-gray siltstones, irregularly bedded mudstones, and gray shales. In Ohio the base of the Sharpsville sandstone is generally placed at the base of the first massive bed of siltstone in the shale sequence above the Berea, except in those areas where the Aurora or the Chardon member is present near the base of the Orangeville shale. In northwestern Pennsylvania the Sharpsville sandstone is the first massive siltstone above the Bartholomew siltstone member of the Orangeville shale, except in the local area in the northeastern Crawford County and southeastern Erie County where the Bartholomew siltstone member is absent and its place is occupied by the Hungry Run sandstone member. Locally, as in outcrop 31 in the vicinity of Warren, Ohio, and along French Creek south of Meadville, Pa., the lower part of the Sharpsville is composed almost completely of massive siltstone and very fine grained sandstone. In these localities the unit can be used for local correlation. Elsewhere, the Sharpsville is composed of thin flaggy sandstones and intercalated silty shale, and its boundaries cannot be accurately determined.

Near Meadville, Pa., blue-gray siliceous limestone occurs near the base of the Sharpsville sandstone. Locally the limestone may be as much as 4 feet thick, and can be used to correlate exposures in adjacent gullies.

SEDIMENTATION

BEDFORD SEDIMENTATION

With the close of the Devonian the long period of quiet, shallow seas in which the sedimentation consisted of little but the slow, monotonous deposition of great thicknesses of black mud came to an end in that part of the Appalachian basin which is in Ohio. In northern Ohio the upper part of the black mud hardened to form the Cleveland member of the Ohio shale. In his report which describes the transition of sedimentation from Cleveland to Bedford time, Cushing (Cushing, Leverett, and Van Horn, 1931, p. 88–89) states:

> Sedimentation was interrupted at the end of the Cleveland epoch, and some warping took place in the adjacent lands, which became higher locally and capable of furnishing coarser land wash. Possibly the sea withdrew and then returned, but no conclusive evidence has yet been found that it did so. The stagnant and foul bottom waters, however, became stirred and purified by stronger currents than had existed in Cleveland time, and these currents locally stirred up the black mud and relaid it as the initial deposit of the Bedford. With the sweetening of the waters a bottom fauna entered the basin and lived most abundantly where the bottom mud was least stirred by currents. But the organisms were mostly small forms with thin shells that were badly broken up by the moving water. Soon the rate of the coming of mud into the basin increased, and locally stronger currents swept in and deposited great lenses of fine sand. The muddied waters disagreed with the fauna, which dwindled and vanished rather early, so that the waters of the basin during the greater part of Bedford time held but little life.

With faunal change, the reworking of the black mud, and the introduction of the gray mud and silt a new cycle of sedimentation began. A large volume of fresh water, carrying the first clastic sediments of Bedford age from a newly uplifted northern drainage basin, entered the shallow remnant of the Devonian sea that was bounded on the north in the final stage of withdrawal during the Devonian period by a line roughly parallel to the south shore of Lake Erie.

The history of sedimentation in the Ohio part of the Appalachian basin in Bedford and Berea time is mainly the story of what happened when the great influx of sediment-laden water from the north crossed the east-west shoreline and emptied into the relatively tranquil waters of the northern end of the sea. The first effect was the deposition of mud and silt at the mouth of the new river and the establishment of a delta. As the river system grew during Bedford time, the delta deposits spread over a wide area, until the delta became the dominant sedimentary feature of the ancient landscape, comparable in area to the present-day Mississippi Delta. (See fig. 27.) Most of the sedimentary history of Bedford and Berea time in Ohio has been influenced or even caused by the presence of the great delta. For this reason the writers will discuss the delta and the river system, here named the Red Bedford Delta and the Ontario River, presenting the evidence for them and noting their influence on the regional sedimentary history. (See pl. 7.)

RED BEDFORD DELTA

GENERAL FEATURES

As referred to in this paper the Red Bedford Delta is a genetic unit that includes all the various types of sediment originating as integral parts of the delta during Bedford time. Though composed predominantly of grayish- to dusky-red shale, the delta contains other types of rocks as well. For example, gray shale is

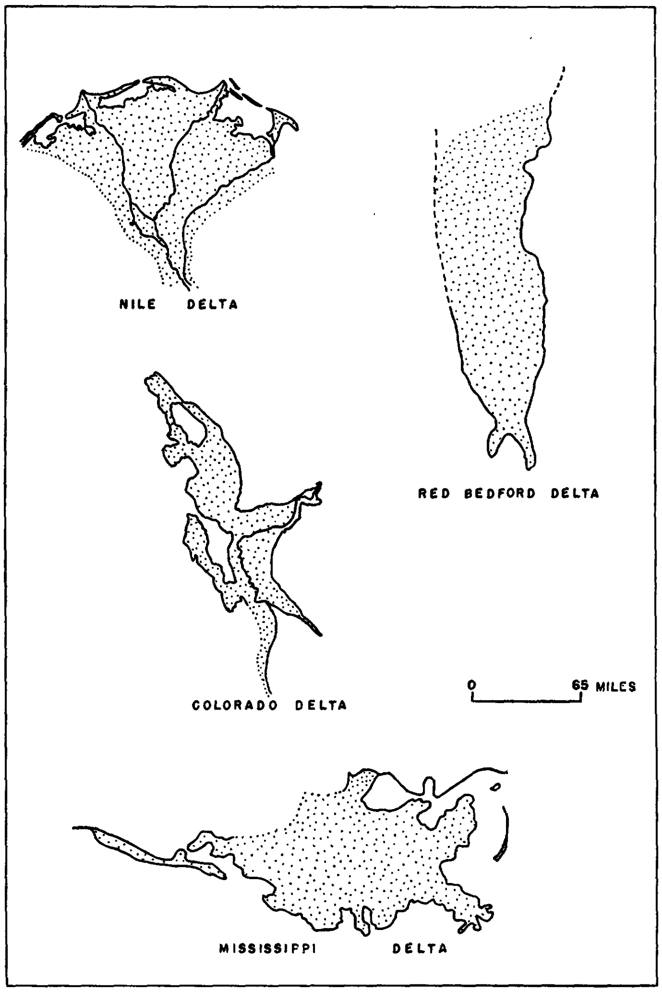


FIGURE 27.—Diagram showing the areal extent of the Red Bedford Delta compared to the areas of some modern deltas.

abundant in many parts of the deposit, as are numerous lenses of fine-grained sandstone and siltstone. The term "red" is applied to the Bedford Delta to distinguish it from delta deposits of possible Bedford age in other areas.

The term "Red Bedford Delta" is fitting not only because of the great quantity of red shale contained but because the red color is the main criterion for tracing the extent of the delta. By means of the red color the outlines and approximate thickness of the delta can be traced reliably throughout the present surface and subsurface extent of the delta. The map of the Red Bedford Delta (pl. 7), therefore, is a map of the extent and thickness of the red beds only, and not a map of the entire delta deposit. The full extent and thickness of the entire deposit may be slightly greater than that shown on the map. The name "Red Bedford Delta" applies only to the delta formed during Bedford time, although the Ontario River, which produced this delta, continued carrying sediments to the sea in Berea time as in Bedford time. The discussion here pertains mainly to the first, or Bedford phase, of the two great phases of delta deposition.

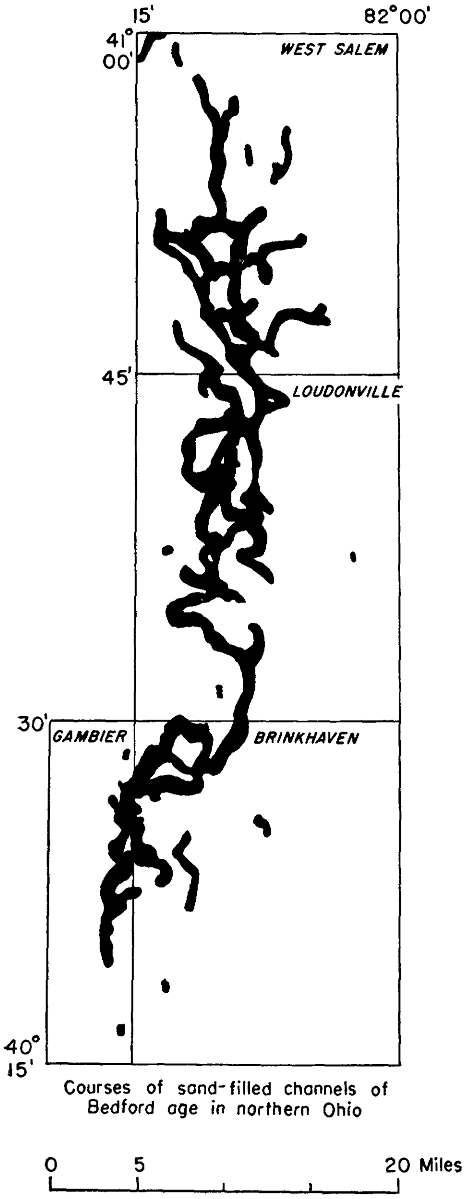
As shown on the map (pl. 7) the Red Bedford Delta extends a distance from north to south about 210 miles. If the western boundary line were extended to the northwest beyond the outcrop, restoring the hypothetical pre-erosion boundary, and if the indentation in Wayne, Holmes, and Coshocton Counties, which is thought to be due to pre-Berea erosion, is restored, the inferred width at the northern part of the delta would be roughly 75 miles, and at the middle part of the delta about 60 miles. The southern end narrows to a minimum width of 20 miles, excepting the bifurcate tip, the prongs of which are only about 5 or 6 miles wide. The great length of the Red Bedford Delta compared to its width, as shown on the map (pl. 7), is especially striking, particularly if no allowance is made for the reduction in width, because of erosion, in the northern and middle parts. If the present limits of the red beds are taken, the average width of the northern and middle parts of the delta is about 50 miles.

The thickness of the deposits of the Red Bedford Delta ranges from about 150 feet in the central part to a feather edge on the flanks. Two notable exceptions occur, however. In the northern part of the delta, glacial and recent stream scour have eroded the top of the delta in many places in its broad outcrop. Scour in pre-Berea time appears also to have reduced the original thickness of the red beds at several localities in this area. Second, a sinuous linear area of thin red beds is present extending lengthwise along the center of the delta. The thickest red beds are concentrated along the central longitudinal axis of the delta, but another smaller area of thick red beds is present in the northwestern part of the delta, probably representing a subsidiary lobe of deltaic deposition. How many other similar lobes may have been present before erosion is unknown.

FLUVIAL ORIGIN

EVIDENCE

One of the main features of the delta is the presence of a central river system on the main axis of deposition, as indicated by a well-integrated series of sand-filled channels lying in the red Bedford shale. These sand-filled channels of the Ontario River, area B of figure 11, are sinuous and branching and have typical cross sections. (See pls. 8, 9; fig. 28.) They are for the most part continuous for more than 40 miles in Ashland, Holmes, and Knox Counties, and trending from north to south they form a section of the river system that deposited the Red Bedford Delta. The course of this system is well shown in plate 9 and on the Berea



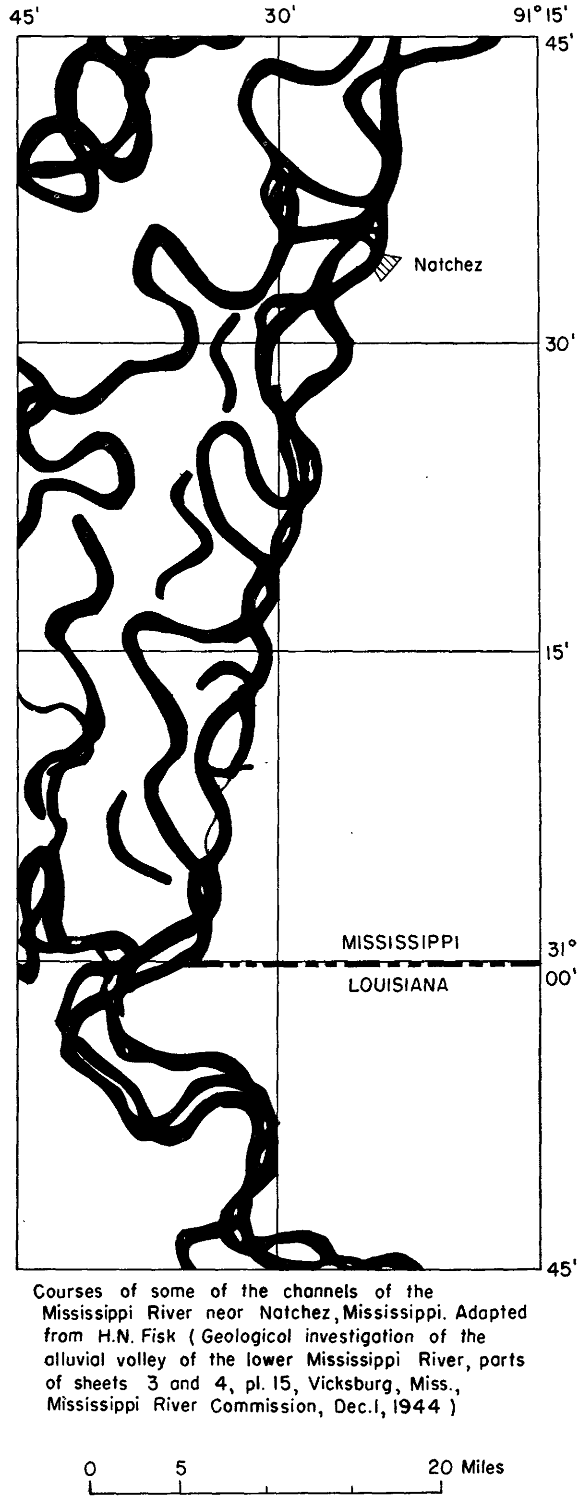


FIGURE 28.—Diagram showing the similarity of configuration of the Bedford stream channels of northern Ohio and the meandering channels of the lower Mississippi. The Bedford channel system cannot be completely delineated because parts of the area of channeling remain undrilled. Therefore some parts of this channel system have a disjointed aspect which is the result of a lack of data rather than peculiarities of the deposition.

isopach map (pl. 1). The evidence is insufficient to trace the river system continuously from the northern part of the delta to the southern tip, but many areas show small remnants of the channels. Chief among these is the Chatham-Lodi area of Medina County, where the channels are particularly well shown by the records of closely spaced core drilling. The channels are the lower of two sets of channel deposits and are not to be confused with the upper set, from which most of the oil and gas production has been obtained and which are largely of Berea age. Other channel remnants that have been found are in Perry County and to a lesser degree in Athens County. Probably future drilling will make possible the tracing of yet undiscovered sections of the main river system.

A younger system of sand-filled channels of Berea age lies above the channel sands of Bedford age, and at places is separated from them by red shale. These channels of slightly later age, which are incised into the Red Bedford Delta, indicate that essentially the same river system was present in Berea time. The most notable occurrences of this phase of the channel cutting are seen in the channel sandstones of Berea age in Lorain County described in detail under the heading of Berea sedimentation. Channel sands of Berea age are present also in Erie and Cuyahoga Counties, and in the Chatham-Lodi area of Medina County.

The fact that deep stream channels were cut into the Bedford shale and even older sediments proves conclusively that at least the northern part of the Red Bedford Delta stood well above sea level prior to the deposition of the Berea sand. The southern part of the delta, which contains at least a few small channels, was probably also deposited subaerially, inasmuch as it is the land area along which the Second Berea bar was formed. In the absence of any evidence to the contrary, it is reasonable to assume that all of the red beds of the Bedford that have been preserved were laid down in a relatively uniform environment. Possibly the red color present in the original sediments remained in them if they were deposited above sea level, but changed to gray when deposition occurred below sea level, provided the interaction of carbonaceous material in the water was sufficient to create a reducing environment. The presence at many places of oscillation ripple marks in the thin layers of siltstone in the gray Bedford shale shows that the gray shale was deposited under water. Ripple-marked siltstones have not been observed in the red Bedford shale, which indicates that the red shale was deposited mainly in a subaerial environment. The discussion of the significance of the red color is presented more fully below, and is referred to here only as minor supporting evidence for the subaerial deposition of the greater part of the Red Bedford Delta.

The fluvial origin of the Red Bedford Delta is indicated by the presence of stream channels. Criteria diagnostic of large-scale marine or lacustrine deposition are not present; hence the possibility of deposition other than fluvial seems extremely remote. Aeolian deposition, which has sometimes been invoked to explain the origin of red beds, does not seem plausible to account for the red beds of the Bedford. Aside from improbabilities arising from the type of bedding and the distribution and character of the sediments, aeolian deposition on such a large scale is not likely to be the mode of origin because it requires an arid climate. The northern Appalachian basin during Mississippian time appears to have been fairly humid, at least during part of the yearly cycle, because of the great quantity of water-borne sediments carried into the basin from different directions during Bedford and Berea time. The carbonaceous plant fragments and thin lenses of coal found in the channel sandstones of the Berea also indicate that the Mississippian epoch in the Appalachian basin, as elsewhere, was humid enough to sustain the life of the flora that later developed into the luxuriant vegetation of the Pennsylvanian epoch.

HYPOTHESES OF ENVIRONMENTS OF DEPOSITION

Because the red Bedford shale is of fluvial origin, three alternative environments of deposition appear possible. The red shale might have been deposited as coastal plain deposits, river valley alluvium, or delta deposits. The vast areal extent and longitudinal configuration of the red beds reasonably preclude any other possibilities.

Coastal-plain hypothesis

If the coastal-plain hypothesis is correct, the red beds were derived from a nearby upland area and spread out as a long low-lying plain paralleling the shoreline. The sediments would have been composed mainly of preexisting red soils or of detritus from the active erosion of older deposits of red shale. Streams transported the sediments down the gentle seaward slope of the plain, and extended their coalescing delta fans seaward as the deposition progressed. No nearby land area existed east of the red-bed deposits that could have supplied the sediments from that direction. Instead, as discussed more fully below, the area just east of the red beds was occupied by open sea during the time of red-bed deposition. The only upland area that conceivably could have contributed red mud in accordance with the coastal-plain hypothesis would have been the area of the Cincinnati arch to the west.

This area is not an adequate source because it probably never contained sufficient parent red beds to supply the vast quantity of red mud present in the red phase of the Bedford. The parent beds must have been either preexisting red beds, or deep red soils formed through a long period of weathering, but the eastern flank of the arch during Mississippian time, if it stood sufficiently high, would have exposed mainly nonred Paleozoic limestones and shales. None of the Paleozoic formations that could have been exposed at that time contained any original red color, except possibly a small area of Brassfield limestone in southern Ohio. When it is considered that the red beds of the Bedford cover about 10,000 square miles, average 100 feet thick, and have a volume of about 200 cubic miles, it seems very unlikely that sufficient residual red soils could have accumulated on the eastern flank of the arch to have supplied the sediments composing the Red Bedford Delta. Also, because the parent rocks of the hypothetical red soils would have been largely limestones, many times the amount of weathering would have been required to produce the same amount of red soil as would the erosion of rocks of original red color. Furthermore, no red beds of Bedford or near-Bedford age have been found adjacent to the arch in the Ohio basin.

There is, moreover, no evidence that the Cincinnati arch stood sufficiently high during Bedford time to permit the necessary gradient for streams to transport the red sediments to their present location. The thickest part of the red beds is in the north, yet this part lies adjacent to the lowest part of the present-day arch—the Ontario sag. The arch probably stood highest near the Cincinnati area, but the red beds opposite this area are at their thinnest. More conclusively, in southern Ohio there is a 50-mile gap where red beds are not present between the arch area and the Red Bedford Delta. If the red sediments came from the arch, this gap could be explained only by subsequent erosion. However, the evidence on the outcrop conclusively proves uninterrupted marine deposition of drab sediments between the arch and the nearest red beds from earliest Bedford to latest Berea time, allowing for no period of deposition and erosion of red beds in this area.

The coastal-plain hypothesis requires a western source and numerous small streams flowing eastward or, less likely, an eastern source and west-flowing streams. The river channels mentioned in the discussion of the fluvial origin of the Red Bedford Delta trend southward, and indicate a northern source.

River-valley-alluvium hypothesis

The hypothesis that the red beds of the Bedford originated as an alluvial deposit in a river valley fits the known facts much more closely than the coastal-plain hypothesis. The difficulties encountered in that hypothesis are mainly eliminated in the valley-alluvium hypothesis. The source area for the red beds, instead of the Cincinnati-arch area, becomes the vast Canadian upland, which was theoretically capable of providing an adequate amount of red mud derived either from red soils or preexisting red beds. Except for an area in northern Ohio and Ontario where later erosion has demonstrably occurred, the red sediments are contiguous with their projected source area. The requirements of a northern source and a single south-flowing river system are perfectly fulfilled by the valley-alluvium hypothesis. In addition, the great length of the red-bed deposit in relation to its width favors this hypothesis.

However, one insuperable obstacle prevents the acceptance of the river-valley-alluvium hypothesis. No valley capable of confining the red sediments of the Bedford can be shown to have existed. On the west in the vicinity of Toledo, Ohio, the eastern flank of the Cincinnati arch may have been sufficiently elevated above the sea to halt the westward spread of the red beds. To the south, however, the flank of the Cincinnati arch trends to the southwest and is too far distant from the area of the deposition of red beds to have exerted any confining influence on the main river system. Deposition of the red beds stopped 100 miles short of the axis of the arch in the Cincinnati area, and probably did not lap upon the flank of the arch much south of the vicinity of Toledo, Ohio. The evidence of uninterrupted marine deposition throughout Bedford and Berea time in the area lying between the Red Bedford Delta and the arch indicates that at least in the southern half of the area the red beds were bounded on the west by an arm of the sea instead of by the sloping side of a valley.

On the eastern side of the red beds the possibility of the existence of a confining valley slope is more remote. The northern outcrop of the Bedford shows that the gray Bedford shale, lying adjacent to and east of the red beds, was deposited in a marine environment that existed throughout the period of deposition of the red Bedford shale. Furthermore, the Euclid siltstone member and the Second Berea sand, which are interpreted as offshore bars, bound the red beds on the east. Although they are slightly older than the red beds, they apparently continued to mark the approximate shoreline throughout the time the red Bedford shale was being deposited. The Second Berea bar, which is more extensive and more fully known than the Euclid member, has a straight margin on the east and an irregular margin on the west, indicating that the sea lay to the east and that a land or shoal area lay to the west.

It does not seem likely that a river valley could have existed during Bedford time in the area now defined by the red beds. River valleys by definition are dry-land features. Indeed, during latest Devonian time the northern Appalachian basin, including the area in which the red beds were deposited, was covered by the sea. To make dry land of this area and to conceive of the initiation of a great river valley consequent upon the slope produced by the upwarp, or even guided by a hypothetical structural depression are certainly ideas that are entirely unsupported. The evidence of continuing marine deposition on either side of the red beds is very convincing; therefore to assume the presence of a valley as suggested above is unreasonable.

Delta hypothesis

The final alternative is that the red Bedford shale originated mainly as a delta deposit. It is the alternative favored by the writers as best explaining the known facts. Examination of the other alternatives first has led by a process of elimination to a consideration of the merits of the delta hypothesis.

Near-surrounding of the red beds by the open sea.—It has been shown above that the area of red-bed deposition was not bounded on either side by valley slope but that open sea extended east and west of the red sediment. The appropriate corollary, then, is that the red beds of the Bedford were deposited beyond and at right angles to the shoreline from the point of fluvial egress from the parent land area and built southward into the sea as a delta deposit. This corollary adequately fits the definition of a delta as stated by Barrell (1912, p. 381). "A delta may be defined as a deposit partly subaerial built by a river into or against a body of permanent water."

The sea appears to have surrounded the red Bedford shale on all sides except the north, and the red beds, in large part representing the subaerial delta plain, seem to have formed a long peninsula, at least the northern half of which remained for the most part above water until late Berea time.

Upward convexity.—In identifying a delta deposit the determination of upward convexity as seen in cross section is an important criterion. If a flat sea floor is assumed, a delta deposit, built upward from the sea floor, should show a flat bottom and a flat top but should be distinctly tapered toward the sea floor at both margins, imparting an upward, if flattened, convexity to the cross-sectional view of the whole deposit. Figure 29 shows a cross section of the Mississippi delta plotted from the U. S. Coast and Geodetic Survey's chart of the Mississippi River delta (no. 1272, 1945). The upward convexity exhibited in the figure is the same as would be expected in any transverse profile of a delta built upon a flat sea floor. Such a profile would not be present if the deposit were formed of river-valley alluvium. The traditional view of the cross-sectional appearance of river valley deposits as generally cited in textbooks has a flat top and a rounded bottom. The illustrations in Lobeck (1939, p. 238) are good examples of this concept. Such a transverse profile is probably accurate for young or mature aggrading streams where the sloping valley walls are actually covered by alluvium. However, an aggrading stream in old age, where the valley walls are low and far apart, would probably show a profile consisting of two horizontal parallel lines, perhaps slightly upturned at the sides. The upper line would probably be upwarped somewhat near the stream because of natural levees. (See fig. 30.)

The subsurface data are not sufficiently accurate for use in plotting cross sections of the red beds in detail great enough to show the possible upward convexity of the surface of the delta. Nevertheless, an indirect method is available for determining the kind of profile that is present. If the top of the red beds is assumed to be nearly flat and continuous with the deposits on either side, as would occur if the red beds were valley alluvium, then the subsequent deposition of the marine phase of Berea sand should show no differential thinning over the area of red-bed deposition. The sand might be slightly thicker along the axis of the red beds where it filled the remnants of the river channel. However, if the red beds were built up from a flat sea floor as a delta and existed as a peninsula until finally covered by the sea in the final marine phase of Berea deposition, a marked thinning of the Berea sand would be expected

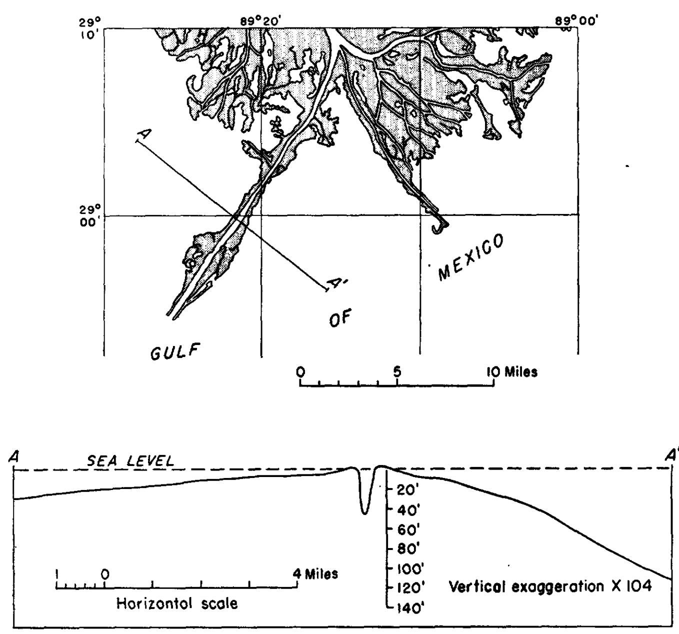


FIGURE 29.—Lower Mississippi delta and profile showing convexity of delta sediments.

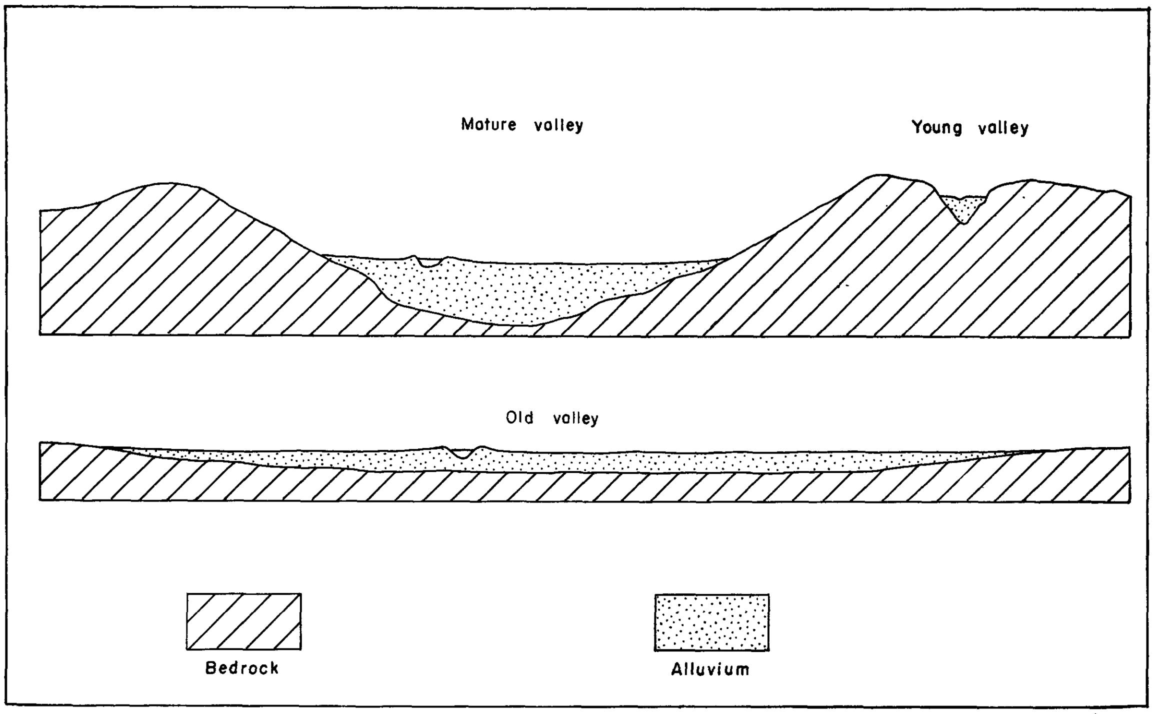


FIGURE 30.—Cross sections of three partly aggraded stream valleys showing that the top of the alluvium and the top of the bedrock are more nearly parallel in the old valley than in the younger valleys.

over the area of red beds. The Berea sediments would have a tendency to gravitate to the hollows and low-lying areas first, and the waves and marine currents would tend to keep the shoal areas free of most of the new sediment until the low areas were nearly filled to the level of the shoals.

A glance at the isopach map of the Berea sand (pl. 1) reveals a longitudinal belt of remarkably thin Berea sand centered directly above the axis of the northern half of the Red Bedford Delta. The Berea, whose thickness in this area averages only 10 feet, is nearer the source and would be expected to be thicker than in many areas where the sand is more than 40 feet thick. This anomaly is best explained if the red beds have the upward convexity that is one of the criteria of deltaic origin.

The southern half of the area of the red beds is covered by Berea sediments of moderate thickness, and neither differential thinning nor thickening is indicated. It appears likely that the southern half of the Red Bedford Delta slowly subsided, as is suggested by evidence from well records. In the southern area much more gray shale intervenes between the red Bedford shale and the Berea than in the north, indicating a pre-Berea settling of the sea bottom, including the area of the red beds.

Flanking offshore bars.—One of the common geographical aspects of many large modern deltas is the presence of flanking offshore bars. The deltas of the Nile and Mississippi Rivers are good illustrations. An offshore bar is positive evidence of the best sort that a shoreline is nearby, approximately parallel with the strike of the bar. The straightest and steepest margin of the bar indicates the seaward side. Thus the Second Berea bar and the Euclid siltstone member have been referred to above as proof that the sea lay just east of the area of red-bed deposition. In addition, it should be stressed that offshore bars are a normal complement of delta deposition. Two of the most necessary prerequisites of bar formation, and an adequate means of bar preservation, are generally fulfilled in a delta environment. First, delta sediments are likely to produce a flat, shallow sea bottom if one does not already exist. Second, a delta provides an abundance of unconsolidated sediment that can be winnowed by wave action, and the coarser material eventually formed into a bar. The Second Berea bar and the Euclid member were probably built by the winnowing of delta sediment by wave action in the earliest part of delta formation. Later, when the delta sediment had filled the lagoonal areas between the bars and the advancing delta front, the bars were overwhelmed by the great volume of delta sediment, and thus the unlikely occurrence of permanent preservation was accomplished.

Configuration.—The original configuration of the red beds, as nearly as can be estimated by restoring the eroded margins of the deposit, resembles an inverted isosceles triangle whose base line in the north is 75 miles long and whose height is 210 miles from the base line to the apex in the south. The Red Bedford Delta is closely related to the bird's-foot type of delta, as exemplified by the Mississippi. The fineness of grain size, present in both the Red Bedford and the Mississippi Deltas, contributes greatly to the development of long, linear deposition supported by a minimum of channels. In deltas composed of coarse-grained material the river system has a marked tendency to develop an intricate distributary pattern, including underground drainage, which results in more lateral and less frontal deposition.

A second controlling factor in the development of linear deltaic deposition is the relative ability of the currents in the sea to dispose of the delta sediments or at least to modify their ultimate configuration. Doubtless the currents of the Gulf of Mexico have influenced the deposition of the Mississippi Delta more than marine currents in Bedford time affected the deposition of the Red Bedford Delta. The abundance of oscillation ripple marks in the siltstones of the Bedford indicates a lack of strong currents in the Bedford sea. Also, the arm of the sea into which the red sediments of the Bedford were carried was certainly much shallower and smaller than the Gulf of Mexico and could not have sustained any powerful currents. The configuration of the red beds, then, though it cannot fairly be used as proof of deltaic origin, is not unlike the pattern that would be expected, given the environment and type of sediments that were controlling factors in the deposition of the Red Bedford Delta. The Mississippi Delta appears to offer the closest approach among modern deltas to the Red Bedford Delta, and the differences appear to be chiefly a matter of degree. The Red Bedford Delta is slightly larger in areal extent and more linear because of the reasons outlined above, but the Mississippi Delta, being thicker and deposited in deeper water, contains a greater volume of sediment.

The delta in Berea time.—The tremendous quantity of sediment that was deposited in the northern part of the Appalachian basin during Berea time must have entered the sea at a number of places where river systems crossed the shoreline and emptied their loads of sediment into the sea. One such place where the introduction of Berea sediment appears to have been concentrated is the area of Lorain and Cuyahoga Counties, coinciding with the area where earlier red sediments of the Bedford were introduced into the basin. The full description of the delta in Berea time is taken up under the heading of Berea sedimentation, but the important point to be noted here is that if the Berea sediments in this area are shown to have a deltaic origin, the likelihood is greatly enhanced that the older red beds of the Bedford also originated as a delta deposit, and, in fact, are an earlier phase of the same delta that continued into Berea time.

Shifting of channel courses.—The red beds of the Bedford are uniformly red shale, containing few if any beds of coarser material except for the sandstones and siltstones that occur as channel deposits. In a typical delta deposit composed mainly of fine-grained sediment, the channel deposits generally contain the only beds of coarser material. In a delta such as the Mississippi or the Red Bedford, shifting of the stream courses takes place usually by a break-out or evulsion through the side of a channel when aggradation has proceeded to a sufficient degree. The stream then takes an entirely new course, keeping the coarser material concentrated along the channels, and the finer sediments remain relatively pure. The red beds of the Bedford conform to this concept of delta deposits. An aggrading stream in a valley, however, in depositing its load swings slowly from one side of its valley to the other, seldom altering its course radically by break-outs. Instead, it is likely to leave many small lenses of coarser material interbedded in the alluvium as the channel shifts constantly back and forth in the valley area.

Paleogeography.—The paleogeographic setting of the northern part of the Appalachian basin in early Mississippian time is the subject of a later part of this report. The interpretation of the red beds as a delta deposit most nearly fits the regional geologic history of a shallow sea basin being filled and reduced in size throughout Bedford time by a great influx of converging delta sediment. Near the close of Bedford time the red beds reached their greatest extent, and the sea was largely displaced from the basin by the accumulated sediments.

Evidence for delta deposit chiefly subsurface.—Although the red Bedford shale was examined in many surface exposures, most evidence of the depositional history of the red beds was obtained from the subsurface study of the Bedford shale.

Fundamentally, the great advantage of a subsurface investigation is that a three-dimensional study can be undertaken that will produce a more realistic regional picture than the usual two-dimensional study that is possible in an area of few outcrops. A regional outcrop study is likely to be limited to a single detailed cross-sectional study along an outcrop belt revealed by the haphazard circumstance of erosion. The geologist may be required to study exposures lying along the strike of the sediments, or across it, or somewhere in between—the choice is not usually his; erosion has made the choice for him. In the subsurface, however, provided the data are adequate, critical sections may be studied in any desired relationship to the sedimentary units present, and in addition areal studies can be made of the thickness of beds and the character of the rocks. The advantage of surface geologic work lies mainly in the direct observation of minor features of the rocks, such as bedding, grain size, ripple marks, and so on, which may provide indispensable clues to the sedimentary history of the formation being studied. Obviously, where feasible a study of both surface and subsurface data provides the best picture of the regional geology of an area.

In the study of the red beds of the Bedford the usual surface criteria for distinguishing delta deposits were not generally diagnostic in themselves. For instance, the classical concept of topset, foreset, and bottomset beds as being distinctive of delta deposits was not applicable. In fact, even after deltaic origin had been adopted as a working hypothesis, the determination of topset, foreset, and bottomset beds remained suppositional. All the bedding planes of the Bedford shale, red or gray, that can be observed on the outcrop are approximately flat lying. Cross bedding is not discernible, and the only deviation in bedding from the horizontal is to be found in the laminations in the oscillation ripple marks in the siltstones of the Bedford or in the locally deformed flow rolls. Foreset beds, therefore, are probably impossible to distinguish. Lobeck (1939, p. 233) states:

> Theoretically deltas consist of *bottom-set*, *fore-set*, and *top-set* beds. These are all well developed in the small deltas formed in glacial lakes and now exposed and dissected. But along the sea the almost horizontal fore-set and bottom-set beds merge together. The fore-set beds of young deltas of coarse material may slope at angles of 30 or 35° but the frontal slope of large marine deltas is much less, that of the Rhone being less than ½°.

Doubtless the predominantly fine-grained forset beds of the Red Bedford Delta had a similar gentle dip, and are therefore indistinguishable from the flat-lying bottomset beds.

However, granted the assumption of deltaic deposition, topset and bottomset beds possibly can be differentiated if color, position, and slight differences in bedding can be relied on as adequate criteria. If so, the bottomset beds can be identified as the gray Bedford shale lying below the red Bedford shale and characterized by alternating, sharply defined beds of shale and siltstone typical of marine deposition. Oscillation ripple marks, which also suggest a marine environment, occur at places in the siltstone layers. Presumably the bottomset beds are gray, because any red color that might have been present was altered to gray by the chemical action of organic matter in the water.

The topset beds, then, are represented by the red beds and by the gray beds occurring within or above the red beds. Presumably the red beds indicate subaerially deposited topset beds that were never under water for any appreciable length of time until subsequent burial by later deposits. The gray shale, on the other hand, may be subaqueously deposited topset beds laid down in patches, as marsh or lagoonal sediments, or in broad sheets as the effect of possible short-lived marine incursions over parts of the delta plain. Again, the gray color of the sediment may have been chemically altered from an original red color in standing water or in a local area of concentrated carbonaceous debris.

Barrell (1912) divided his discussion of the recognition of delta deposits into two main parts. In the first part of his paper Barrell implies that deltas as a whole are to be recognized not by their minor features but by their "larger relations"—that is, by the presence of the component parts consisting of topset, foreset, and bottomset beds; by evidence of possible overlap; and by an understanding of the delta cycle of sedimentation. The first criterion, as discussed above, and the second were of little use in proving the existence of the Red Bedford Delta. The third criterion—an understanding of the delta cycle of sedimentation—did not in itself prove the existence of the delta.

The second part of Barrell's discussion on the recognition of delta deposits is devoted particularly to the means of distinguishing terrestrial, or delta plain, deposits from subaqueous delta deposits. His criteria are generally minor features, described under such headings as fossils, coloration, bedding, texture, mud cracks, and others. In the outcrop studies of the red and gray Bedford shale, though several such features assisted in the interpretation of the sedimentary history of the Red Bedford Delta and provided clues to the identification of the component parts of the delta, they did not provide proof in themselves of the presence of the delta.

Instead, a new set of criteria had to be developed, based on the characteristics of delta deposits as a whole and their relationships to the beds that enclose them. These criteria are embodied in the several points of proof cited above and are particularly suited to subsurface studies.

HISTORY OF THE RED BEDFORD DELTA

The history of the Red Bedford Delta can be divided conveniently into three main parts—(1) delineation of the outline, (2) subaerial sedimentation, (3) uplift and erosion in the north, subsidence in the south. The first two of these parts are shown by the paleogeographic maps of early Bedford time (pl. 13 *B*) and of the beginning of late Bedford time (pl. 13 *C*). The third part is subdivided and is represented on the maps of the end of late Bedford time (pl. 13 *D*) and of early Berea time (pl. 13 *E*).

DELINEATION OF THE OUTLINE—EARLY BEDFORD TIME

The first sediments that crossed the east-west shoreline at the northern end of the Ohio Bay in Bedford time were fine-grained silt and mud that fanned out southward for great distances along the bottom of the shallow sea. The color originally may have been red, like most of the later sediments of the Red Bedford Delta, but only a uniform gray remains in the consolidated rocks today.

Near the shoreline in the area of Cuyahoga, Lorain, Erie, and Huron Counties, these sediments were laid down on the reworked black mud of the Cleveland member of the Ohio shale and were deposited to a thickness as great as 10 feet or more. They were well sorted by wave and current action into distinct beds of muds and silts, and wave ripple marks formed at many places. Deposition proceeded rapidly, and the unequal loading of the more mobile material led to the formation of flow rolls (see p. 888–889). Where a temporary equilibrium between the rate of deposition and the effectiveness of marine action was reached, incipient bars formed. The equilibrium seldom lasted very long, however, for the most active loci of deposition shifted rapidly as new distributaries were developed, and the incipient bars were overwhelmed and left behind as the subaqueous delta front pushed successively farther away from the former shoreline.

DELINEATION OF THE OUTLINE—BAR FORMATION

The lateral expansion of the delta sediments was finally checked along the eastern margin by the establishment of at least two offshore bars (fig. 31), the Euclid siltstone and the Second Berea sand. Another bar or a series of bars may have connected the Euclid siltstone and the Second Berea sand, but its existence cannot be confirmed now because of subsequent erosion along the east-central edge of the delta. Lateral expansion along the western margin of the delta may also have been checked by flanking offshore bars, but this possibility cannot be determined because of later erosion and a lack of subsurface data. Along the northernmost part of the western edge of the delta the Cincinnati arch may have prevented the expansion westward. To the south the lateral development was first slowed and then brought to a virtual standstill by the greater volume of sediment required to displace the deeper water and by the increasingly greater distance from the original mouth of the river system. Once these limits were reached, the energies of the river system were diverted to filling in the by-passed low areas and to the eventual building up of a vast peninsular delta.

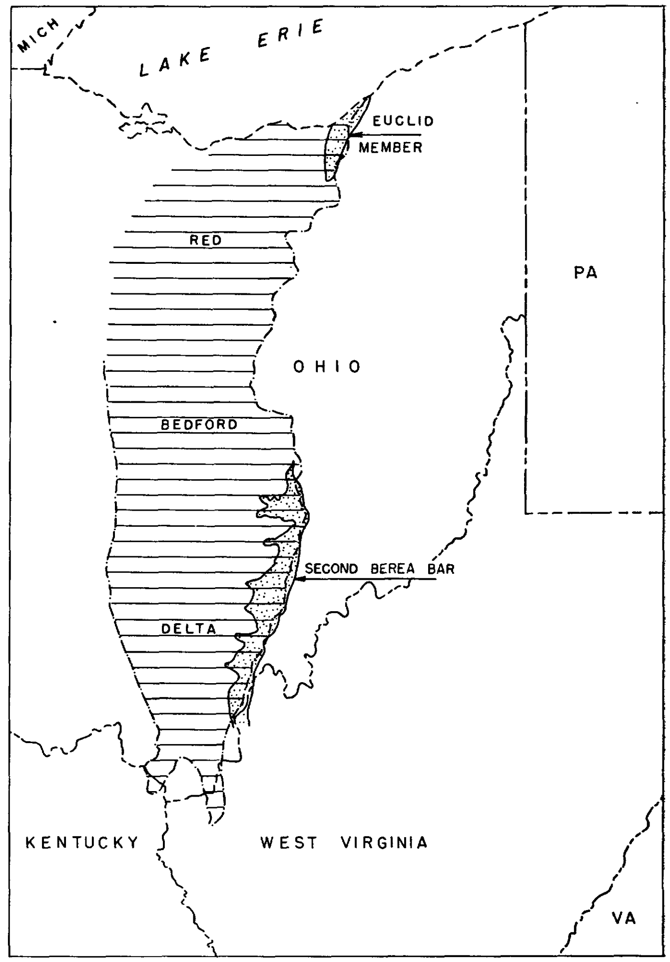


FIGURE 31.—Sketch map showing the relation of the red sediments of the Red Bedford Delta to the flanking barrier bars.

The Euclid siltstone member (fig. 31) is known from relatively few outcrops, but these indicate that it extends about 30 miles in a northeasterly direction across central and northeastern Cuyahoga County. The member may be about 5 miles wide and probably has an average thickness of 15 or 20 feet and a maximum of 20 feet. It is composed of hard, dense, massive- to thin-bedded siltstone. In composition, stratigraphic position, and probable origin, it closely resembles the Second Berea sand. In this paper the Euclid member is interpreted as the northernmost bar fringing the eastern side of the Red Bedford Delta.

The sand of the Second Berea bar (fig. 32), although wholly a subsurface formation, is much better known than the Euclid member. More than 1,300 wells, most of them gas producing, serve to outline the shape of the deposit very closely and provide sufficient information for the construction of a thickness map (pl. 2) and detailed cross sections (pl. 10). In addition, sample chunks of the Second Berea sand that were blown from the wells during shooting operations show a lithologic

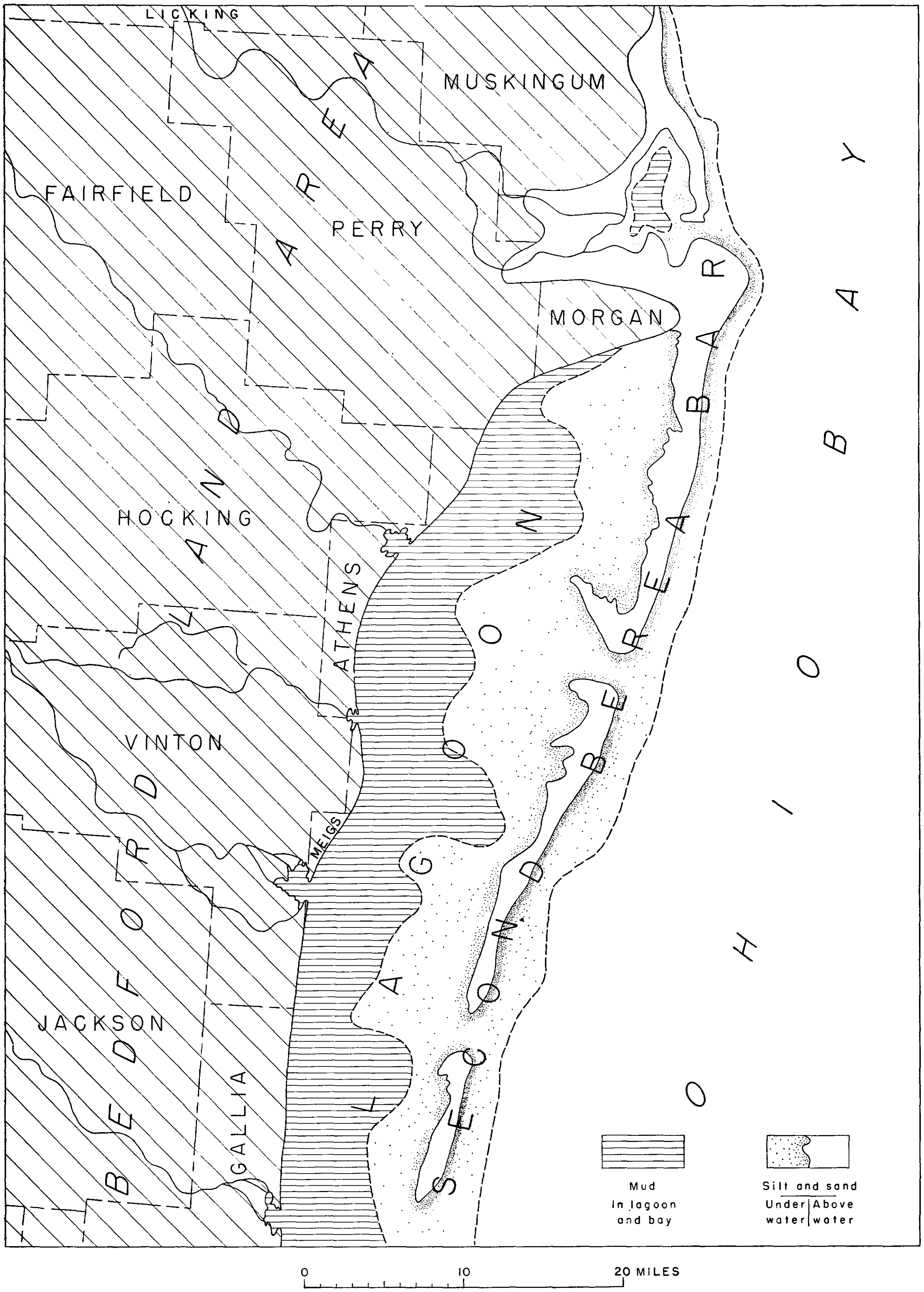


FIGURE 32.—Map of the Second Berea bar during Bedford time.

character almost identical to that of the Euclid siltstone.

The Second Berea sand is an ancient shoreline deposit strongly resembling a modern barrier bar, such as those along the present Gulf Coast of Texas. The sand body is about 85 miles long, 3 to 15 miles wide. The relatively straight eastern margin is the seaward side of the offshore bar, and the irregular western margin is the result of unequal deposition in the lagoon on the landward side of the bar. The westward bulge in Ames Township, Athens County, for example, probably represents tidal deltas built by currents flowing westward through an inlet in the bar and fanning out behind it in the lagoon.

Cross sections B–B′, C–C′, D–D′, E–E′, and F–F′ of plate 10 show the shape and relative vertical dimensions of the Second Berea bar. The thickness of the sand averages less than 20 feet over much of the area of the bar, but in a few places it exceeds 30 feet. In profile the base of the sand body is remarkably even, indicating that the bar and lagoonal deposits were built upward from a relatively flat sea floor. The top of the bar is convex upward. The sand thins rapidly from the crest eastward but very gradually from the crest westward. The Second Berea bar can be traced in a straight line northward from eastern Gallia County to Morgan County, where the continuity of the bar is broken by an inlet and a shallow bay. At this point the bar deposits are close to the shore. North of the bay, which is partly enclosed by a spit, the Second Berea continues as a shoreline deposit. It extends northward for about 15 miles, gradually narrowing and finally disappearing in central Muskingum County. As shown in cross section C–C′, the Second Berea was not deposited in the shallow bay in Muskingum and Morgan Counties, probably because the quiet waters received only fine muddy sediments. The narrow belt of sand along the west side of the bay (fig. 32) represents part of the sandy shore deposit that was built along the east side of the Red Bedford Delta. The bar and shoreline deposits appear to have been concentrated by wave and current action, which removed the finer material from the delta sediments, leaving a residue of coarse silt along the strand.

SUBAERIAL SEDIMENTATION

When the full outline of the delta had been attained, or perhaps shortly before, the upper reaches of the delta near the original shoreline were receiving large quantities of red mud that buried the underlying gray mud and silt. The red sediment filled in the interdigital swamps and hollows and built up a subaerial flood plain on either side of the central river system. At some places, however, where patches of gray shale are present in the Red Bedford Delta, local reducing environments probably effected a transformation from red to gray.

The deposition of the red mud continued rapidly and unabated until much of the entire delta stood well above sea level. Distributary channels were less numerous than would be expected in a delta composed of coarser-grained sediments but approximated the number and persistence of the channels found in a bird's-foot delta like that of the Mississippi, composed predominantly of fine-grained material. The channel courses of the Red Bedford Delta, like those of the Mississippi, contain practically all the concentrated coarser material, except for the coarse siltstone of the flanking bars.

The lower lenses of sand in the Chatham-Lodi oil field are sand-filled channels of Bedford age. These channels are in places cut through the Bedford shale into the underlying black Cleveland member of the Ohio shale to a depth of about 40 feet, and the sand in them is overlain by a section of red Bedford shale ranging from 1 to 100 feet in thickness. To the south, along the center of the Red Bedford Delta a sand-filled channel system (pl. 9) can be traced continuously for more than 40 miles, extending from Ashland County to central Knox County. The channel system follows a meandering course and appears to have cut-offs and ox-bows. In some places it is completely enclosed in red Bedford shale. Farther south, local areas of elongate, thick sand deposits in Athens, Morgan, Muskingum, and Perry Counties (see cross sections E–E′ and G–G′, pl. 10) represent parts of the abandoned stream system that were filled with sand and silt and covered by red mud during the normal course of meander migration. The southern part of the delta, however, contains fewer channel remnants, possibly because the sedimentary history was less complex than in the northern part, but also because less closely spaced drilling has revealed only a small fraction of the buried channel sands that undoubtedly are present.

At some places in the subsurface the channel sands of Bedford age can be differentiated from the channel sands of Berea age. The best criterion for separating these sands is the presence of more than 10 feet of red shale above the channel sand of Bedford age. A thin covering of red shale might result from local erosion and redeposition of red shale during Berea time, but a thick cover of red shale could have originated only during Bedford time. The presence of a thick channel sand in an area where the Berea sand is uniformly thin, as in area I (fig. 35), is additional evidence of a Bedford age for the channel sand.

The sand in the channels of Bedford age is very similar to the sand in the channels of Berea age. Therefore, at most places on the outcrop where the diagnostic red-shale cover has been removed from the channel sandstones of the Bedford, it is not possible to distinguish these channel sandstones from those of the Berea. The writers believe, however, that some channel sandstones of Bedford age have been mapped as Berea in the outcrop in Erie and Lorain Counties. Probably the first massive sandstone above the black Cleveland member of the Ohio shale on Chappel Creek, Vermilion Township, Erie County, Ohio, is a channel sandstone of Bedford age. However, the absence of red shale above the sandstone precludes a conclusive age determination.

The climax of the deposition of the Bedford red beds was reached when the capacity of the delta area to contain more flood-plain sediments was exhausted and when the pressure to extend the confining lateral boundaries was renewed. The thickness of red beds exceeded 150 feet in the northwestern lobe of the delta as well as in the central area near the main channel. The Second Berea bar and lagoonal deposits and the Euclid siltstone member were buried under a blanket of red and gray sediments as much as 40 or 50 feet thick, but the red mud did not extend the subaerial part of the delta appreciably beyond the limits of the offshore bars. Aggradation of the delta ceased as a period of uplift and erosion began.

UPLIFT AND EROSION IN THE NORTH, SUBSIDENCE IN THE SOUTH

At the close of Bedford time, or in earliest Berea time, the Ontario River and its distributaries had aggraded their channels to such a degree that they were forced to seek new outlets to the sea. The old channels in the southern part of the delta were choked by silt and fine sand of the Bedford that were the forerunners of the tremendous quantities of Berea sediments soon to be transported in increasingly large amounts from the Ontario region. Possibly the excessive aggradation in the south was accompanied by a slight uplift of the northern part of the Cincinnati arch, the Findlay arch, and perhaps by uptilting of the entire Ontario region. Such crustal movements would materially increase the capacity of the Ontario River to transport material in the northern part of the Red Bedford Delta and would provide the impetus for a change in the main distributaries of the Red Bedford Delta.

Whatever the causes, the Ontario River broke through its banks at one or more places on the east side of the delta and poured into the Ohio Bay in the area of northern Wayne County. The part of the delta south of the break-out, suddenly cut off from its source of sediments, became stagnant and reverted to swamplands, eventually settling beneath the waters of the Ohio Bay. At this time some of the uppermost beds of the delta sediment may have lost their red color in the reducing environment thus created.

Once begun, the break-out of the Ontario River grew rapidly. The length of the river system had been decreased suddenly by at least 150 miles, causing a sharp increase in gradient, and the flow had been concentrated into one or at most a few large distributaries instead of being dissipated in numerous diverging channels throughout the length of the delta. The transporting ability of the river system was greatly increased, and the channels were cut rapidly into and below the red beds. Concurrently, the eastern shoreline of the delta for 50 miles south of the break-out was deeply eroded by stream action and by the development of strong longshore currents. Upstream from the new river mouth the steep-walled, incised meanders received the coarser sediments of Berea age that had been deposited temporarily higher along the river in the Ontario region but which now were being picked up and transported into the Ohio Bay by the rejuvenated Ontario River.

THE COLOR OF THE RED BEDFORD DELTA SEDIMENTS

Explanations of the origin and preservation of red color in sediments have held the interest of geologists for years, as can be seen from a glance at the bibliography listed in the latest review of the red-bed problem by Van Houten (1948, p. 2123–2126). The solutions that have been offered until lately have been of many types but none have evoked any enduring, widespread agreement among geologists. Recently, however, the reasonable alternative hypotheses have been reduced to just a few, and many geologists are nearing a degree of unanimity, though as yet the final answer has certainly not been agreed upon.

A study of the red beds of the Bedford offers an almost unique opportunity to check the validity of some of the most promising red-bed hypotheses by applying them to this newly described "case history" in red-bed sedimentation. The sedimentary history of the Red Bedford Delta described above was deduced not from the fact that the Bedford sediments are predominantly red but almost solely from other lines of evidence having little or nothing to do with the red-bed problem. Thus an impartial description is provided of a complete paleogeographic setting in which potentially red or actual red sediments were deposited. The incidental red color serves mainly as a distinguishing feature that greatly facilitates delimiting the extent and thickness of the deposit.

The most probable modes of origin of lenses of red rocks in varicolored formations are summarized below in a table adapted from Van Houten (1948, p. 2110).

Synopsis of postulated modes of origin

Mode	Climate	Process
A. Red pigment developed at place of deposition.	1. Warm, humid 2. Warm, arid, or semiarid	Development of red soil. Concentration of hydrated ferric oxide during and after deposition, subsequently dehydrated.
B. Red pigment derived from source area.	3. Indifferent 4. Warm, seasonally humid	Erosion of red bedrock. Erosion of red soil.

Numerous objections to the formation of red color in sediments according to mode A in the table are discussed in detail by Van Houten, whose conclusion is that chemical limitations, especially, prevent acceptance of any hypothesis of thick red beds formed in place by the alteration of previously drab sediments. Although no study of the chemistry of the red pigment of the red beds of the Bedford has been attempted by the writers of this paper, it nevertheless appears most unlikely that the red color could be due to alteration of gray or drab sediments subsequent to deposition. If alteration in place were the cause, it would fail to account for the selectiveness of the process involved in coloring some of the sediments red and leaving others, particularly the coarser sediments, untouched. In the first process listed under mode A in the table a warm humid climate is required for the development of red soil. Although the climate during Bedford time was probably warm and humid, the deposition of the delta sediments was probably so rapid that only small amounts of soil would have had time to form. The second process listed under mode A requires a warm arid or semiarid climate. On the contrary, the available evidence indicates a reasonably humid climate.

The second major proposition, that red beds are derived from the erosion of parent red rocks, is believed by Van Houten to account for red color only locally or under special conditions. Although it is theoretically possible for the red beds of the Bedford to have originated in this manner, it is not probable. The tributaries and headwaters of the ancient Ontario River during early Mississippian time probably crossed outcrops of red rocks, such as the Queenston shale and other red beds of Paleozoic or pre-Cambrian age, but these outcrops, in all likelihood, were not sufficient to have provided large quantities of sediment rapidly enough to build the Red Bedford Delta.

The remaining alternative, that red beds are mainly derived from the erosion of red soils, is favored by Van Houten and is believed by the writers to provide the most plausible explanation of the red pigment in the sediments of the Red Bedford Delta. The Late Devonian in the northern part of the Ohio basin was a time of crustal stability and a minimum of erosional activity, as shown by the thick accumulation of black mud deposited there. During this time in Ontario thick soils were probably produced under a warm or temperate, fairly humid climate that favored the formation of red-hematite pigment. When the uplift came that initiated the cycle of deposition of Bedford and Berea sediments, the first available sediment to be transported by the rejuvenated drainage was the deep accumulation of red regolith. The red clay was winnowed from the soil, and the sand was concentrated in the bottom of the gullies. It was not until most of the red soil cover had been removed that the stream gradient was sufficient to move the deposits of quartz sand and silt that constitute the bulk of the Berea sediments and transport them into the Ohio Bay.

The patches and beds of gray shale or siltstone in the Bedford shale have already been noted in many places above. It seems reasonable that much of the gray Bedford shale where it is associated with the red beds, was originally of red color. Undoubtedly at many places along the Red Bedford Delta at any given time, a suitable environment existed that would reduce the primary red color of the sediments locally. Small swamps, ox-bow lakes, stagnant lagoons, and the like would probably entrap sufficient carbonaceous matter to alter the red pigments; local and brief marine incursions might also deposit organic material that could cause reduction of the hematite responsible for the red coloration. The delta plain generally, however, was probably free from a reducing environment except as noted above. Sedimentation probably proceeded too rapidly for an extensive and permanent cover of vegetation to grow, and aggradation of the delta plain with new red mud was repeated and frequent, preventing the small, though occasionally concentrated, pockets of decaying carbonaceous material from changing the sediments from red to drab colors except in isolated patches.

DEPOSITION OF THE GRAY BEDFORD SHALE

The gray Bedford shale, which is most frequently logged as "gray shale" or "gray shale and shells" by the drillers, extends from the eastern edge of the Red Bedford Delta across the eastern third of Ohio. The eastern edge of the Bedford shale cannot be determined satisfactorily at many places, because the thinning wedge of gray shale and interbedded siltstones of the

Bedford lie upon similar-appearing beds of siltstone and shale in the Upper Devonian rocks. At places where the Cleveland member of the Ohio shale or the Cussewago (Murrysville) sand underlies the Bedford shale, delineation of the gray Bedford shale is possible. However, neither the Cleveland shale nor the Cussewago (Murrysville) sand is present over a large part of southeastern Ohio, and in this area the eastern limit of sedimentation during Bedford time is not defined.

The presence of 40 to 140 feet of siltstone and shale and small amounts of sand below the definitely recognizable Berea in area C in Stark and Tuscarawas Counties (fig. 11) shows that some sediment was accumulating in this local basin in Bedford time. Apparently the source area of these clastics lay north and east of Ashtabula County, and the material was probably derived from the exposed Chagrin rocks. A small stream system, here called the Ashtabula River, transported the silt and mud into the northern part of the Ohio Bay. Outcrop and subsurface data show that a sheet of silty mud covered the Cussewago (Murrysville) sand in Columbiana, Mahoning, and Trumbull Counties during middle Bedford time. As shown in figure 33, pre-Berea erosion appears to have cut out much of this sediment, because at some places the Berea sand lies upon the Cussewago (Murrysville) sand or is separated from it by a few inches of silty shale. Elsewhere in the area as much as 30 feet of shale occurs between these two sands. The intervening shale has been traced into the surface exposures of the gray Bedford shale in Ashtabula, Geauga, Lake, and Trumbull Counties, Ohio and in the western parts of Crawford and Erie Counties, Pa.

The eastern limit of the deposition of Bedford sediments appears to trend southwestward from the vicinity of Meadville in Crawford County, Pa., into the vicinity of Wellsville in southern Columbiana County, Ohio; swinging southward across Jefferson, Belmont, and Monroe Counties, and western Washington County into eastern Athens County; paralleling the Second Berea bar across eastern Athens County and Meigs County, Ohio; and crossing the Ohio River into Mason County, W. Va. Although little evidence is available to mark its position, the boundary line apparently crosses Mason, Cabell, Wayne, and Mingo Counties into the area of little drilling in southern Mingo County.

The area of greatest silt deposition in Bedford time lay in area G (fig. 11) in eastern Kentucky between Pike and Lewis Counties. At many places the entire sequence between the Sunbury or "Coffee" shale and the black Ohio shale is siltstone of which about 90 percent seems to be Bedford in age. Although some of the silt was carried down the Ontario River and discharged into the northern part of this area, by far the greatest amount of the silt and some very fine sand was carried into the area from the southeast by one or more rivers. The sediment was spread in a shallow, slowly sinking basin as is shown by the oscillation ripple marks present throughout much of the siltstone of Bedford and Berea age in northern Lewis County, Ky.

A belt of gray Bedford shale, including a few thin siltstones, lies between the Red Bedford Delta and the outcrop of the Bedford south of Lithopolis, Franklin County, Ohio. This shale becomes progressively siltier to the south and grades into the siltstone of the Bedford in northern Scioto County. The gray Bedford shale is probably the result of the deposition of mud in an aqueous environment in which carbonaceous matter removed the red color by the reduction of the existing ferric iron.

SEDIMENTATION OF THE CUSSEWAGO (MURRYSVILLE) SANDSTONE

On the northeastern rim of the Ohio Bay the Cussewago (Murrysville) Delta was growing concurrently, in part at least, with the Red Bedford Delta. The Cussewago (Murrysville) Delta (area D shown in fig. 11) may have begun to form in Late Devonian time near the probable source of sediment in the region of western Maryland and north-central Virginia. It undoubtedly reached its culmination during early Bedford time when the delta fan had advanced into northeastern Ohio and confined the seaway between its front and the flank of the Red Bedford Delta.

In Ashtabula and Trumbull Counties, Ohio, and Crawford County, Pa., the surface outcrop of this delta deposit is the Cussewago sandstone, but in the subsurface it is generally known as the Murrysville sand. The Cussewago sandstone is typically a medium-grained greenish-brown friable sandstone which may contain pebbles or beds of siltstone and shale. Its thickness, although irregular, at its maximum does not greatly exceed 30 feet along the outcrop. The Cussewago sandstone disappears abruptly in western Trumbull County and in eastern Crawford County. The excellent section (Fettke and Bayles, 1945) in the Conemaugh Gorge through Laurel Hill, northwest of Johnstown, Pa., just east of the New Florence quadrangle, provides the best exposures of Mississippian rocks on the east side of the Appalachian basin in Pennsylvania. The unit assigned by Fettke and Bayles to the Murrysville is the Cussewago (Murrysville) sandstone of western Pennsylvania and northeastern Ohio. The general lithologic aspect is similar, and the included pebbles of quartz, chert, and igneous rock appear almost identical in composition to the pebbles that occur in the Cussewago in Erie and Crawford Counties. In addition,

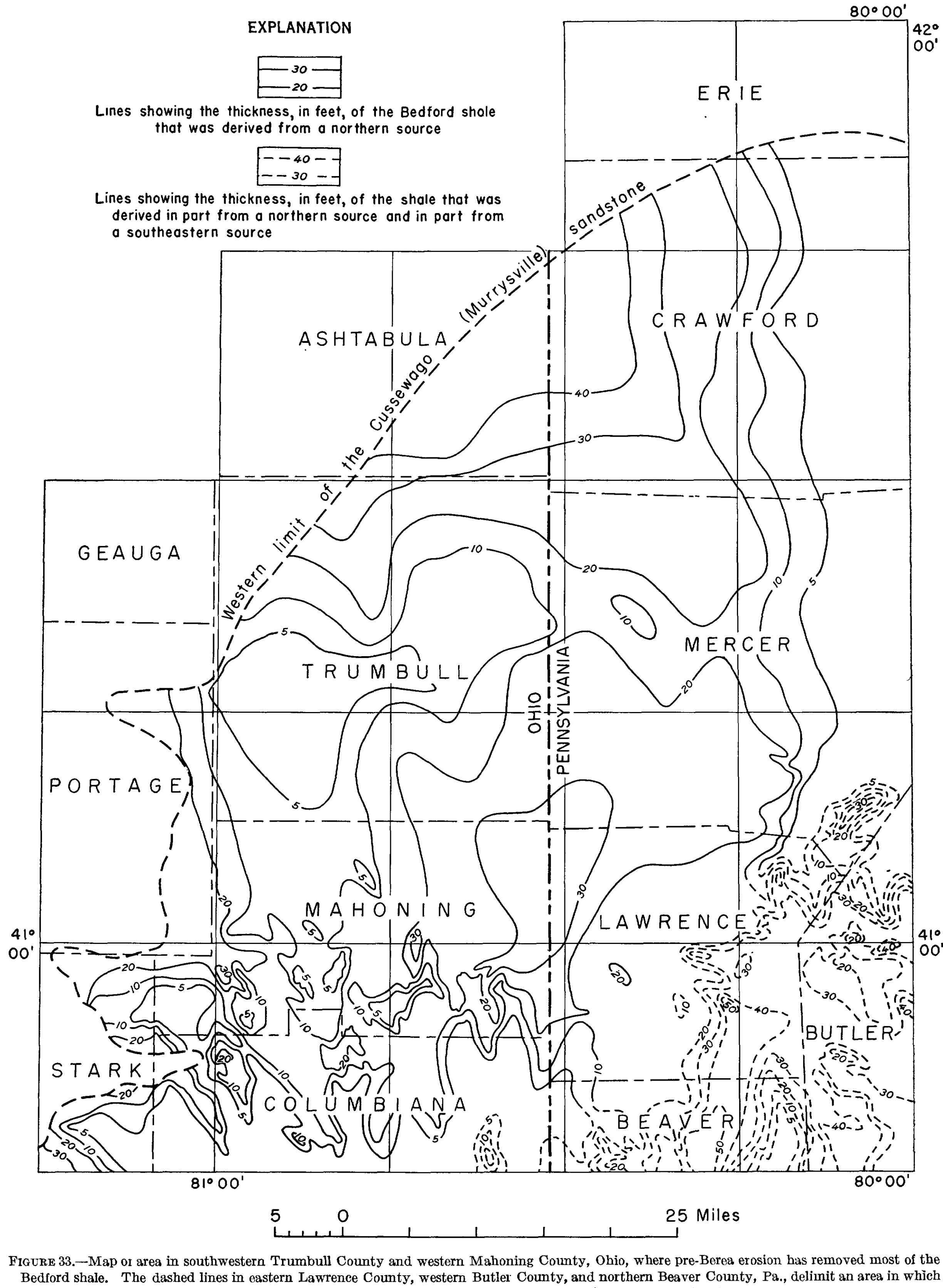


FIGURE 33.—Map of area in southwestern Trumbull County and western Mahoning County, Ohio, where pre-Berea erosion has removed most of the Bedford shale. The dashed lines in eastern Lawrence County, western Butler County, and northern Beaver County, Pa., delimit an area in which the thinning wedge of Bedford shale from a northern source grades laterally into a wedge of shale from a southeastern source.

subsurface correlation shows that Fettke and Bayles' Murrysville of the Conemaugh Gorge section is the same as the Cussewago (Murrysville) sand in the subsurface.

The thickness lines and the extent of the Cussewago (Murrysville) sand, as shown on the map (pl. 1), present a distinctive sedimentary pattern. The main axis of deposition, as shown in figure 34, extends diagonally across the map northwestward from Westmoreland County, Pa., to southeastern Trumbull County and northeastern Mahoning County, Ohio. The main axis of deposition lies within an area of sand bounded by the 80-foot isopach line (pl. 1.). At right angles to this axis are two parallel subsidiary axes. The first of these runs from the extreme southwestern corner of Pennsylvania, crossing the main axis in the vicinity of northern Allegheny County, and extends northeastward through Armstrong County and southern Clarion County to the edge of the map. The second subsidiary axis lies across the northwestern end of the main axis and extends northeast from Carroll County, Ohio, to Crawford County, Pa. The outcrops of the Cussewago sandstone lie entirely within the borders of this cross axis. The subsidiary axes, except where they cross the main axis, are separated by large areas containing no sand at the horizon of the Cussewago (Murrysville). The northeastern area of no sand, centering in Venango County, Pa., almost coincides with the area in which the Corry sandstone was deposited, but areas of Cussewago (Murrysville) and Corry deposition appear to be separated by a belt a few miles wide in which neither Cussewago (Murrysville) nor Corry was laid down.

The thickness lines for the Cussewago (Murrysville) sand are necessarily generalized, for the variability of the sand in lithologic character and thickness makes impossible as detailed an isopach map as has been made for the Berea sand. For simplicity a number of small areas containing no sand have been omitted.

Two main stages of the Cussewago (Murrysville) Delta are easily recognized, corresponding to the two subsidiary cross axes of sedimentation mentioned above. These axes appear to represent two similar periods of deposition in shallow troughs that lay across the path of the advancing Cussewago (Murrysville) Delta.

SEDIMENTATION OF CUSSEWAGO (MURRYSVILLE) EQUIVALENT IN NORTHERN WEST VIRGINIA (AREA F)

South of the Cussewago (Murrysville) Delta in area F (fig. 11) a similar delta was built into the basin from the east at about the same time as the Cussewago (Murrysville), or possibly slightly earlier. This delta merges into the southernmost lobe of the Cussewago (Murrysville) Delta. The part that is traceable in the well records is much smaller than the Cussewago (Murrysville) and is less well known, but may formerly have been of equivalent size. The delta deposit is fanlike and was probably deposited subaerially in succession with several older but similar deltas in the Late Devonian epoch.

The rocks of the area F delta are not like the fine-grained marine sandstone or siltstone in nearby Berea sand but are usually much less uniform. Shale, silt sand, and even pebbles are present in samples from the same well. Samples from wells in the eastern part of area F contain the most pebbles and coarse sand. Mineralogically the sand is similar to the Upper Devonian and the so-called "Berea" sands of the West Virginia outcrop, but no definite correlation with outcrop sands is possible until further sample studies have been made.

The approximate outline of this delta can be seen on the isopach map (pl. 1), but especially noteworthy is the sudden thickening of sediments to the eastward, which is well shown by the proximity of the 40- and 80-foot isopach lines. This apparent thickening may be due in part to the normal thickening of the delta toward its source, but the configuration of the isopach lines strongly suggests that the original gently sloping delta sediments were eroded in a wide belt along the outer edge of the delta to form an erosional front roughly along the present position of the 40-foot isopach line. Probably during this period of erosion the channel of the Gay-Fink River was incised into the delta and became the course through which some Berea sediments of area N (fig. 35) were transported.

The delta of area F may have extended south and east of its present known limits and have been also the parent delta for the Cabin Creek Channel (see p. 78–79). Little information is available to prove or disprove linking the Cabin Creek Channel to the delta of area F as a later distributary similar to the Gay-Fink Channel. If the Cabin Creek Channel is not directly related to the delta of area F, it may connect with another delta deposit, the presence of which is hypothetical.

SEDIMENTATION OF THE BEREA SANDSTONE

The Berea sandstone at its type locality and in areas J, K, H, I, and parts of M was derived from a northern source. The sand in area N was derived from eastern sources, and sand and siltstone in areas M and G were most probably derived in part from southeastern and southern sources. The areas of sand and siltstone of Berea age, which are shown in figure 35, were delimited as an aid in the description of the sedimentary history of the Berea sand in the Appalachian basin. The actual lithological boundaries of the various areas are

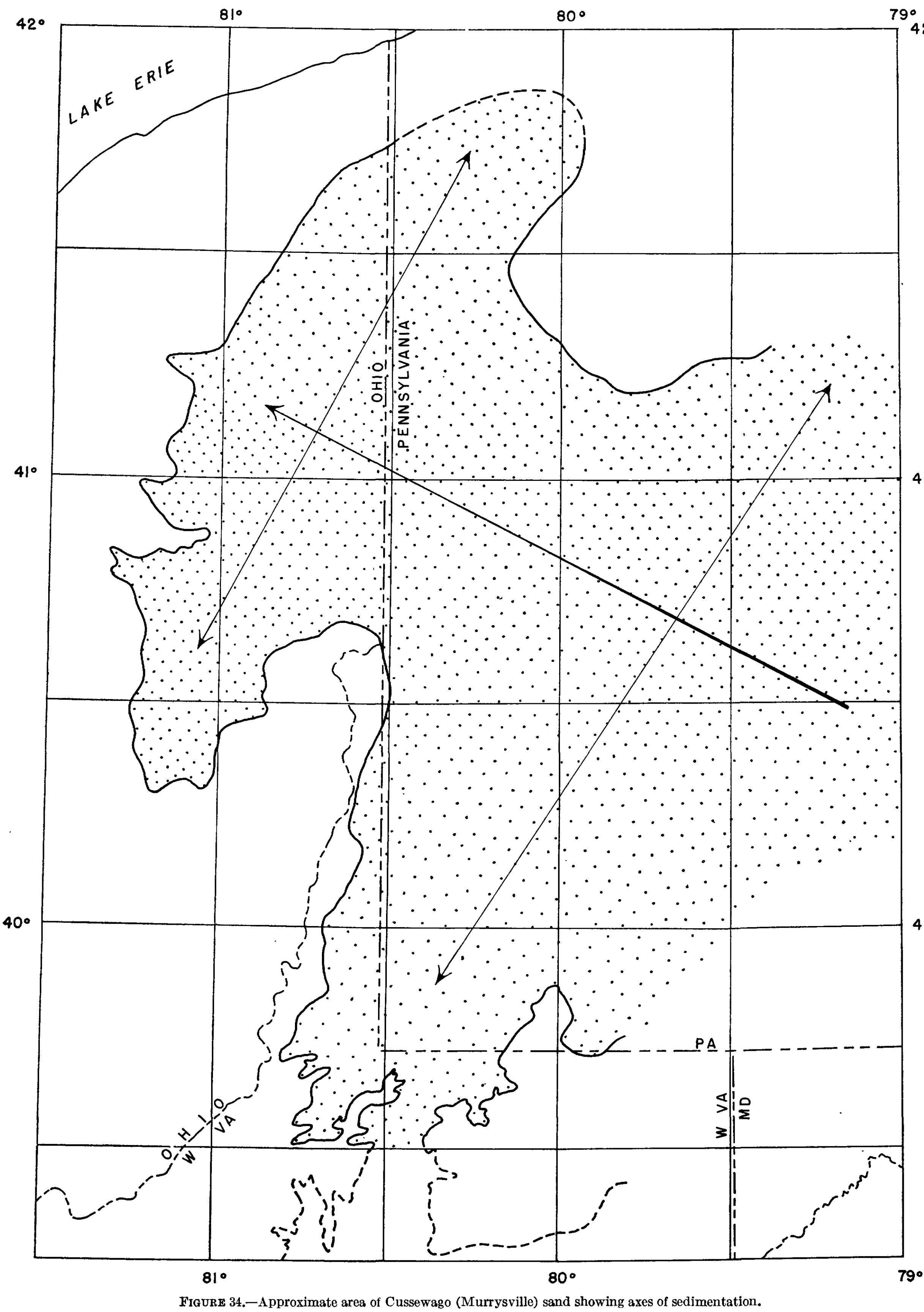


FIGURE 34.—Approximate area of Cussewago (Murrysville) sand showing axes of sedimentation.

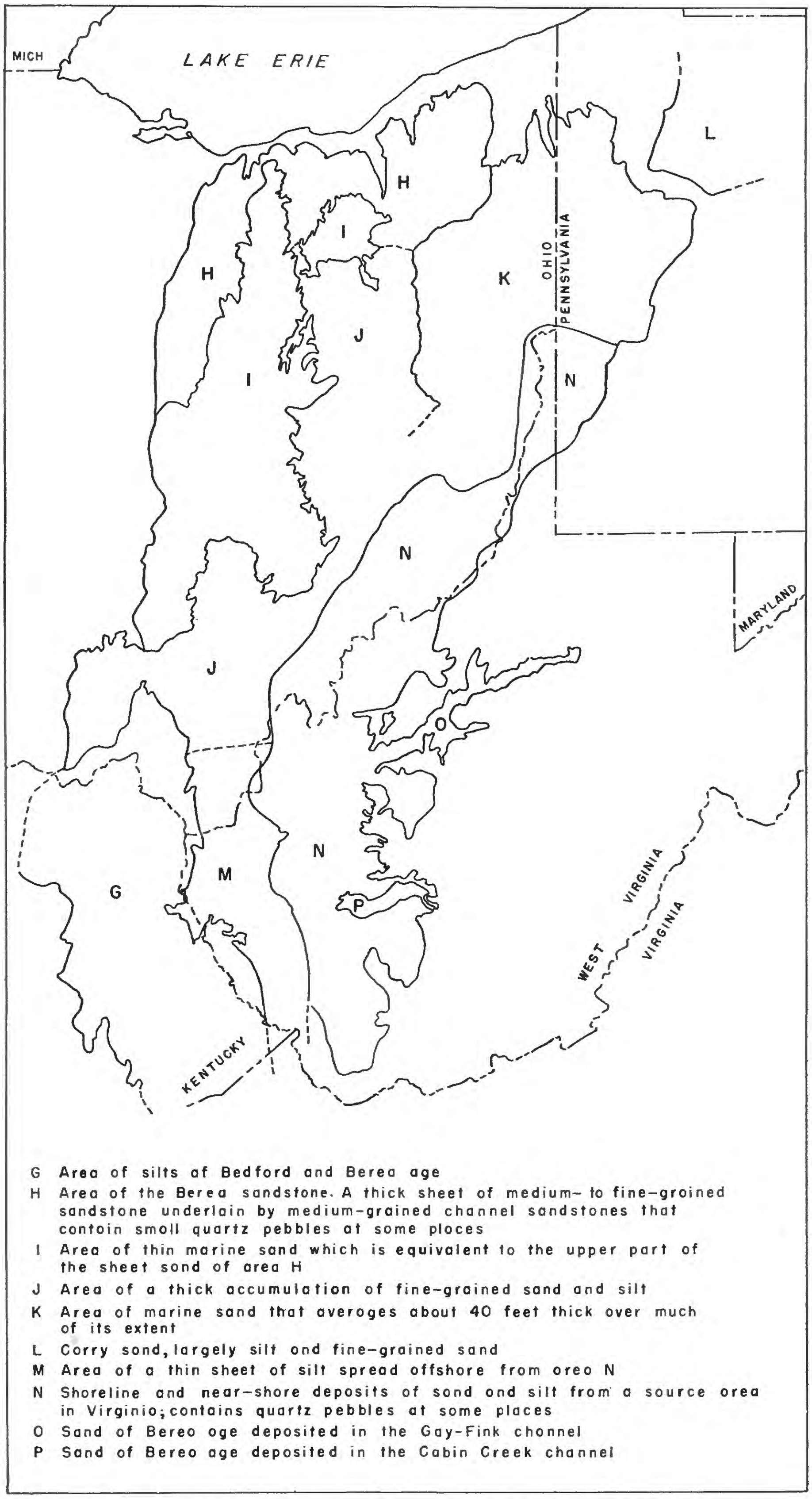


FIGURE 35.—Map showing the different areas of silt or sand deposition in the Berea and the Corry sandstones in early Mississippian time as described in this paper.

not sharp, for the areas were arbitrarily divided on the basis of slightly differing sedimentary histories.

In many of the outcrops in the northern part of area H, the Berea sandstone can generally be divided into two phases. The upper phase consists of a relatively uniform sheet of sandstone, which ranges in thickness from 20 feet in Huron County to 40 feet in western Cuyahoga County. The upper third of this phase of the Berea is thinly bedded containing many well-formed oscillation-type ripple marks. The lower two-thirds of the upper phase of the Berea is more massively bedded and is generally cross-bedded. The ripple marks and cross bedding indicate that this part of the Berea was deposited first in a subaerial and later in a shallow-water environment.

The lower phase of the Berea is composed of many channel sandstones. (See figs. 36, 37, and 38.) A thorough examination of the Berea from eastern Trumbull County to southern Morrow County shows that the channel sandstones exhibit similar sedimentary characteristics throughout this area. The large and famous quarries of the Berea sandstone in Cuyahoga, Erie, and Lorain Counties and many of the less well-known quarries in Ashtabula, Geauga, Huron, Lake, Richland, and Trumbull Counties were cut in these channel sandstones. Some of the most instructive exposures of the channel sandstones can be studied in the Buckeye quarry of the Cleveland Quarries Co. at South Amherst, Amherst Township, and the Nicholl Stone Co. quarry at Kipton, Camden Township. Both quarries are located in Lorain County. Although these two quarries do not contain examples of all the kinds of sedimentary structures that have been observed in the channel sandstones in area H, much of the evidence for the genesis of these sandstones was obtained from a careful study of the Buckeye and Nicholl quarries. Figure 39 shows the probable course of the channel in which the sandstone of these quarries was deposited.

Core drilling in the vicinity of the Buckeye, Nicholl, and other quarries in addition to well records in and near the channel sandstones show that these sandstones were deposited in deep channels which had been cut into and at some places through the Bedford shale and Cleveland member of the Ohio shale into the upper beds of the Chagrin shale, as shown in the cross section of figure 43. Figures 20 and 36 show the cut on the east bank of the Cuyahoga River on Granger Road near Willow, Independence Township, Cuyahoga County. In this exposure the channel was cut into the lower part of the red Bedford shale but not sufficiently deep to penetrate the Euclid siltstone. At Squaw Rock in the South Chagrin Reservation of the Cleveland Metropolitan

FIGURE 36.—Bedford shale and Berea sandstone on U. S. Highway 17, Newburg Township, Cuyahoga County, Ohio. Showing the Berea sandstone filling a scour channel cut into the Bedford shale. Note the steep-angle fluvial crossbedding in the cliff back of the man in the center of the photograph.

FIGURE 37.—East end of the scour channel shown in figure 36. Shows the nearly flat lying beds of the marine cap (*a*), steeply inclined cross bedding of the sheet sand (*b*), and the massive channel sandstone (*c*). Unfortunately, some slumping of the sandstone blocks on the wall of the scour channel gives the erroneous impression that the channel wall was undercut. An old road (*d*), which shows as a heavy horizontal line about 10 feet above the seated man, is cut almost on the contact of the channel sandstone and the overlying cross-bedded stream-laid sheet of sandstone.

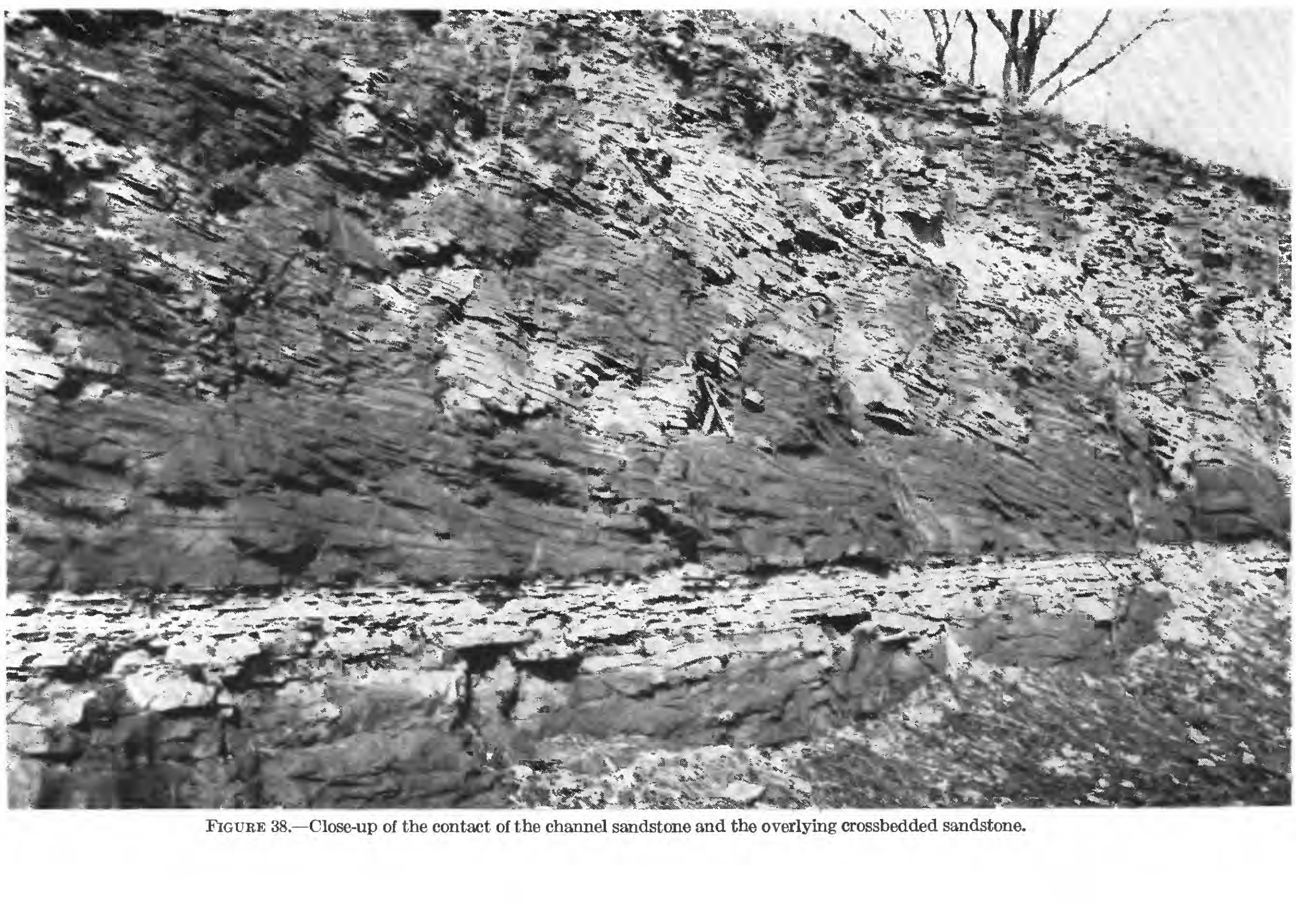


FIGURE 38.—Close-up of the contact of the channel sandstone and the overlying crossbedded sandstone.

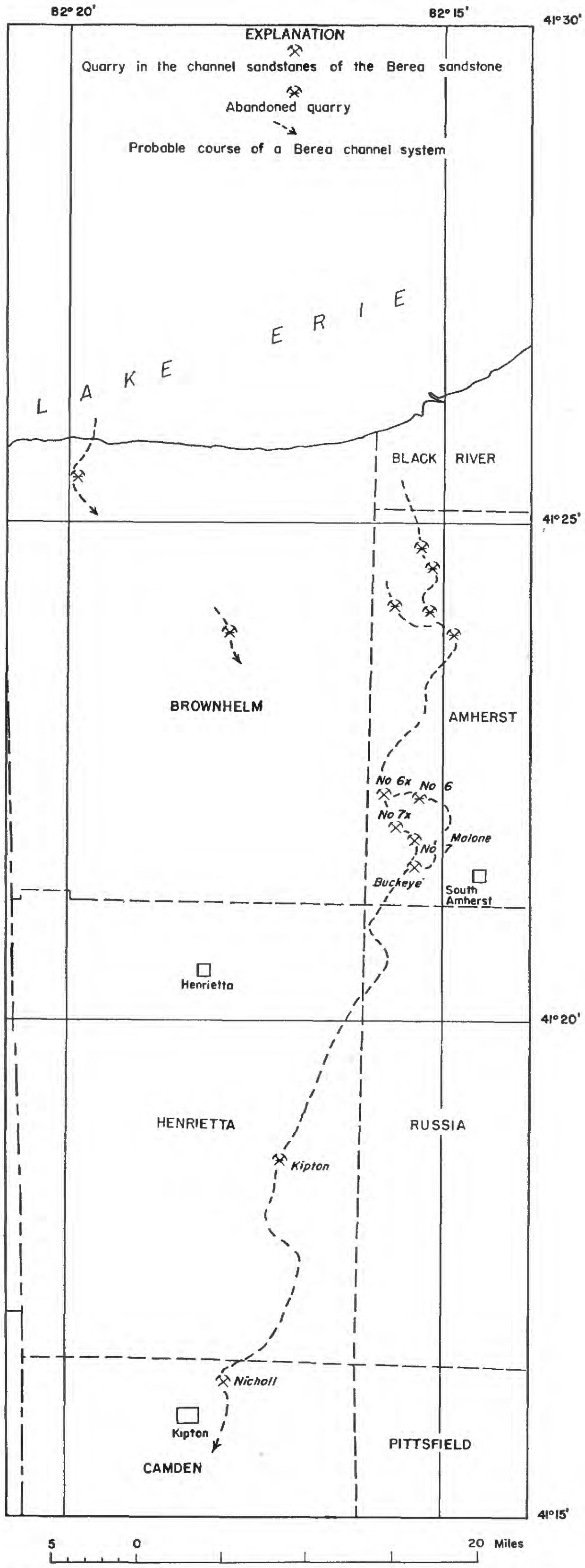


FIGURE 39.—Map of a part of Lorain County, Ohio, showing the probable course of a Berea channel system from the north through the Buckeye quarry, Amherst Township, and the Nicholl quarry, Camden Township.

Parks near Chagrin Falls, Chagrin Falls Township, Cuyahoga County, outcrop 3 (pl. 4), the scour cut through some of the thin flagstones in the Bedford. Pre-Berea scour at the Buckeye quarry cut through both the Bedford and Cleveland shales and into the underlying Chagrin shale.

Many of the deeper channel sandstones are steep walled, and in places where quarrying or erosion has breached the side walls the contact with the surrounding shale is sharp. In general the shale adjacent to the sandstone is undeformed. However, slight crumpling can be seen in the red shale next to the south wall of the Nicholl quarry at Kipton. This deformation appears to have occurred after the deposition of the sandstone and may have resulted from loading by glacial ice. At the quarry there is almost no disturbance of the Berea sandstone. Undisturbed horizontal beds of shale underlying undisturbed Berea sandstone were found at a depth of 90 feet in the No. 7 quarry at South Amherst.

A few normal faults were found in the channel sandstones. Of the three normal faults observed in the east wall of the Buckeye quarry the largest has a maximum displacement of 8 inches. The faulting occurred prior to the lithification of the sandstone, for the displacement decreases along the fault plane away from the point of greatest dislocation and does not extend to the edge of the channel.

The bases of the channels in which the Berea sand was deposited are convex downward, as shown by figure 43. The bedding planes in the channel sandstones are for the most part either flat lying or gently inclined except in the upper parts of the channels where the channel sand phase of the Berea grades into the overlying sheet sand phase. Here fluvial crossbedding is dominant, and many local dips can be observed ranging from 5° to 25°. The Buckeye quarry shows abundant crossbedding; some thinly laminated even bedding characteristic of deposition in deep, quiet water; and numerous examples of current ripples.

At some places flat discoidal pebbles of gray, red, or black shale occur in the sandstone. Dark-gray to black water-worn shale pebbles, which may have been eroded from the Cleveland member of the Ohio shale, were found in a lens of pebbles in the Nicholl quarry at Kipton. In that quarry the presence of many pebbles of red shale and iron-stained siltstone which were derived from the Bedford shale and incorporated in the Berea sandstone indicates that the Bedford shale was consolidated prior to deposition of the Berea sandstone. Generally these pebbles lie in small scour channels whose surfaces show current ripple marks. (See figs. 40, 41, and 42.) The ripple marks clearly show that the stream which deposited the sand flowed essentially parallel to the long axis of the channel, although this

FIGURE 40.—Current ripple marks exposed in quarrying at a depth of 120 feet in the east end of the Buckeye quarry at South Amherst, Lorain County, Ohio.

FIGURE 41.—Current ripple marks in a block of Berea sandstone in the No. quarry at South Amherst, Ohio.

FIGURE 42.—Cross section of the current ripple marks shown in figure 41. Note the progressive displacement of the ripple crests to the left upward through the block.

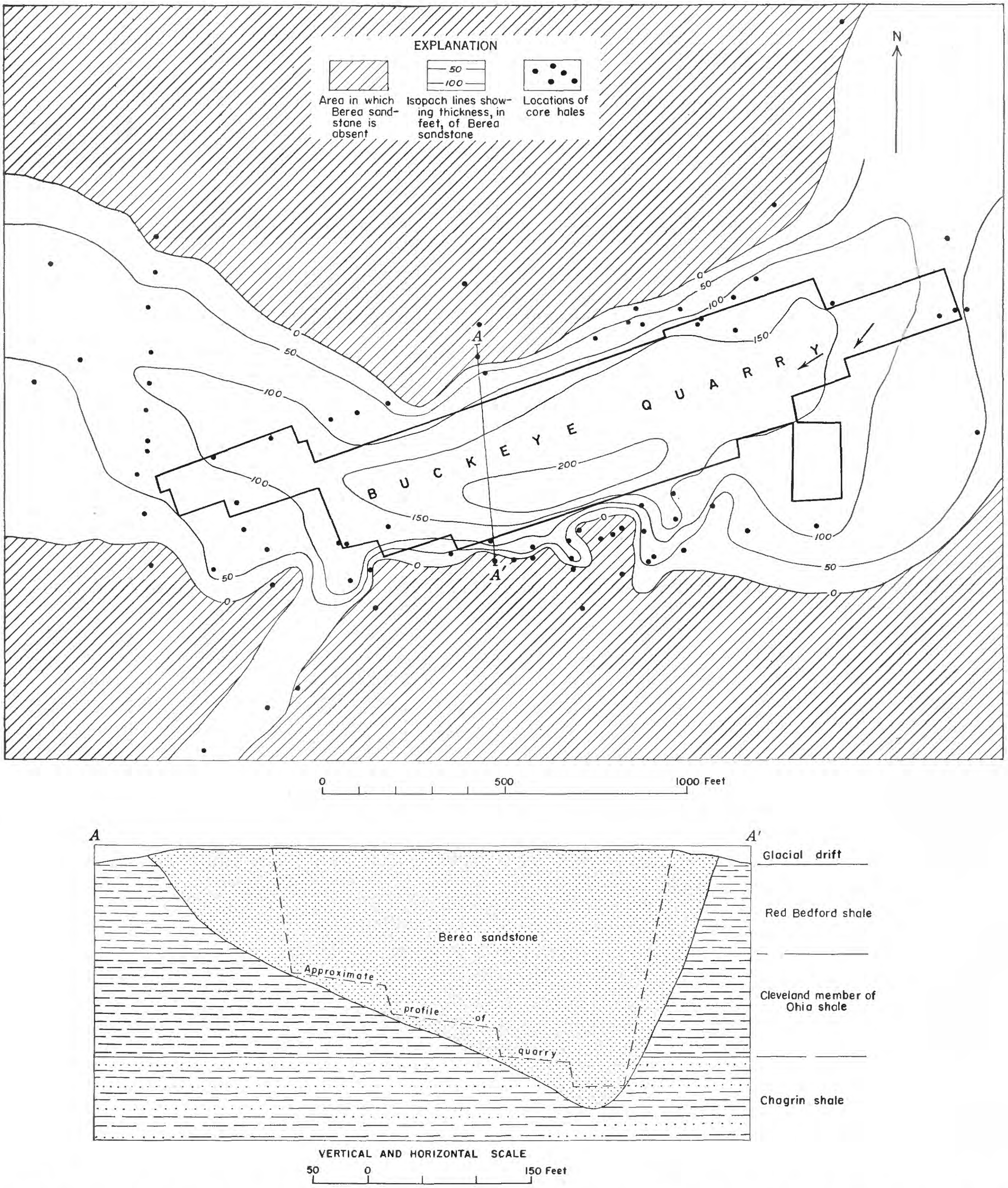


FIGURE 43.—Map and cross section of the Buckeye quarry of the Cleveland Quarries Co., South Amherst, Ohio. Note that deepest fill in channel and steepest wall lie near outside of meanderlike curve and that the channel is deepest in its narrowest stretch and shallowest in its widest stretches.

direction may not be parallel to the long axis of the quarry in which the ripple marks are exposed. The arrows in figure 43 show the direction of current in the Buckeye quarry as indicated by the ripple marks.

Along the outcrop of area H (see fig. 35), glacial erosion has stripped away much of the upper thinner-bedded Berea and left many of the thicker channel sandstones standing as long, linear ridges which rise 50 feet or more above the surrounding low plane. The linear trend of the channel sandstones is obscured in many places by a series of beach ridges which were built by several of the post glacial ancestral stages of Lake Erie (Cushing, Leverett, and Van Horn, 1931, p. 69–81). Because the Berea sandstone dips gently to the south in area H, the northern edge of the outcrop shows only the channel sandstones whereas along the southern margin of the outcrop only the thinner-bedded upper phase of the Berea is to be seen. Casual examination of the relatively steeply dipping cross bedding in the thinner-bedded sheet sandstone has led to the erroneous impression that the Berea sandstone of area H is made up of a great many sand bars. Although much of the crossbedding in the upper part of the Berea sandstone was formed in shallow water, the channel sandstones did not form as offshore bars.

Many of the early geologists working in northern Ohio, including Newberry (1870a), Orton (1888b), Burroughs (1911; 1913; 1914), Prosser (1912a), Cushing (Cushing, Leverett, and Van Horn, 1931, p. 47–48), and others recognized that these large sand bodies in the lower part of the Berea were sand-filled scour channels. Much later, however, some geologists in attempting to draw an analogy with the area of isostatic load-adjustment on the present delta of the Mississippi River have questioned the channel-fill mode of origin. Alternate hypotheses offered suggest that the channel sandstones were either barrier bars built into deep water or parts of the sheet sand which, having begun to settle by some means, sank slowly under a steadily accumulating mass of sand.

In order to review the evidence for the genesis of these sandstones, much time was spent studying the quarries and other outcrops in area H. The Cleveland Quarries Co. furnished core-drill data from the vicinity of South Amherst and Birmingham. In addition, the closely spaced core-drill records in the Chatham-Lodi oil pool of Medina County were examined.

The following observed facts substantiate the scour-and-fill origin of the large sand bodies in the lower part of the Berea in area H:

1. The sinuous alinement of the sand bodies as shown in figure 39 is best explained as the filling of a system of distributary channels on a delta.

2. The shape of the Buckeye quarry as shown in figure 43 is that of a meander of a large river, being deepest on the outside of the curve and shallowest on the inside or slip-off side of the meander.

3. The nongradational contact of the Berea sandstone and the Bedford shale or Cleveland shale; the lack of deformation along the sandstone and shale contact; and the presence of pebbles of black Cleveland member of the Ohio shale, red Bedford shale, or bluish-gray siltstone of the Bedford included in the sand bodies clearly demonstrate that the shales were well lithified and not in a plastic state prior to the scour of the channels in which the Berea sand was deposited.

4. The great change of thickness in very short distances and the relatively uniform horizontal bedding throughout much of the vertical thickness of the sandstone can be explained most easily as deposition in slowly moving water in a scour channel. The presence of some current ripple marks within the elongate sand bodies showing that the current flowed roughly parallel to the long axis of the sand body is additional evidence for the deposition in a long, linear trough or channel.

Meager evidence exists to support the offshore bar accumulation or the local-adjustment hypothesis of origin of these sandstone bodies. Crossbedding exposed in the upper parts of many of the quarries suggests that the sandstone bodies may have been deposited as sand bars. However, the crossbedding is largely a part of the upper phase of the Berea in this area. At some places such as the quarries at Berlin Heights in Erie County, some subsidence appears to have occurred during the deposition of the sandstone. The movement, however, was slight.

The load-adjustment hypothesis for the genesis of the sand bodies requires the differential subsidence of parts of the sheet of Berea sand in response to unequal deposition. It has been suggested that the foundering of incipient or partly formed offshore bars built upon plastic mud of the Bedford might have produced these sand bodies.

Many facts, however, show that the sandstone bodies did not settle or sink into the sediment below. The settling of large masses of sand into plastic mud would tend to dewater and compact the mud directly below the sinking sand until the mud offered sufficient resistance to halt the downward sinking and shift the direction of settling of the mass. Thus the subsiding sand mass would be tilted and oversteepened on one side. An influx of plastic mud and a great deal of flowage of the sand would result along the oversteepened side of the settling sand body. Therefore, if load adjustment had produced the sand bodies in the Berea, each of these sand bodies should be surrounded by a belt of distorted and contorted shale, and zones of entrapped shale containing some deformed beds of sand would be found enclosed in the sand bodies. However, these features were not observed in the channel sandstones. Also, to sink a mass of sand 200 feet thick into plastic mud requires a column of mobile material at least as thick as the sand mass. To sink the Buckeye quarry requires that all the Bedford shale, all the Cleveland member of the Ohio shale, and some of the upper part of the Chagrin shale should be in a plastic or mobile condition. This requirement certainly does not fit the observable facts. If subsidence of the sand bodies occurred, it would tend to steepen the bedding planes in the lower part of the body as accumulation of sand continued. Thus in the lower part of the sand bodies the bedding planes near the edge of the mass should be dipping in toward the center of accumulation at a very high angle, whereas the bedding planes in the upper part of the sand mass should be essentially horizontal. However, horizontal or nearly horizontal bedding planes were observed adjacent to the contact of the sand and shale at the edge of the sand body in the lower part of the Buckeye quarry. Thus the greater part of the observable data shows that the load-adjustment hypothesis is incorrect.

The required existence of sand bars from late Chagrin time until early Berea time, the nonaccordant bases of the channel sandstones, and the downward convexity of the bases of the channel sandstones rule out the possibility that the channel sandstones are offshore bars. Also the linear trend of these sand bodies from north to south, assuming they were offshore bars, would place the shoreline in Berea time either to the east or west of area H, which does not fit the regional paleogeography.

The channel-fill hypothesis is supported by the greater part of the observable evidence, and no data have been observed which can be applied to the load-settling hypothesis alone. As shown by the sections in figure 44, the channel sandstones are thought to have originated in the following manner:

In late Bedford time a part of the Red Bedford Delta in northern Ohio and southern Ontario was uplifted slightly. The upwarp, which probably amounted to less than 600 feet, was sufficient to increase the gradient of the major streams flowing down the delta and enabled them to incise their meandering channels deeply into and in some places through the Bedford shale. This uplift apparently affected more than just the Red Bedford Delta because down-cutting of channels appears to have occurred throughout most of area H as far east as western Ashtabula County. Although some deep channels were cut in Huron and Geauga Counties, the maximum down-cutting appears to have occurred in Lorain County. The streams rapidly down-cut their beds and lateral planation was greatly reduced. The long sinuous channels produced by the down-cutting were not completely integrated by the time deposition of the Berea sediments began, because the bases of many of the channels are discordant. A part of the down-cutting probably was the result of a break-out along the eastern side of the Red Bedford Delta in Medina and Wayne Counties. This break-out increased the gradient of the streams and facilitated down-cutting. The greater depth of channels in Lorain County may be the difference between down-cutting in Geauga County as a result of uplift as opposed to down-cutting accelerated by the evulsion of the Ontario River in Lorain and Medina Counties.

The introduction of large amounts of sand and silt into the streams marks the beginning of Berea deposition. The great influx of sand was apparently in part the result of drainage changes in the river system to the north in Ontario. The sand overloaded the streams in the incised distributary system, and they began aggrading the newly cut channels. The deeper scour pockets formed quiet pools along the streams in which the accumulated sandstones show the bedding characteristic of sands deposited in semiponded waters. Driftwood, clots of pollen, and other debris were trapped and buried in the quiet pools. Because the streams were overloaded and aggrading, lateral cutting of the incised channels was restricted although some sapping of the side walls occurred, as is indicated by the presence of shale and siltstone pebbles in the Nicholl quarry at Kipton. During part of the time, the main distributary channels fanned out across central Cuyahoga County, as is shown by the small pebbles and slightly coarser sands in the channel sandstones in the vicinity of Peninsula.

The filling of the channels was accomplished by middle Berea time, and the distributary streams spread sands across the inter-channel areas. At some places on the inter-channel areas, the deposition of sands and silts in shallow lakes established the conditions necessary for the formation of the flow-roll zone of the Berea. Stream-type cross bedding and some current ripple marks found in the basal part of the sand above the channel sandstones indicate that the deposition of the lower part of the sheet of Berea was in large part subaerial.

The thin sand sheet of area I which averages less than 20 feet in thickness, is in part the same as the upper marine part of the sheet of Berea sand in area H. Some of the sand was originally deposited in late Bedford time in the upper part of and along the edges of the channels of the main stream system of the Red Bedford Delta. Cross sections in the channeled areas show thickening of sands along the sides of the channels, which is sugges-

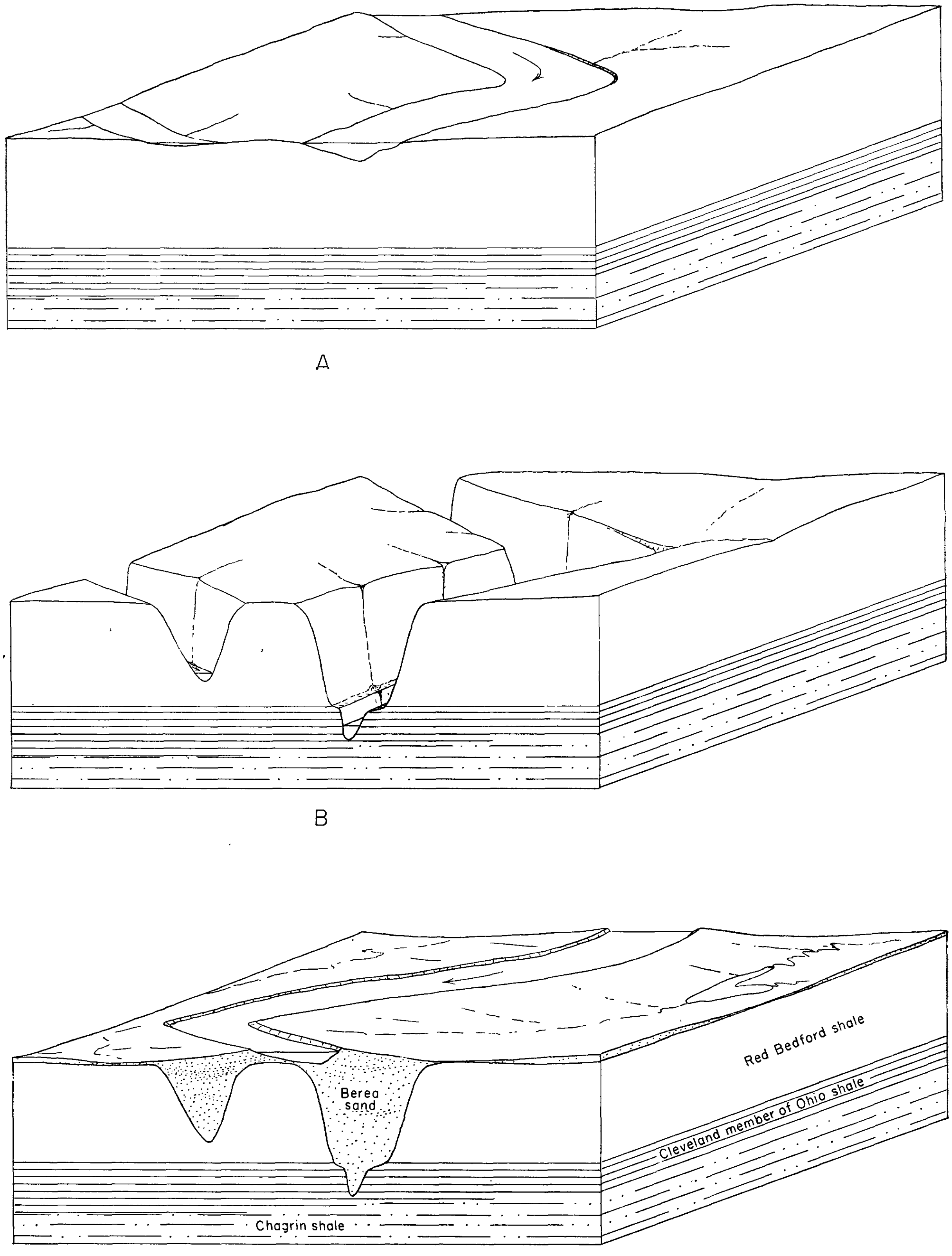


FIGURE 44.—Schematic diagram which shows the development of the sand-filled channels during Berea time in northern Ohio. The upper block "*A*" shows the low undulatory land surface on the northern part of the Red Bedford Delta in late Bedford time. The middle block "*B*" shows the steep-walled channels at the time of maximum down-cutting. The lower block "*C*" shows the sand-filled channels covered by the relatively thin sheet sandstone; note that drainage pattern changed after channels were filled.

tive of natural levees and sand bars that have been in part reworked and modified by later current action.

Apparently much of area I stood above sea level throughout the early part of Berea time and was inundated by a northward transgressing sea in middle or later Berea time. The advancing sea reworked the existing sands into a thin marine pavement. The thickest parts of this sheet sand lie along the course of the main channels in the middle of the Red Bedford Delta and the areas of thinner sand occur in belts essentially parallel to the general trend of the channel system. The thin sand sheet of area I grades laterally on the east into the upper part of the thicker sands of area J. Area J was covered by the sea prior to the flooding of area I, so that more sediment was trapped in area J, thus forming the mass of thicker sand in area J.

The northeastern extension of area I may be too large. The few well records in the area are inconclusive as to exact thicknesses of the sand. A very thick sand is recorded in some of the wells at the place normally occupied by the Berea sand. This thick sand is probably indicative of a connection between the thick channel sandstones of the Geauga County outcrops and the thick sand area in northern Stark County. The presence of small pebbles in the Berea in Harrison County and the occurrence of similar-appearing pebbles on the outcrop in the vicinity of Peninsula in Cuyahoga County also indicate that a connection existed from area H across the northeastern part of area I in either eastern Cuyahoga or western Geauga County into area J in Stark County.

The mass of thick sand in Stark and Tuscarawas Counties and northern Guernsey County in the northern part of area J on figure 35 is composed of a distinct upper sand sheet from 40 to 60 feet thick and a lower, less often recorded mass of siltstone and sand which ranges in thickness from a few feet to more than 140 feet. Some parts of area J that contain the great thickness of sand were small, locally subsiding basin areas throughout most of Bedford and Berea time, and in these areas sand and silt of the Bedford and Berea were deposited almost uninterruptedly throughout most of the cycle of deposition. Some of the coarse sand that occurs in the lower part of the rocks of Bedford age in southern Tuscarawas County may be reworked Cussewago (Murrysville) sand. This sand may have been derived from the northern part of area K by post-Cussewago scour and carried into the local basin area in Tuscarawas County. Lenses of shale, called "breaks" by the drillers, are found throughout the belt of thick sand in Stark and Tuscarawas Counties. These breaks are composed of soft gray silty shale which represents sudden influxes of mud during Bedford time. In general these beds of shale occur in the lower siltstone-sandstone unit and are local in extent. Apparently they cannot be correlated widely from well to well.

Area J received the greater part of the Berea sand which was carried in from the north and west as a result of the change in the Ontario River system that occurred either in latest Bedford or earliest Berea time. The mud, silt, and fine sand of the Bedford partly filled the depressions in area J, and the Berea sand spread across area J and into area K as a relatively uniform sheet. Excepting a few lenses of coarser sands in the eastern part of area J and the western part of area K, which are thought to be the result of wave sorting, the sands are coarsest in the north and decrease in grain size to the south and east. Thus, the Berea which is composed largely of medium- and fine-grained sand in northern Ohio becomes a siltstone containing only small amounts of very fine sand in the southern part of area J.

Scour-and-fill type deposition occurred in two places in the northern part of area J. The larger area covers some of southern Medina County, northern Wayne County, and northern Stark County. The closely spaced drilling in the Chatham-Lodi oil pool, Chatham and Lodi Townships, Medina County, Ohio (pl. 1), which lies in the transition zone between area H and area J shows many sand-filled scour channels of both Bedford and Berea age. Determining the age of the channel sandstones in the Chatham-Lodi area, however, is difficult because some of the red shale that caps these scour channels appears to have been reworked and redeposited locally. Except for the area of the Red Bedford Delta, the siltstones of the Bedford cannot be separated satisfactorily from those of the Berea at many places in the subsurface.

South of the Chatham-Lodi oil field, the drilling is not spaced closely enough to permit tracing the individual channels in the Berea sand, but as shown on plate 1 the over-all pattern consists of a relatively narrow belt of shallow scour channels which connects the area of scour-and-fill deposition of southern Medina County to the area of thick sand in northern Stark County. The depth of the scour pockets decreases to the south and east along this belt away from the Chatham-Lodi oil field, and all traces of scour are lost in the belt of thick sand in southern Stark County.

The thick Berea sand in central Holmes County and northwestern Coshocton County (see pl. 1) marks a second area of scour-and-fill deposition in area J. The scour pockets are smaller and the channel system is less well integrated than the system of distributary channels across Wayne County that connect area J and area H. The thick Berea sand in Holmes and Coshocton Counties was probably deposited in channels that were scoured in the period of channel migration in earliest Berea time. The distributary channels of the Ontario River which occupied the center of the Red Bedford Delta in Bedford time were abandoned by the river in earliest Berea time. The Ontario River broke out of the Red Bedford Delta and cut a system of distributaries across Wayne County and into northern Stark County. The generalized trend of these distributary channels is shown in figure 45. Much of the

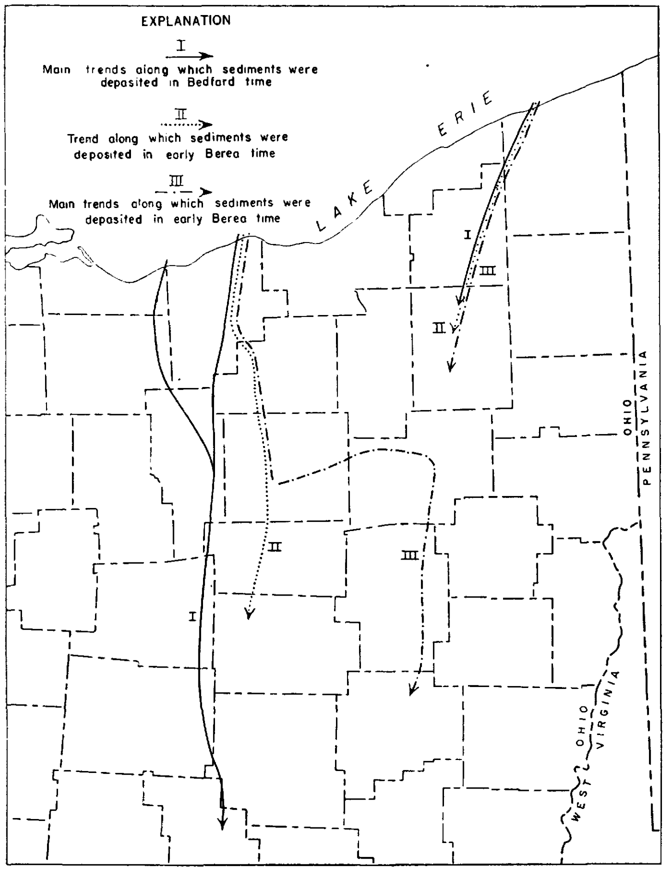


FIGURE 45.—Diagram showing the three major trends along which sediments were transported during the cycle of Bedford and Berea deposition.

finer-grained sediment in early Berea time was carried across Wayne County by the Ontario River and deposited in the local basin area of Stark and Tuscarawas Counties.

The thick channel sands in Holmes and Coshocton Counties were deposited during a brief time in the period when the Ontario River had abandoned its distributaries on the Red Bedford Delta and before complete integration of the channel system which emptied into the Ohio Bay in Stark County. Possibly the scour pockets were cut during an attempt by the Ontario River to form a channel system essentially parallel to the old distributary system on the delta. However, the continued subsidence of the basin Stark and Tuscarawas Counties brought about the deflection of the Ontario River to the east and the abandonment of the channel system in Holmes and Coshocton Counties before it was well integrated.

Area K is separated from area J (fig. 35) arbitrarily at the 60-foot sand thickness line along the eastern side of Stark and Tuscarawas Counties. In area K the Berea sand was deposited in a shallow seaway which existed throughout Berea time. The sediments are progressively finer grained to the east and south, and on the eastern edge of area K the Berea is represented by a thin zone of "shells" and sandy shales. Throughout much of area K the Berea is remarkably uniform in thickness, and the sand does not vary more than 5 feet from the average of 40 feet. This uniform sheet of sand, which has been named the 40-foot Berea by Demarest (1946), is indicative of uniform depositional conditions over a wide area.

Evidence from shallow wells and core-drill records in northeastern Ohio indicates that in post-Bedford time erosion removed most of the Bedford shale in parts of Columbiana, Mahoning, and Trumbull Counties. Figure 33, which is an isopach map of the Bedford in northeastern Ohio and northwestern Pennsylvania, shows part of the area of post-Bedford scour. A few wells in western Trumbull County record a very thick Berea sand which is probably the edge of the channel sands of area H.

Much of the oil and gas in area K is thought to be localized as a result of better sorting of the Berea sand by waves and currents. In general, the grain size of the Berea sand decreases eastward across area K. North of Columbiana County the sand content of the Berea decreases to the east rapidly, and in northeastern Trumbull County and in Crawford County, Pa., the Berea is composed of siltstone containing only a few percent of very fine sand.

Toward the south, area K grades into area J as the Berea sand overlaps sands and silts of Bedford age in southern Tuscarawas County and northern Guernsey County.

The Berea sand of area J decreases in thickness and grain size toward the south and east. Along the junction of areas J and N in Noble County, Ohio, the logs of many wells record only "shells" or sandy shale at the stratigraphic position of the Berea sand. The increase in thickness of the Berea east of this line in the westernmost part of area N is due to the overlap of two sheet sands, one from the north and one from the east. In the area of thin sand in Noble County, Ohio, and western Monroe County, Ohio, a conglomeratic sand about 8 feet thick is recorded in several wells lying from 6 to 10 feet below the horizon of the Berea sand. The presence of recognizable Berea sand and Sunbury shale above this pebble-bearing bed shows that the conglomeratic sand is not a part of the Berea. Most probably these small quartz pebbles were reworked from the edge of the Cussewago (Murrysville) sand to the north and carried into their present position in middle or late Bedford time.

Toward the south, sediments of area J merge into sediments of areas M and G. The sediments of area M are separated from those of area J because much of the fine sand that lies in the eastern part of area M came from the south rather than from the north. The thin sheet sand of area M is coarsest on the east and grades laterally westward into the thick mass of siltstone of area G. Apparently the sand and silt which make up area M were carried into the basin from the south by one or more rivers and spread northward along a shoreline which existed for a time on the eastern side of area M. The sand of area M contains some material from area N and some from area J.

SEDIMENTATION IN KENTUCKY DURING BEDFORD AND BEREA TIME

A thick belt of siltstone of Bedford and Berea age trends northwestward across eastern Kentucky and southern Ohio, area G in figure 11. This belt is composed almost completely of siltstone. The siltstone of Bedford age cannot be differentiated from the siltstone of Berea age in this area. From a comparison of the thickness of these rocks in area G with adjacent area M (fig. 35) as shown by well logs, the writers conclude that by far the greater part of the siltstone in area G is Bedford. A mass of silt of this magnitude may have been brought in from a northern source during Bedford time, but the great quantity of silt, the distance from a northern source, and the gradation of the siltstone of the Bedford northward into shale suggest that most of the silt must have been derived from other sources.

An eastern source for some of the silt composing area G is suggested by the Gay-Fink and Cabin Creek Channels and the shoreline lying west of these channels in area M. Silt, fine sand, and mud were carried down the channels and deposited along the shoreline of area M, where the winnowing action of the waves and currents spread the silt across area M into the deeper waters of area G.

An alternative source for part of the Bedford sediments of area G may have been to the southeast. The foreland and flood plains of the Appalachian highland are believed to have lain to the southeast in western Virginia. A low promontory may have jutted northwest in the vicinity of the State boundary of Kentucky and Virginia, and a stream carrying silts from this lowland may have entered the southeast end of area G. Evidence is nowhere conclusive for a southeastern source of these sediments, but a part of the Price sandstone of southwest Virginia may represent a southern continuation of the siltstone of Bedford age in Kentucky.

A third source for some of the Bedford sediments may have been the Cincinnati arch, which was a low island at this time. A small amount of mud may have been washed into the Ohio Bay from this area, but source beds for the siltstones of the Bedford in area G were not present on the island.

SEDIMENTATION OF THE WEST VIRGINIA TYPE BEREA SAND IN AREA N

The Berea sand in area N forms a thin crescent extending from southwestern Pennsylvania adjacent to the central part of the West Virginia panhandle through southeastern Ohio to the southernmost part of West Virginia. On the west the Berea sand of area N grades successively into the rocks of areas K, J, and M. At no place is the dividing line sharply drawn. On the eastern side, the Berea apparently abuts against a linear area of Devonian shale that was above water but low-lying during part of Berea time. At places small outliers of the Berea are present above the shale, and more may be discovered by future drilling. In addition, two narrow belts of Berea sand at right angles to the main part of area N cut across this area of shale and are of such significance that they are described below under separate headings. The first of these, the Gay-Fink Channel, divides the area of shale approximately in halves. The other, here called the Cabin Creek Channel, nearly bisects the southern half, and may, by future drilling, be found to extend all the way across the belt of shale.

Other similar sand bodies may exist in this belt of shale, but they have not yet been discovered by drilling.

The Berea sediments of area N, which consist mainly of siltstone and some fine-grained sandstone, were spread along the eastern edge of the Ohio Bay as shoreline deposits and a thin marine pavement. As shown by well samples, sand is present only in the thicker parts of the sheetlike deposit and may have accumulated as incipient offshore bars or as beaches. Petrographic studies by Rittenhouse (see pl. 11) indicate that the Berea sediments of area N were derived from at least two sources. The Berea along the western margin of area N north of the Gay-Fink Channel apparently came from the north or northwest and represents part of the outer fringe of the great quantity of Berea sediments that entered the basin through the Ontario and Ashtabula Rivers, whereas most of the Berea sand farther east appears to have been derived mainly from the east—probably from earlier Paleozoic sediments beyond the eastern limits of the present study. The Gay-Fink Channel provided an apparently necessary course for transportation of the eastern sediments across the belt of shale into area N. Marine currents spread the sediments northward from the mouth of the Gay Fink Channel along the shoreline and probably an undetermined distance southward as well. It is interesting to note that the line that marks the boundary between the eastern and northern types of Berea sand in area N also approximately divides the area of oil production in the Berea into Pennsylvania grade oil on the east and Corning grade on the west.

South of the Gay-Fink Channel in area N, the Berea sediments are similar petrographically to those north of the Gay-Fink Channel. However, here the Cabin Creek Channel probably provided the means of transportation for the sediments that were derived from the east and which were laid down as shoreline deposits of sand and silt along the eastern edge of the sea. Samples from five wells indicate that the Berea derived from the east rests on sediments characteristic of the Berea found along the western margin of area N south of the Gay–Fink Channel. This underlying western belt of Berea, which is slightly thicker than that of the eastern type, is composed mostly of very fine sand containing a few lenses of coarser sand and occasional small quartz pebbles. In this western belt of area N the sand averages 20 feet in thickness and trends about N. 10° W. from western Wyoming County to Mason County, W. Va. It may represent a shoreline or several shorelines along which were spread the coarser sediments supplied by the Cabin Creek Channel and possibly the Gay-Fink Channel during an earlier stage than that during which they supplied the typical eastern type Berea. It is difficult to see how the coarser sediment of this belt could have come from the north across a large area now occupied by siltstone, which on the basis of petrographic information resembles the northern Berea more closely than the eastern Berea. If these coarser sediments did not come from the east along the Gay-Fink and Cabin Creek Channels, most probably they had a southern source, possibly the same area that supplied sediments to areas M and G.

GAY-FINK CHANNEL

One of the most conspicuous parts of the Berea is the long narrow body of sand shown as area O on figure 35. Although Heck (1941, p. 807, fig. 1) included most of this sand body on his index map, he has described only the west half in Jackson, Roane, and Calhoun Counties, W. Va. The full extent, here designated the Gay-Fink Channel, is about 60 miles long, exclusive of a 19-mile eastward extension which is outlined by a long narrow gas field crossing area F. (See pl. 1 and fig. 11.) This extension is believed to be sand-filled in a channel cut in the underlying sand of the area F delta. The width of the Gay-Fink sand body 20 feet thick or greater ranges from 0.3 to 1.6 miles, and the width of the sand body between the zero contour lines ranges from 0.5 to 3 miles. The exact thickness and limits of the 19-mile extension east of Fink are not known because the drillers' logs do not differentiate the sand-fill of Berea age from the enclosing delta deposits of area F of probable Cussewago (Murrysville) age. The extension of the channel is outlined mainly from the records of gas production, and the petrographic studies of Rittenhouse (pl. 11) provide confirmation by showing that samples from two wells in the extension have a heavy mineral content different from the samples from wells in the remainder of area F. The wells in the extension contain elements intermediate between the samples studied from the Berea sand in the main part of the channel and those from the remainder of area F.

In his study of the westernmost 25 miles of the Gay-Fink Channel, which he named the Gay-Spencer-Richardson oil and gas trend, Heck noted a number of features which he interpreted on the premise that the sand body originated as an offshore bar. However, in the course of the present investigation, which was regional in approach, and on the basis of new internal evidence such as the petrographic studies by Rittenhouse, the writers believe that the preponderance of evidence favors the hypothesis that the Gay-Fink Channel is a sand-filled river channel. The chief points supporting the channel hypothesis are presented below.

1. *Winding course.*—The channel is a winding, continuous sand body 60 miles or more in length, within which the thickest sand follows a winding course suggestive of a river channel. The course of the thick sand wanders from side to side within the zero contours and may in places divide into two lenses of thick sand on opposite sides of the sand body, as often occurs in modern river channels. As shown by figure 46, the line of maximum sand thickness in the Gay-Fink Channel is much more irregular than the line of maximum sand thickness in the Second Berea bar. Also, figure 46 shows that the line of maximum sand thickness of the Second Berea bar lies near the eastern or sea face of the bar, whereas the line of maximum sand thickness of the Gay-Fink Channel wanders from side to side in the sand body.

2. *Irregular sorting.*—The sorting of the sand in the Gay-Fink Channel is apparently not the type that would be expected in a sand bar, as is suggested by a number of abnormally large producing wells. In a bar, the sorting of the sediment which in large part determines the porosity and permeability of the sediment is likely to be relatively uniform along the strike of the bar, providing structural control is favorable as in the Second Berea bar. This type of sorting in bars

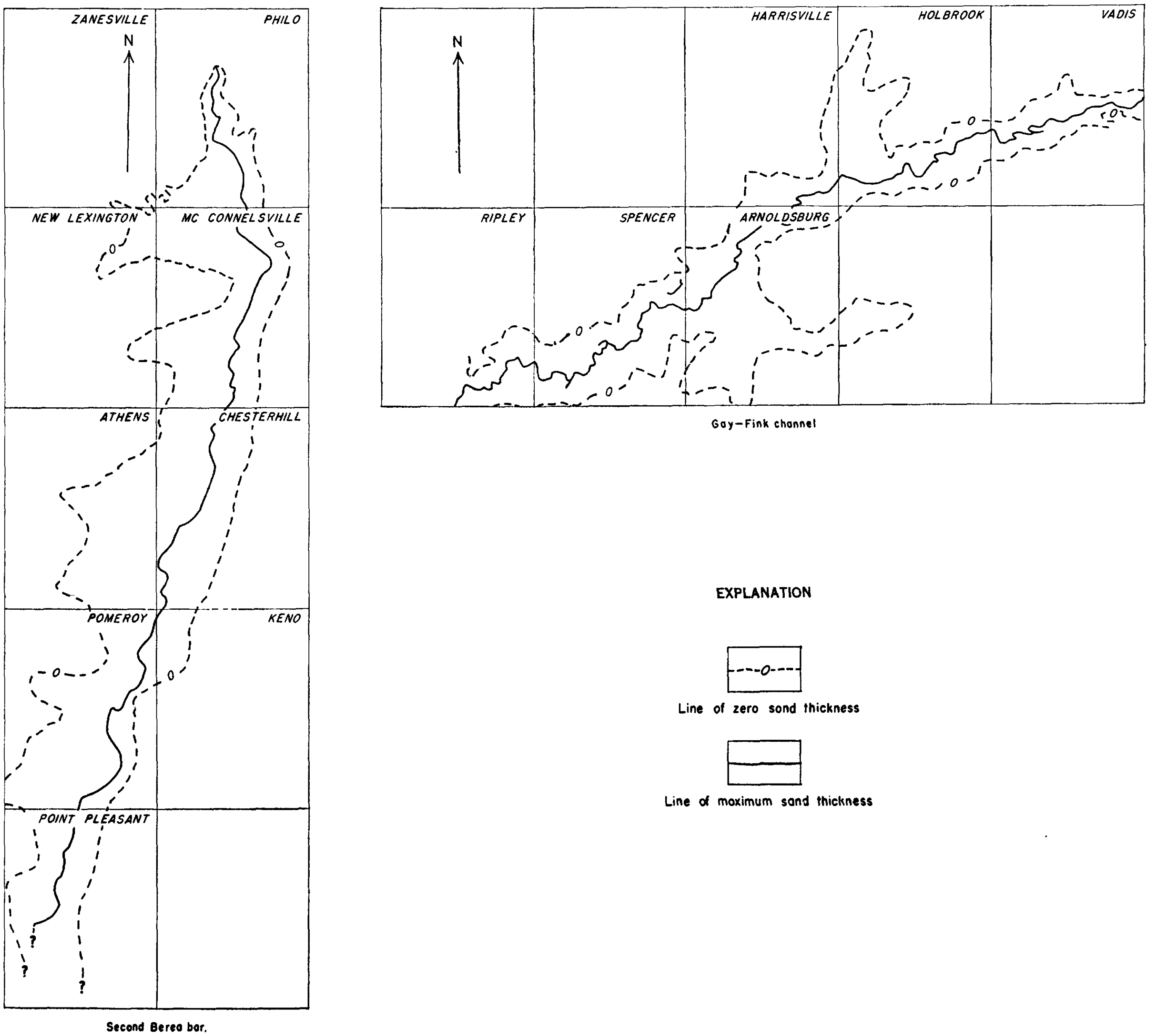


FIGURE 46.—Diagrams comparing the Second Berea bar and the Gay-Fink Channel with respect to the relative sinuosity of the line of maximum sand thickness and its relation to the lines of zero sand thickness.

results in elongate groups of wells of nearly uniform production. The uniformity of production is the result of essentially uniform conditions of deposition along the face of the bar. In a stream channel, however, much lensing of sand and imperfect sorting is to be expected. Lenses of pebbles and loose coarse sand distributed erratically through the Gay-Fink sand body result in occasional wells of abnormally large production. The presence of pebbles in the Richardson pool east of Richardson, Calhoun County, W. Va., was noted by Heck (1941, p. 811–812, fig. 1), and Rittenhouse (1946) has described a well in the channel in southern Ritchie County, W. Va., showing an upward gradation in the Berea sand from pebbles at the base to fine sand near the top. Such a gradation would be typical of river deposits but not of bar deposits unless migration of the bar had occurred.

3. *Incisement of the channel.*—Although it is impossible to determine directly whether the sand body in the main part of the channel between Gay and Fink was built up from a flat sea floor, or was incised into a level plain, the 19-mile eastward extension of the channel from Fink does provide pertinent evidence. A cross-sectional view of the sand in the extension of the channel (fig. 47) a short distance east of Fink shows that the extension of the channel sandstone, which is differ-

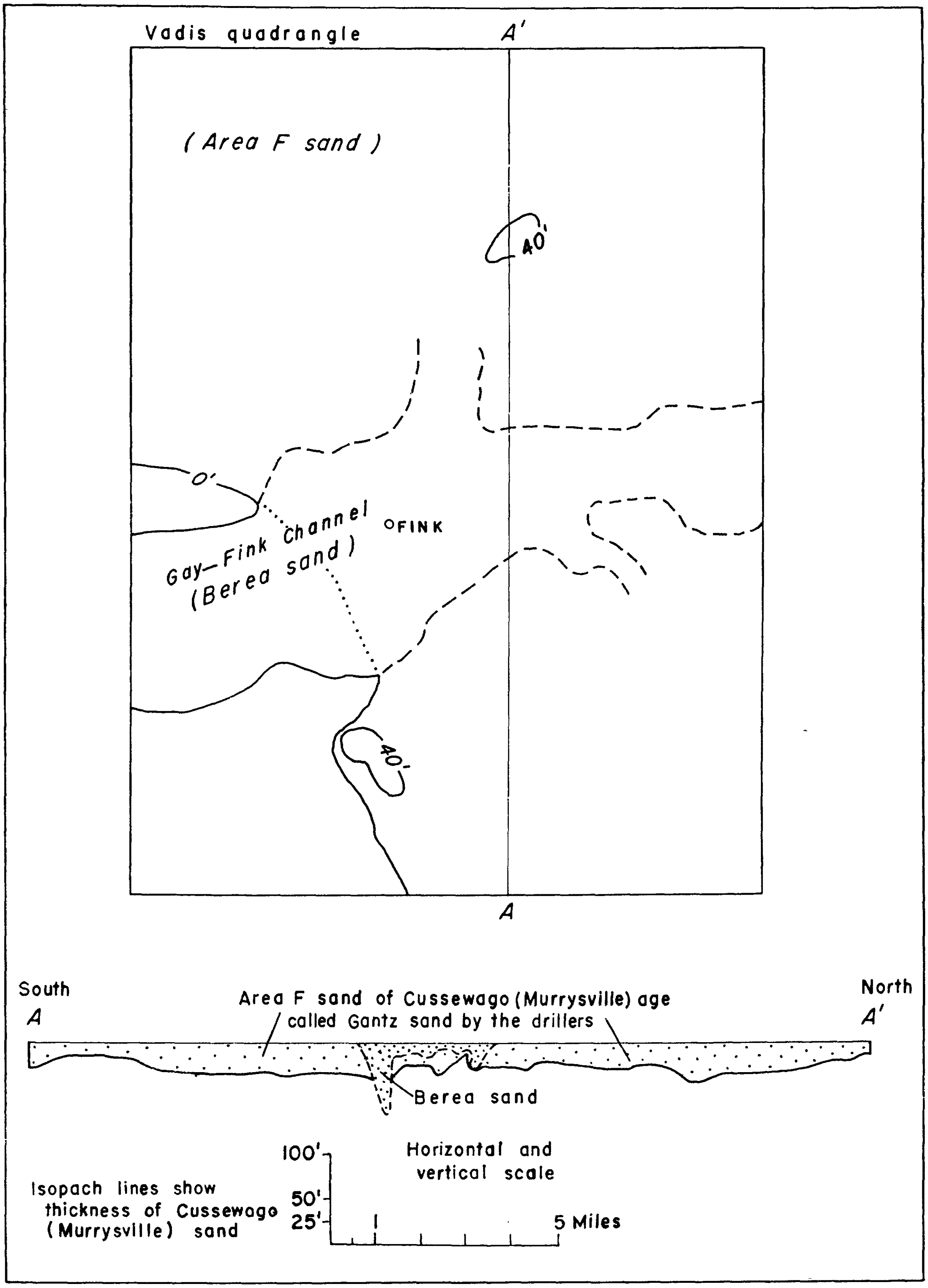


FIGURE 47.—Map and cross section showing the relation of the Berea sand of the Gay-Fink Channel to the area F sand of Cussewago (Murrysville) age in the vicinity of Fink.

entiated only by gas production and petrographic analyses, maintains a fairly uniform top in line with the surrounding delta sand of area F. As this delta sand correlates with the Cussewago (Murrysville) sand, it is older than the Berea sediments. The sand filling of the Gay-Fink Channel, which correlates well with the sheetlike Berea sand of Ohio and western West Virginia, is, therefore, younger than the delta sediments of area F. If the sand body were a bar laid down after the delta deposit and on top of it, a linear thickening along the extension of the channel would show in the well logs. On the contrary, no such thickening occurs, indicating that incisement into the delta must have taken place. River sands then refilled the channel, and because they were better sorted and more porous than the enclosing delta sands they became the reservoirs of gas and oil.

4. *Source of the sediment.*—The presence of pebbles in the Berea sand of the channel confirms an eastern source for the sediment in the channel rather than a northwestern source. If the Gay-Fink Channel is interpreted as the channel of an ancient river flowing westward across pebble-bearing sediments in the vicinity of the present outcrops of Paleozoic rocks in eastern West Virginia, the occurrence of pebbles in the Gay-Fink sand body presents no difficulty. On the other hand, if the sediments in the Gay-Fink Channel were derived from the northwest as is suggested by Heck in his dicussion of the origin of the Gay-Spencer-Richardson trend, the transportation of pebbles across area N, which contains almost 100 percent siltstone or very fine sand at the horizon of the Berea, is difficult to explain. In addition, these pebbles are similar petrographically to the material found along the outcrop in West Virginia, but dissimilar petrographically to the pebbles found in the Berea sand of northern Ohio.

5. *Tributaries.*—Two small sand bodies are present almost at right angles to the main trend. One of these is located largely in Calhoun County and is connected to the sand of the Gay-Fink Channel from the south. The other, which is located in Ritchie County, joins the main channel from the north. Neither of these smaller sand bodies (see pl. 1) is well known, because sufficient well records are not available, but their presence appears confirmed on the basis of available evidence. They seem to be best explained as tributaries to the Gay-Fink Channel. Other outliers in the surrounding area may later prove to be channel remnants as well, or may be instead the result of deposition during an advance of the sea during Berea time.

6. *Original slope.*—At the close of the Devonian period the westward or northwestward encroachment of the great deltas in the Appalachian basin formed an almost solid front trending slightly east of north for hundreds of miles through eastern West Virginia and western Pennsylvania. The Cussewago (Murrysville) Delta and the area F delta of West Virginia maintained the same general directional trend in early Mississippian time. During late Devonian time and during early Mississippian time the shoreline of the Appalachian trough faced generally west or northwest and extended along the coalescing fronts of the deltas. Thus the original slope of the basin when the Berea sand of the Gay-Fink Channel was deposited should have been approximately at right angles to the shoreline, except that the deepest part of the basin may have been slightly to the south and nearer the middle section of the trough, as indicated by the uninterrupted deposition of the Chattanooga shale. The northern end of the trough already had become shallower during earliest Mississippian time with the advent of the Bedford and Berea sediments coming in from the north. An uplift in the north, causing the initiation of the cycle of sedimentation of Bedford and Berea time, was probably in progress as well. The original slope, then, on which the sand body of the Gay-Fink Channel was later deposited, probably dipped to the west or slightly south of west toward the deepest part of the basin. After emergence of part of the eastern flank of the basin, any stream channel would be consequent on the original slope, flowing in a westerly or southwesterly direction, which is the direction taken by the Gay-Fink River.

CABIN CREEK CHANNEL

Another elongate channel deposit of Berea sand (area P, fig. 35) lies parallel to and about 50 miles south of the Gay-Fink Channel. This sand body is known in part as the Cabin Creek oil and gas field and is now outlined by more than 650 wells. Because of insufficient drilling the eastern end of this channel has not yet been determined. On the west the sand of the Cabin Creek Channel joins the main body of sheetlike deposit of the Berea in area N (fig. 35). The sand at Cabin Creek was described as follows by Theron Wasson and Isabel B. Wasson (1929):

> At Cabin Creek, the Berea has a range of 15 to 52 feet in thickness, with an average of about 35 feet. It is divided into two parts, cap above and "pay" below. * * * The thickness of the cap is uniform in the field, averaging 15 feet, although it thins both northwest and southeast of the field. The cap is clear, white, hard quartzite, drilling always as fine chips, never as grains. The quartzitic structure is evident from the smooth glistening surface of a freshly broken piece. Under the microscope the built-up sand grains, which interlock, are clearly seen. Its porosity, by Melcher's method, gives only 4 per cent.
>
> The "pay" occurs without a break below the cap, and the transition seems to be fairly sharp. The "pay" is 35 feet thick in the best part of the pool but it pinches out on the southeastern side of the field. The limits of the field on the northeast and southwest are controlled by this pinching-out of the "pay." The cap is continuous; the "pay" is a lens below the cap. The

deduction follows that where the total Berea thickness is less than 15 feet, it is all cap. The limit of the field on the southeast side is determined by the non-existence of the "pay". The Berea "pay" is pure quartz sand with here and there flaxseed bodies of dark shale. The texture of the sand ranges from very fine-grained to pebbly. The pebbles are small, white, and well rounded. This pebbly phase is erratic, occurring in thin streaks, or patches of small extent. The grains are angular and most of them sparkle under a lens. There is little cement, the sand drilling easily into individual grains. The porosity averages about 16 per cent.

Wasson and Wasson (1929) are of the opinion that the Berea sand of the Cabin Creek field "is clearly a near-shore sand deposit of an advancing sea." On the basis of the evidence now available, however, the present writers believe that the sand body of the Cabin Creek field originated as a channel deposit.

The chief reasons for interpreting the sand at Cabin Creek as a channel instead of a bar are in part the same lines of evidence that pertained to the Gay-Fink channel. Because of the relative positions of the two sand bodies it is probably unwise to suggest that one might have been a bar and the other a channel. Most probably the sand bodies of the Gay-Fink and Cabin Creek Channels had a common mode of origin.

The sand of the Cabin Creek Channel, like that of the Gay-Fink, is a sinuous body of thick sand, typical of river channels, winding back and forth between the lateral limits of the sand body. In addition, the occurrence of isolated pebbles in the sheetlike Berea west of Cabin Creek is best explained if the sand at Cabin Creek is interpreted as a channel deposit. The Berea sand of the Cabin Creek Channel, which contains many pebbles, as noted above, provides the most reasonable means by which the pebbles could be transported from an eastern source to their present location in the shore deposits north and south of the channel mouth.

Because of the proximity of the sand body Cabin Creek to the Gay-Fink Channel and because of the same directional trend, the original slope on which the Cabin Creek stream flowed and the shoreline it crossed were essentially the same as those of the Gay-Fink Channel. At the west end of the Cabin Creek Channel is a belt of fine sand and siltstone of greater than normal thickness, trending north-south, representing shoreline deposits spread along the edge of the sea into which the Cabin Creek Channel emptied. If the sand body of Cabin Creek were assumed to be a bar, its position at an angle of 70° or more to this belt of fine sand and siltstone is difficult to explain.

The presence of a hard quartzitic cap rock overlying the less well lithified pay sand is good evidence of the channel origin of this sand body. The presence of the quartzitic cap rock and the purity of the sand have been cited by the Wassons (1929) as evidence that the sand at Cabin Creek was of marine origin. They suggest that the sand body formed as an offshore or barrier bar. Figure 48 shows the relation of this cap rock to the pay sand assuming that the sand body at Cabin Creek was deposited either as an offshore bar having a flat base or as a channel having a convex base and a nearly flat top. In the writers' opinion the cap rock can be better explained as the relatively uniform downward cementation of a sand-filled channel. Local variation in porosity in the channel sand would permit cementation at a greater depth at some places than at others, thus producing slight irregularities in the thickness of the caprock.

MINOR SEDIMENTARY FEATURES IN THE BEREA SANDSTONE

RIPPLE MARKS

Two types of ripple marks are recognized in the rocks of Bedford and Berea age. The most widespread and characteristic are oscillation ripple marks that occur in an area of several thousand square miles in south-central Ohio and the adjacent part of eastern Kentucky. Current ripple marks have been observed in the channel sandstones in the outcrop of area H and, to a lesser degree, in areas I and K (fig. 35). At some places in northern and central Ohio interference ripple marks have been found in the thinner bedded part of the Berea. These ripple marks were produced by the impingement of one set of oscillation ripples upon a preexisting set that had a different orientation. The interference ripple marks are by no means common and occur only locally.

The presence of many well-formed ripple marks in the Bedford and Berea rocks in southern Ohio and the adjacent part of eastern Kentucky has been noted by Andrews (1870), Orton (1874, p. 620), Morse and Foerste (1912, p. 21), Kindle (1917a, p. 49–51), Butts (1922, p. 24), Hyde (1911), Bucher (1919, p. 249–254), and others. Most of these ripple marks are the oscillation type characterized by symmetric profiles, relatively narrow sharp crests, and broad shallow concave troughs. The ripple marks have a relatively constant crestal trend over a broad area; the average trend is about N. 60° W. and a maximum deviation of 35°.

The Bedford and Berea in southern Ohio contain oscillation-type ripple marks. Figure 49 shows the area on the outcrop in which oscillation ripple marks are well exposed. The silt content of the lower part of the Bedford decreases northward along the outcrop away from area G, and ripple marks are not present in this part of the section. In many places in southern Ohio the thin siltstones in the upper part of the Bedford shale contain many ripple marks whose crests have been

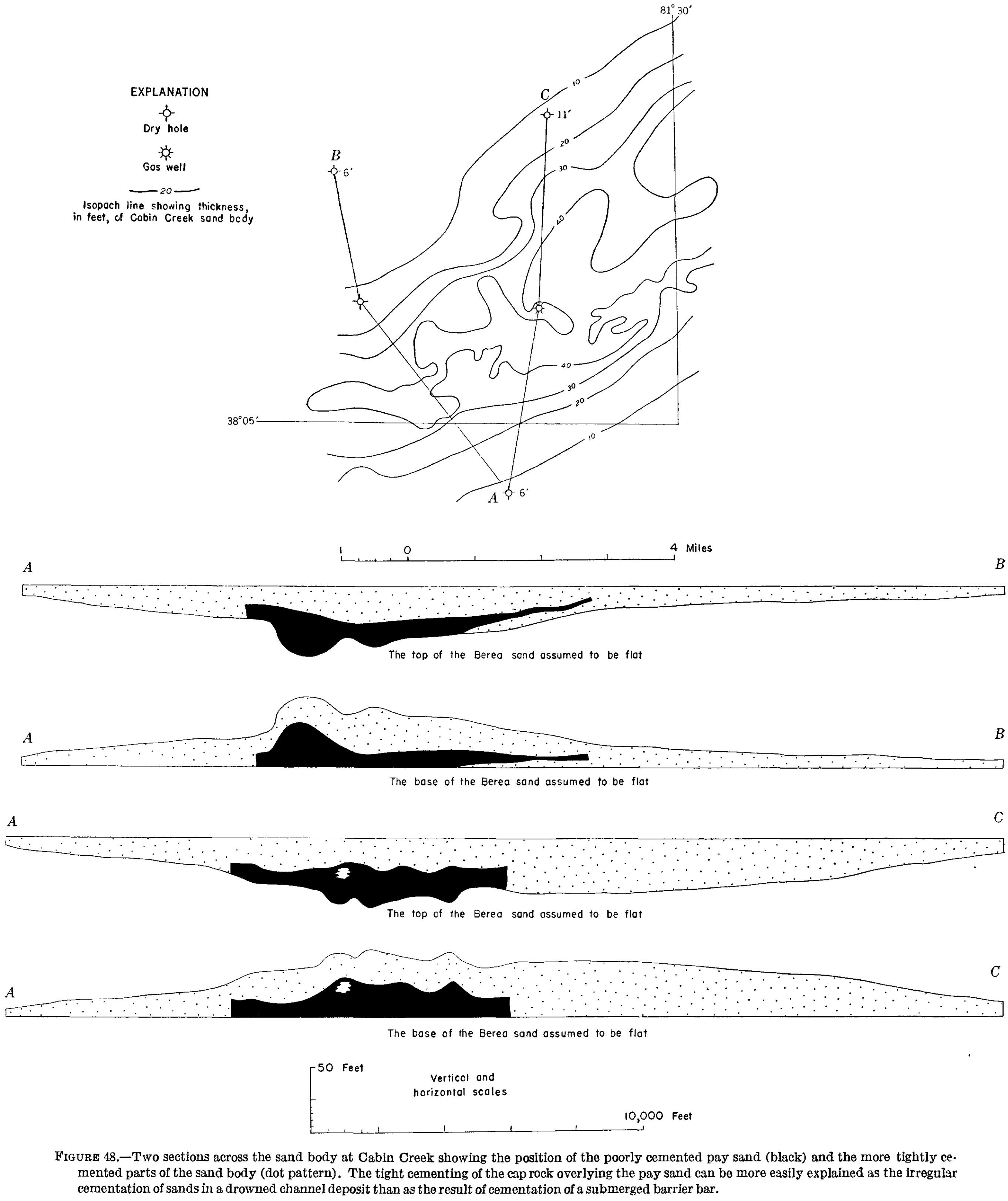


FIGURE 48.—Two sections across the sand body at Cabin Creek showing the position of the poorly cemented pay sand (black) and the more tightly cemented parts of the sand body (dot pattern). The tight cementing of the cap rock overlying the pay sand can be more easily explained as the irregular cementation of sands in a drowned channel deposit than as the result of cementation of a submerged barrier bar.

deformed either by minute cross-crestal scour or by the presence of fucoids lying across the ripple marks. Ripple marks are abundant in the upper part of the Bedford as far north as the vicinity of Chillicothe (see fig. 8), and the Berea sandstone is ripple marked throughout in southern and central Ohio. However, north of Gahanna, the lower and middle parts of the Berea contain many massive beds of sandstone which are more commonly cross bedded than ripple marked.

In many places in northern Ohio, the thin gray siltstones and sandstones that occur at the base of the Bedford contain oscillation-type ripple marks. In many of the exposures, flow-roll contortion has deformed the ripple marks so that on preliminary examination the ripple marks appear to be current type. However, in the undeformed beds adjacent to the flow rolls, the symmetric shape of the ripple marks can be seen. The presence of oscillation-type ripple marks in these basal Bedford strata indicates that at the beginning of Bedford deposition in northern Ohio the area was covered by a very shallow sea.

Although the red Bedford shale, which was deposited largely subaerially, is devoid of ripple marks, the silty gray Bedford shale that was deposited east of the red Bedford shale contains an abundance of oscillation ripple marks. This type of ripple mark is found in the Euclid siltstone and Sagamore siltstone members, which are interpreted as offshore deposits that formed along the eastern side of the Red Bedford Delta. The oscillation-type ripple marks in the Bedford shale in northern Ohio are less regular in trend and smaller than those found in the Bedford in southern Ohio.

The thin basal beds of the Berea sandstone, which make up the flow-roll zone between the channel sandstones in northern Ohio, contain many oscillation and current ripple marks. However, most of the ripple marks in the Berea in northern Ohio are found in the thin-bedded marine cap that makes up the upper 8 to 12 feet of the Berea sandstone in area H. Many of these ripple marks are perfectly formed, and some show both size sorting of the constituent grains and secondary ridges paralleling the main ripple crests but lying in the center of the troughs of the large ripple marks. (See figs. 50, 51.)

In northeastern Ohio the trend of the oscillation ripple marks is very erratic. The trend of the ripple crests in subjacent beds may vary as much as 90°. The ripple marks are smaller than those observed elsewhere in the Bedford and Berea formations. Also the crests of the ripple marks tend to branch and bifurcate in the manner of current ripple marks instead of retaining the straight crests characteristic of the oscillation type. The abundance of interference ripple marks found in this area and the presence of several layers of sun cracks in the lower part of the Berea sandstone indicate near-shore deposition, which probably explains the peculiar development of some of the ripple-mark patterns in this area.

Hyde (1911) reports the occurrence of oscillation-type ripple marks from Adams and Scioto Counties in southern Ohio to the vicinity of Sunbury in Delaware County, Ohio, a distance of more than 120 miles, and notes the parallelism of the ripple trends throughout this area.

Hyde (1911) in his discussion of the oscillation-type ripple marks in the rocks of Bedford and Berea age, pointed to the constancy of the trend of the ripple marks over a distance of 120 miles in southern and central Ohio and to the very close genetic relation between the Bedford and the Berea. He concluded that the general parallelism of the ripple trends over such a broad area was due either to the constancy of direction of the wind making the ripple marks, or to the control exerted by shallow waters close to an existing shoreline or shoal water areas. He concluded that the outcrop data presented by Morse and Foerste (1909) in northeastern Kentucky were sufficient to postulate the presence of a controlling land mass which extended northwestward across eastern Kentucky and abutted against the Cincinnati arch in southern Ohio. The existence of this land area is based upon the increased amount of silt present in the lower part of the Bedford shale in southern Ohio and adjacent Lewis County, Ky., and the abrupt disappearance of siltstones in the shale of Bedford and Berea age in southern Lewis County. Hyde stated that the land area which was low lying in Bedford time was elevated during late Berea time and that post-Berea erosion stripped the Berea and some of the Bedford from the outcrop in northeastern Kentucky. This land mass, according to Hyde's hypothesis, was the agent which controlled the trend of the oscillation ripple marks over that broad area in southern Ohio. If the land area lay parallel to the trend of the ripple marks as Hyde stated, the land mass must have extended in a N. 60° W. direction across eastern Kentucky and into Adams and Brown Counties, Ohio.

After examining the available data on the oscillation ripple marks in southern Ohio, Bucher (1919, p. 249–269) concluded that the correct interpretation of the constancy of ripple-mark trend was the climatological control rather than the shoreline control as advocated by Hyde.

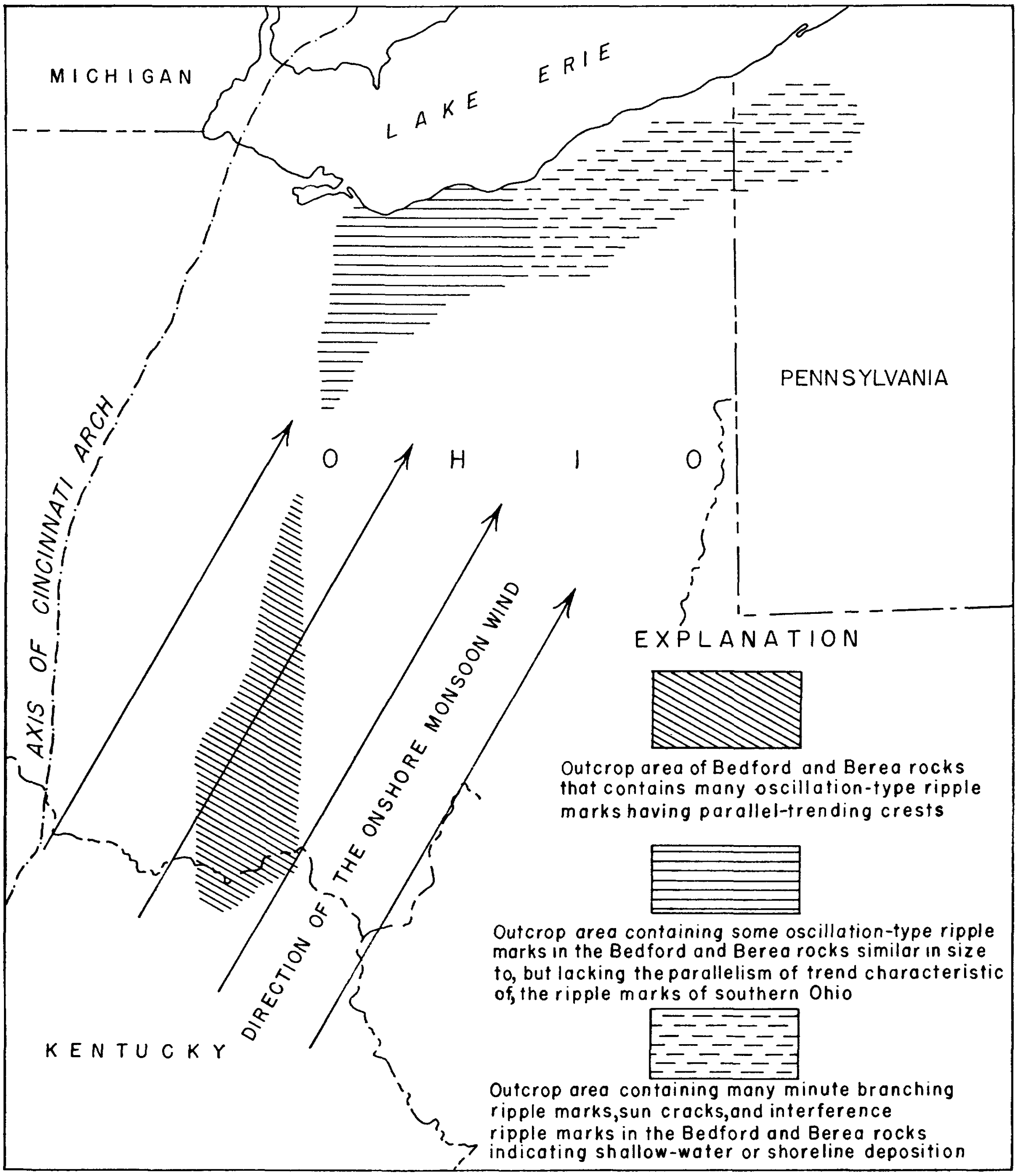


FIGURE 49.—Sketch map showing the areas of ripple marks in beds of the Bedford shale and Berea sandstone.

FIGURE 50.—Oscillation ripple marks, Chappel Creek, eastern Erie County, Ohio. Note presence of ripple marks in successive layers.

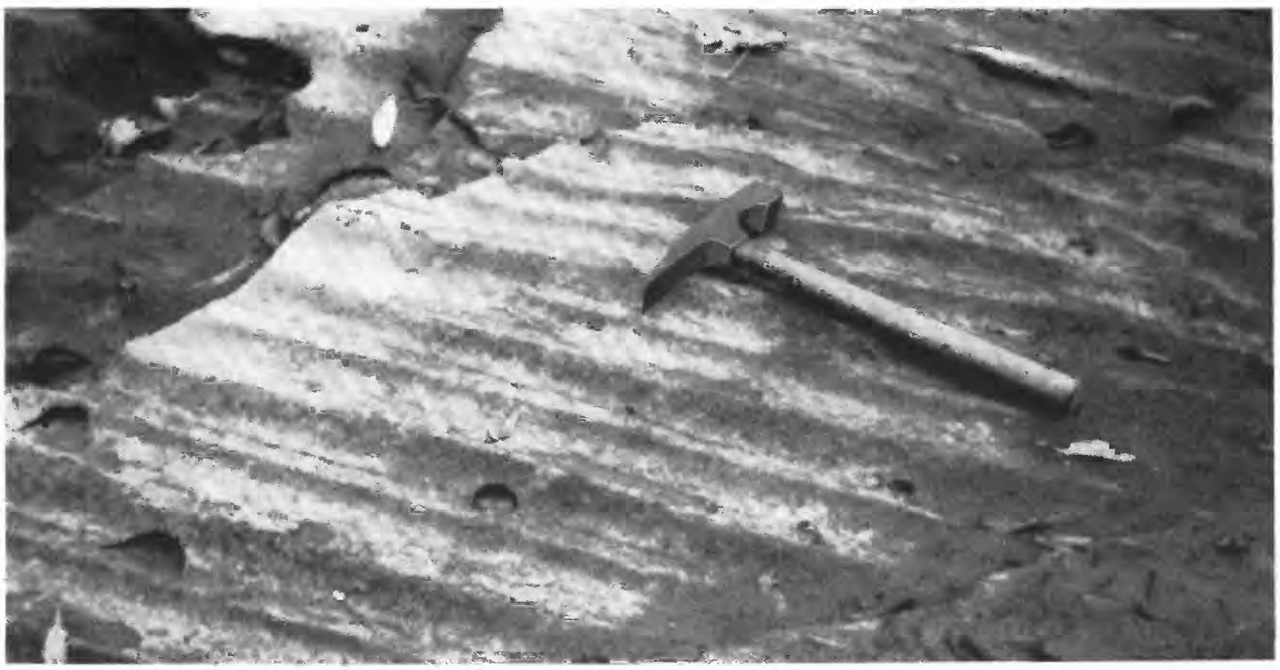


FIGURE 51.—Oscillation ripple marks, Chappel Creek, eastern Erie County, Ohio. Note small secondary crests in troughs of larger ripples

Bucher states:

The facts entering into this discussion may be summarized as follows:

(1) Where the ripples are most typically developed, both formations consist of fine-grained sandstones [siltstones] interstratified with more or less shaly portions.

(2) The beds are from less than one inch to at most two or three feet thick.

(3) The individual layers are not persistent, pinching out and reappearing at different levels, much like the limestones of the limestone-shale series of the Cincinnatian at the type locality.

(4) Where typically developed, almost every layer is rippled.

(5) Only oscillation-ripples are present.

(6) Most of these ripples trend very nearly N. 53° W., with subordinate variations in both directions covering an extreme total range of 69°.

(7) Occasionally, smaller ripples intersecting the larger ones at right angles, or nearly so, are found. Only one case of typical interference pattern, produced by the intersection of equally large ripples, has come to my knowledge.

(8) These ripples were observed over an area 115 miles long and 20 miles wide.

These data indicate that the ripple marks formed in an elongate basin which was so shaped as to permit the greatest action of the ripple-producing winds only from the northeast or the southwest. Bucher ascribes the formation of the ripples either to winds blowing strongest from these directions or to winds having the greatest fetch in these directions. The presence of scour channels and similar phenomena in northern Ohio, he states, was ample evidence that changes in the configuration of the northern end of the basin occurred during Bedford and Berea time. Bucher (1919) concludes:

* * * if the constancy of the orientation of the largest waves was due to topographic causes, the fetch of the wind being greatest in this direction, the wind could have come from the southwest only, because the northeast certainly suffered great topographic changes which would necessarily have affected the formation of waves and thereby the trend of the ripples in the southern portion of the area.

While not impossible, it seems rather improbable that the topographic changes indicated by the erosion channels of northern Ohio should not have influenced the general shape of the basin and incidentally the direction of waves and ripples during the Bedford-Berea time, especially if there should have been no or as little connection with the sea in the southwest and west as indicated by Schuchert's maps. The weight of this argument would be great if the ripples in the Bedford and Berea formations of northern Ohio should prove to be parallel to those of central and southern Ohio. In that case we should be compelled to look to climatic causes for an explanation, to winds blowing strongest and most frequently in one or two opposite directions. Of course, as was said before, almost on any coast facing the open sea, the onshore winds, having the greater fetch, are most apt to produce the largest waves. In view of the complete absence of currents, however, we cannot assume such a direct connection with the open ocean. Hyde's conclusions, based on this argument, are therefore untenable.

Bucher (1919) compares the area of the Bedford shale and Berea sandstone with several modern areas that are controlled by trade winds or monsoon winds and points out that in general the observable data of the areas are similar. He states:

There are two independent facts which lend additional weight to the assumption that the constancy of the Bedford-Berea ripples is due to the action of monsoon winds.

(1) The orientation of the ripples (northwest to southeast) harmonizes well with the general assumption of a great land mass, the North Atlantic Continent, to the northeast, and a wide expanse of water in the southwest.

(2) For a later part of Mississippian time Barrell inferred from fundamentally different data a climate of alternating dry and wet seasons for the region lying to the east of the Bedford-Berea sediments. * * * The shallow water marine sediments of our Mississippian seas probably find their closest analogy in the shelf sea north of Australia, where the sea-bottom is largely covered by "a very fine-grained, impalpable, pale olive-green mud, wholly soluble in dilute hydrochloric acid, and therefore essentially carbonate of lime." Along the Gulf of Carpentaria the dry winds from the deserts to the south must carry quantities of sand into the sea during the dry season from April to November, while in the remaining months the great floods produced by the northwest monsoon must furnish considerable amounts of clastic sediment.

Bucher summarizes his discussion of the Bedford and Berea as follows:

It is in a relatively small, more or less detached portion of such a gulf that Bedford-Berea sediments were laid down. The parallelism of the ripples formed in it may be due to a peculiar shape, offering the wind a much greater fetch in one direction than in any other. In that case the greater expanse of the water in question must necessarily have been to the southwest, since the north suffered considerable changes during the time of the formation of the ripples.

In view of the distribution especially of the Berea formation and of the improbability attached to the assumption that the waterbody kept its general shape while perhaps as much as one-half of it underwent elevation, erosion, and depression, it appears highly probable that winds of constant direction have caused this remarkable parallelism of ripples. The general trend of these ripples and the testimony of the later deposits of the Mauch Chunk shale, render it probable that they were monsoon winds blowing to and from the large North Atlantic Continent in the northeast.

The present writers are in general agreement with Bucher's explanation of the cause of the parallelism of the ripple crests in the Bedford and Berea formations of central and southern Ohio. Field evidence of parallelism of ripple crests of the oscillation ripple marks in northern Ohio is inconclusive for several reasons. Perusal of the paleogeographic maps (pl. 13) will show that throughout much of Bedford and Berea time the area in northern Ohio was emergent and only in earliest Bedford time or in latest Berea time was the area sufficiently depressed for the formation of ripple marks. Most of the ripple marks in the uppermost sheet sand of the Berea do not show a parallelism of trend over a broad area, and it is thought that this is due to the very shallow water in which the ripples formed and the nearness to adjacent land areas. Intercalated with these oscillation ripple marks are some current ripple marks, zones of current scour, and layers of sun cracks all more or less indicative of shallow water in a near-shore environment unfavorable to the development of oscillation ripples. Also the oscillation ripple marks are at many places broken by interference patterns which are produced by the intersection of two sets of oscillation ripple marks having different orientations.

Considering the available data, several of the fundamental assumptions of the shoreline-control hypothesis appear unsound. Hyde ascribed the parallelism of the oscillation ripples to the effect of drag of the waves upon the sea bottom close to a shore and the refraction effect which tends to swing the waves parallel to the shoreline. He assumed that because the sea floor was very gently shelving, the directional control exerted by the shoreline would extend a considerable distance from the shore or shallows area. However, the extent to which a shoreline is capable of controlling the direction of the waves and ultimately the ripple marks formed by the waves appears to be confined to a very narrow belt or a series of partly connected areas lying close to the shore and in the vicinity of the breaking waves. Johnson (1919, p. 505) in his discussion of shorelines states:

> While it is true that wave refraction often brings about a more or less perfect parallelism between wave crests and the shoreline in the immediate vicinity of the latter, the parallelism is, on the other hand, often far from perfect; and a few feet from the shore the waves not infrequently trend at large angles to the shore.

Hyde cited the great increases in the silt content of the Bedford shale along the Ohio River as evidence for the existence of a shoal area or shoreline in the northeastern part of Kentucky. However, an examination of the isopach map of the Berea sandstone (pl. 1) shows that this siltstone mass along the Ohio River in Lewis County, Ky., and Adams and Scioto Counties, Ohio, is a part of the thick mass of siltstone of area G (figs. 11 and 35). Available evidence indicates that the siltstone of area G was deposited in a shallow sea whose eastern shoreline did not extend west of a line between Mingo and Mason Counties, W. Va.

Hyde also assumed that the thinning of the Bedford and Berea strata south of the Ohio River in Lewis County, Ky., was due to uplift of these strata and the removal of the Berea sandstone and part of the Bedford shale by post-Berea erosion. If this thinning was due to post-Berea erosion, the erosion must have occurred prior to the deposition of the Sunbury shale, because the Sunbury rests on the Berea everywhere on the outcrop in Kentucky. This is also true in the subsurface. The thin zone of fossils characterized by *Lingula melie* and *Orbiculoidea herzeri* which is found widely at the base of the Sunbury in Ohio is also present throughout the extent of the outcrop in Kentucky. The outcrops of the upper part of the Berea that were examined in northeastern Kentucky do not show evidence of pre-Sunbury erosion. The thinning of the siltstones of the Berea in Lewis County is, therefore, not due to erosion.

If the control of the parallelism of the ripples in southern Ohio had been due to the presence of a shoreline in northeastern Kentucky, such control must have been local for the reason cited above. To explain the widespread occurrence of these parallel oscillation ripple marks would, under the shoreline-control hypothesis, necessitate the migration of the shore to extend the ripple mark control over a wide area. However, several factors militate against this assumed migration.

1. Unless the shoreline migration was regressive and occurred rapidly, the locally controlled ripple marks would soon be obliterated by the more dominant wind-controlled ripple marks.
2. The shoreline-controlled ripple marks would lie only in the time plane of the existence of the shoreline and would not occur throughout the entire section of Bedford and Berea rocks.
3. The field evidence indicated the presence of a shoreline in the vicinity of Leesville and Galion, Ohio, in early Berea time. However, throughout Berea time this shoreline retreated to the north and in late Berea time lay in extreme northern Ohio in Lorain and Cuyahoga Counties. No evidence has been found to indicate a shoreline working N. 30° E. across the Bedford and Berea sediments in southern Ohio and the adjacent part of northeastern Kentucky. Instead the extreme uniformity of the cycle of deposition indicates that deposition was uninterrupted in southern Ohio.
4. The presence of a structure lying normal to the trend of the Cincinnati arch and abutting the flank of the arch seems highly unlikely, considering the trend of major structures of the Appalachian basin. Such a structure might have been brought into being by large-scale diastrophic movement; however, evidence is lacking for large-scale diastrophism in eastern Kentucky during the cycle of deposition of the Bedford and Berea.

Thus, of the two theories suggested for the control of the widespread oscillation-type ripple marks in the Bedford and Berea rocks of southern Ohio and northeastern Kentucky, the climatological theory appears to be correct.

Asymmetric or current ripple marks are found sparingly in the channel sandstones in the outcrop of area H (fig. 35), and to a lesser extent in the outcrop of areas I and K. Examination of the ripple marks found in the channel sandstones showed that most of the currents which produced the ripple marks were flowing to the south. However, because the scour channels were in part incised meanders, not all of the ripples were oriented with the lee face to the south. These current ripple marks are for the most part small, ranging from ½ to 1½ inches in height and from 3 to 8 inches in wave length. (See figs. 40, 41.) Many interesting cross sections of the current ripples have been produced by the channeling machines used in quarrying the Berea sandstone in northern Ohio. Apparently the currents that transported the sand into the quarries near Amherst decreased in velocity as the channels filled, suggesting that the decrease in the current was a result of the filling and a return to near-grade conditions. The current ripple marks observed at the bottom of the Buckeye quarry tend to be more asymmetric and have a greater wave length than those near the top of the quarry. The ripple marks seen in cross sections near the top of the quarry are nearly symmetric in profile and show that a very slow downstream progression of the ripple crests occurred at the time of deposition of the upper part of the channel sandstone. The migration of the ripple crests was slow, the current of relatively low velocity, and the deposition of sand sufficiently rapid that the succeeding ripple troughs did not obliterate the previously formed ripple crests. This type of semi-symmetric current ripple is probably the product of a relatively slow current carrying appreciable amounts of sand. No doubt the current was close to the lower limit in the range of velocities necessary to produce current ripples.

The current ripple marks found in areas I and K are similar to those found in area H. However, they are generally smaller in size and more irregular than those found in the channel sandstones. At outcrop 37 (pl. 4), the upper part of the Berea sandstone shows an extremely complicated pattern of current ripple mark and current scour pattern. The origin of this pattern is unknown but it may be the result of a small tide rip, the sudden draining of a relatively large amount of ponded water which had been abandoned by a small fall of sea level, or recurring influxes of fresh water from a distributary of the Ashtabula River.

Some current ripple marks have been found in southern Ohio. A very careful examination of the outcrops in the vicinity of Otway, Scioto County, Ohio, showed that some of the ripple marks, which in casual examination appeared to be of the oscillation type, were actually very slightly asymmetric and were current ripple marks.

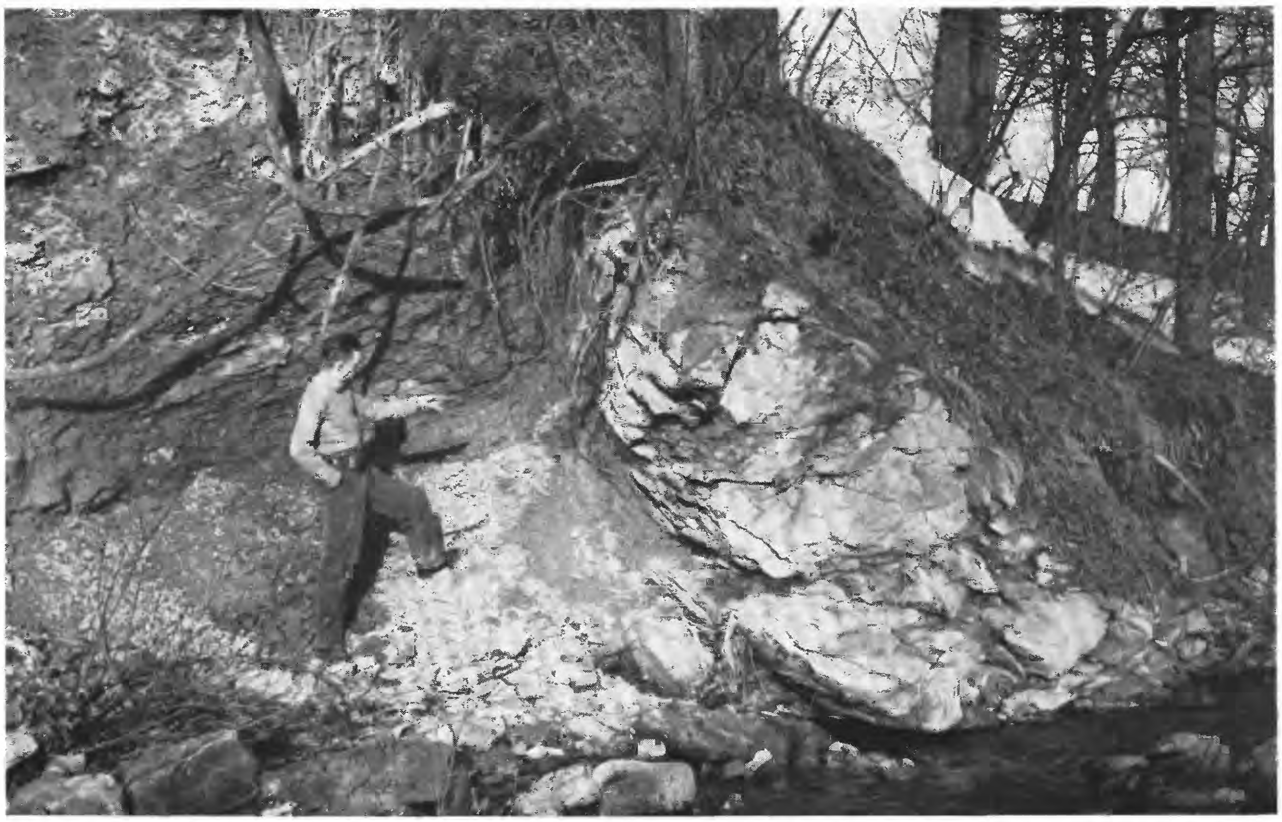


FIGURE 52.—A flow roll in the basal part of the Bedford shale on the west branch of Old Woman Creek, ½ mile northwest of Berlinville, Berlin Township, Erie County, Ohio. The gently dipping beds behind the man were rolled into the contorted mass at which he is pointing. The long axis of the exposed part of the flow roll is about 9 feet.

FIGURE 53.—Euclid siltstone member (*a*) of the Bedford shale shown on U. S. Highway 17 south of Cleveland, on the east side of the Cuyahoga River, Newburg township, Cuyahoga County, Ohio. The top of the black Cleveland member (*c*) of the Ohio shale occurs at the base of the small road marker; the fossil zone of the basal part ot the Bedford shale (*b*) crops out at the feet of the man in the center of the photograph. Note the difference in the Euclid at the right, where it has been faced in the bridge abutment, and at the left, where not smoothed. The massive 4-foot bed above the man's head is a flow-roll zone.

FIGURE 54.—Close-up of the flow-roll zone mentioned in figure 53. Note the apparent great deformation of the rocks. The beds above and below the flow-roll zone are not deformed, indicating that the deformation occurred at the time of deposition.

FIGURE 55.—Outcrop of the basal siltstones of the Berea sandstone (*a*) and the underlying thin siltstones and intercalated shales of the upper part of the Bedford shale (*b*) on U. S. Highway 23, 1 mile north of Waverly, Pike County, Ohio. Arrows point to zone of flow rolls, which is about 5 feet thick, lying above the lowest massive siltstone of the Berea. Note the flat-lying beds above and below the highly contorted beds in the zone of flow rolls.

Probably these ripple marks were produced by the very slight currents of the Ohio sea in Bedford and Berea time. The ripple marks undoubtedly represent oscillation ripples which were only slightly modified by currents.

FLOW ROLLS

Several relatively thin zones of intensely deformed rocks are present in the northern and western outcrops of the Bedford and Berea formations in Ohio. The zones are characterized by many elongate ellipsoidal masses of thin ripple-marked siltstones, sandstones, and intercalated gray, red, and at some places black shales. The sediments have been squeezed into masses resembling sofa cushions or have been rolled while in a plastic state into cylindrical masses that resemble huge jelly rolls. (See figs. 52, 53, 54, 55.) These deformed masses of rock have been known to quarry men by a number of names, such as "nigger head" or "turtle-back" stone (Cooper, 1943, p. 190). They have been described as "concretionary" by Winchell (1874, p. 272–313) and Orton (1878, p. 596–616) and as "flow structures" by Cooper (1943). Because of the characteristic rolled appearance and because the deformation of the strata occurred prior to complete lithification of the rocks, the present writers have named these deformed rock masses "flow rolls" (1945b).

A very persistent zone of flow rolls occurs in the basal 4 to 8 feet of the Bedford shale from Euclid Creek in eastern Cuyahoga County westward to the vicinity of Norwalk in Huron County. South of Norwalk the zone cannot be traced because of inadequate exposures. The thin siltstones and basal shales of the Bedford are contorted into large rolls and pillow-shaped masses at many places. Although the zone is thinner, the deformation occurred in the lower part of the Euclid siltstone member of the Bedford as well as in the lower part of the red Bedford shale. The flow rolls of the lower part of the Bedford range in diameter from 2 to 8 feet and average about 4 feet in diameter. The rolls and pillow-shaped masses are separated horizontally by squeezed and deformed lumps of shale and silty mudstone in which the original bedding laminations have been largely destroyed. Locally other zones of small flow rolls can be found in the Bedford shale, but these are not as extensive as the basal zone.

A more extensive flow-roll zone occurs in the basal part of the sheet of Berea sandstone which overlies the channel sandstones in northern Ohio. This zone of rolls has been observed from Olmsted Falls (fig. 7) on the Rocky River in Cuyahoga County to the vicinity of Otway (fig. 8) in western Scioto County. Several flow-roll zones have been noted in the thick siltstones of Bedford and Berea age in southern Ohio and Lewis County, Ky., but which zone, if any, is the equivalent of the flow-roll zone of the basal part of the Berea of northern Ohio is not known. The flow rolls of the Berea range in diameter from 2 to 12 feet, averaging about 6 feet. The rolls are largest and best formed in northern Ohio, decreasing in size to the south. Cooper (1943, p. 193–201) gives an excellent description of the flow-roll zone and the types of rolls occurring in the zone in the vicinity of Columbus. Outcrops show every gradation from the undisturbed section of interbedded fine-grained sandstone, siltstone, and silty shale to the highly contorted and involute rolls in which the individual beds are buckled into small fan or isoclinal folds or mashed back upon themselves. At many places where the beds of sand were greater than 8 inches thick, the flow structures are pillow-shaped and very little shale or mudstone is included in the roll. However, in the same exposure or at other localities where thin sandstones from ½ to 4 inches thick separated by almost equal amounts of shale were caught in the deformation, the rolls have the more typical jelly-roll form.

The formation of the more nearly perfect flow rolls is apparently dependent in part upon the presence of soft silt-free mud in the zone of deformation. East of the Red Bedford Delta where the Bedford shale is more silty only a few small flow rolls were observed. Also in the southern part of the western outcrop of the Bedford and Berea formations where the Bedford is more silty than the red Bedford in northern Ohio, the flow rolls are smaller and not as involutely coiled. Between the Cuyahoga River and Norwalk where the largest flow rolls of the Berea sandstone are found, the rolls apparently formed upon the upper few feet of red Bedford shale which appears to have been in a plastic state as a result of the rewetting of the shale during deposition of the early Berea. Although the largest flow rolls are found in the basal part of the sheet of Berea sand, the rolls did not form where the sheet sand was underlain by the channel sands of the Berea.

That the beds involved in the flow-roll deformation yielded while in a plastic state is shown by the oversteepening of many of the ripple marks in the sandstones and siltstones. The ripple crests have flowed into the adjacent troughs, and in some exposures flowage has almost masked the ripple marks. The surfaces of many of the sandstones or siltstones in the rolls are covered by fine networks of normal and high-angle reverse faults of minute displacement. Some of the beds have been faulted and the drag along the fault plane has been greatly exaggerated by flowage of the semi-consolidated beds. Many of the smaller flow rolls which resemble sofa pillows were formed by the folding back of a small section of a silt or sand bed into a short isoclinal fold around which flowed the softer mud which the coarser grained sediment had originally covered. The tight folding of the beds could not have been accomplished after their lithification in this region of undisturbed rocks. At many places the thinner parts of the coarser-grained rocks in the flow-roll zone have been faulted and ruptured by the upwelling of the soft sediment below. The tops of the upwelled mud lumps have been removed by erosion, showing that the deformation occurred while the sediments were unconsolidated and during the time of deposition of the sediments. The movement which formed the flow rolls was confined vertically to the beds within the zone, for the beds above and below the zone of deformation are not disturbed. Many of the rolls were partly destroyed by scour prior to the deposition of the horizontal bed which now caps the zone. Because the movement was confined to the zone, the flow rolls formed almost in place. Examination of many exposures shows that in addition to the mud welling up through the beds of silt and sand, the coarser-grained sediments sank into the mud or into the voids created by the lateral flowage of the mud. Apparently the net gain in thickness of the flow-roll zone by the formation of the rolls did not exceed 25 percent of the original thickness of the beds. Some outcrops show that the flow rolls are thinner than the undistorted strata.

Cooper (1943, p. 201) states: "Surface slope is considered the fundamental cause of the Bedford and Berea flows, although it cannot be proved that any particular flow was caused thereby."

The present writers believe that the formation of flow rolls depends more upon the horizontal flowage of sediments in response to either unequal loading of the softer substratum or unequal unloading of the more mobile substratum of mud than to the initial slope of the surface upon which the sediment was deposited. To be sure, an initial slope of several degrees would aid in the formation of the rolls once they start to form. Kindle (1917b, p. 323–332) cites many structures in some modern estuarine environments whose genesis is probably the result of the unequal unloading by scour of mobile material lying below a less mobile cover. These structures resemble the flow rolls of the Bedford and Berea formations. Apparently flow rolls were formed largely by horizontal pressures built up by the irregular deposition of the basal silts of the Bedford or the basal sands of the Berea upon a plastic foundation. The release of the pressure caused either by upwelling of the mobile substratum through the cover or the cutting of the cover by scour permitted the mobile material to migrate. At places where the mud ruptured the covering sheet of sand or silt the edges of the break were rolled back by the upwelling mud, and a zone of intense local deformation formed around each place of upwelling. The mud flowing into small scour channels carried parts of the overlying sand sheet into the channels, and produced the involutely coiled flow rolls oriented roughly parallel to the axis of the scour channels. Because the action occurred rapidly, the sheet of sand was contorted without destroying the ripple marks. If several thin beds of sand or silt moved into a channel or depression as a unit, the typical jelly-roll structure would result. The presence of flow rolls at elevations below adjacent outcrops of relatively undisturbed black shales of the upper part of the Cleveland member of the Ohio shale or basal part of the Bedford shale suggests the filling of shallow channels or hollows by lateral flowage of the relatively soft materials into scour channels. Similar evidence of channeling on a small scale associated with flow-roll development has been noted in the flow-roll zone of the Berea sandstone in northern Ohio.

Sedimentary structures similar to flow rolls have been reported from the Upper Devonian rocks of New York and Pennsylvania, and they have been called storm rollers (Chadwick, 1931). However, it appears very unlikely that the infrequent but violent storm waves could roll up the unconsolidated silt, mud, and sand into flow-roll structures. More probably large storm waves would tend to erode and destroy rather than mold and form flow rolls. The origin of "storm rollers" is probably the same as flow rolls—that is, they form as the result of relatively minor adjustments in the sediment partly in a subaerial environment, rather than under water during the violent activity at the height of a storm.

From casual examination of the flow-roll zones in the Bedford shale and Berea sandstone and of the channel sandstones of the Berea in area H (fig. 35), some geologists have suggested that the channel sandstones were formed as flow rolls on a much grander scale or that the flow rolls formed as a result of the deformation which accompanied the "sinking" of the channel sandstones. However, from evidence presented in this discussion of flow rolls and the discussion of the genesis of the channel sandstones, it is readily apparent that neither of these hypotheses is tenable.

SUN CRACKS

Prosser (1912a, p. 252–253) first noted the presence of sun cracks in the Berea sandstone in northeastern Ohio. He reported their occurrence in the Big Creek section, outcrop 16, and in the Bates Creek section, outcrop 17, of plate 4. In mapping the outcrop of the Berea sandstone in northeastern Ohio, the writers found similar occurrences of sun cracks at outcrops 18, 21, 23, 24, and on Crooked Creek 1.3 miles south of outcrop 20. Also float blocks of sandstone in several of the adjacent outcrops showed some specimens of sun cracks, although the layer was not found from which the float was derived.

The sun cracks, which range from 0.25 to 1.5 inches in width and from 0.5 to 1.0 inch in depth, generally show a rectilinear pattern suggestive of a sand-filled joint system, although at some places the normal polygonal sun-crack pattern is present. The larger blocks of the rectangular system range from 6 inches to 1.5 feet on a side, and in some places a second and smaller system appears to have developed across the larger system. This may indicate several periods of exposure prior to the covering of the sun-cracked sediment.

The sun cracks formed in several zones containing thin beds of shale near or at the base of the Berea in northeastern Ohio. The beds that make up these zones are predominantly hard bluish-gray silty shale, and the cracks are filled by a very white micaceous medium-grained sandstone, which is generally slightly coarser than the average sandstone of the Berea in the area. The bluish-gray shale ranges from 3 inches to 2 feet in thickness and contains many small irregular lenses of gray silty sandstone interbedded in the shale.

An attempt was made to correlate the zones of sun-cracked rocks in northeastern Ohio; however, the plotted sections show that probably more than one zone of sun cracks exists in this area. At outcrop 17, plate 4, the zone of sun cracks occurs at the base of 56 feet of Berea sandstone, and 1 mile to the northeast at outcrop 18 the sun cracks occur in a 6-foot shale break 39 feet below the top and 25 feet above the base of the Berea. A group of oscillation ripple marks trending N. 40° E. lies just above the zone of sun-cracked shale in outcrop 24.

The presence of sun cracks in the lower part of the Berea in northeastern Ohio indicates subaerial deposition for at least a part of the Berea sandstone in this area. The decrease in size of the oscillation ripple marks in northeastern Ohio noted elsewhere in this paper could be the result of a decrease or an increase in the depth of the sea during Berea time, but the presence of the sun cracks indicates that the decrease in the size of the ripple marks probably resulted from the shoaling of water.

A somewhat similar zone of sun cracks was observed in outcrop 55 (pl. 4) lying just above the siliceous limestone 12 feet below the top of the Cussewago sandstone. Although the sun cracks were observed in the Cussewago only at outcrop 55, they may be present but obscured by debris at other places.

CARBONACEOUS MATERIAL IN THE BEREA SANDSTONE

Carbonized plant fragments are widely distributed throughout the Berea sandstone in northern Ohio. Although isolated specimens are present in the thin-bedded upper part of the Berea, most of these plant fossils occur in the channel sandstones. Many of the fragments appear to be parts of stems and branches which have undergone wear during transport to the place of burial. Typically, the fragments are worn and the corners rounded similar in appearance to the driftwood that collects along the shore of Lake Erie. In general, only the gross outlines of the plant are preserved, but in some places pyritization has preserved much of the cell structure of the wood.

Several large plant stems were found in the float blocks of the Berea that lie below the falls of the Vermilion River at Elyria. The largest specimen measures 21 inches long, 5 inches wide, and about 1/2 inch thick. The surface was covered with a reticulated pattern that resulted from sand filling the check cracks in the wood during burial.

Many well-preserved but slightly flattened specimens of plant fossils can be obtained from the Nicholl quarry at Kipton. In general the chunks of carbonized wood are smaller than those found at Elyria, but are better preserved because they have been exposed by quarrying and are therefore unweathered.

In many of the quarries, especially in the South Amherst group, the sandstone contains small lenses of coaly material ranging from a film to as much as 3 inches in thickness. A lens of coaly material 25 feet long, 15 feet wide, and about 3 inches thick was exposed in the Buckeye quarry in 1945. It consisted of bands of coaly material, carbonized plant fragments, and white fine-grained sandstone. In some of the layers pyrite has replaced more than half of the plant tissue and preserved much of the original cell structure. About 80 percent of the coaly material was fusain consisting of many well-preserved fragments of wood in which the cell structure was plainly visible. The remaining 20 percent consisted of small lenses of vitrain ranging in thickness from 0.05 to 0.3 inch. The vitrain had conchoidal fracture and a shiny lustrous surface. Selected specimens of vitrain burned readily with a smoky yellow flame, yielding a small amount of ash. Some gray silt and white mica also were present in the lens of coaly material. Apparently these deposits of plant debris in the Berea sandstone represent accumulations of driftwood, spore cases, and clots of pollen which were entrapped in the quieter reaches of the stream channels of the Berea Delta. Rapid burial of the material prevented complete oxidation of the plant tissues and aided the conversion of the wood to fusain and the pollen clots to vitrain.

The widespread occurrence of isolated plant fragments as well as the alinement of the zones of coaly material parallel to the course of the axis of flow within the river channels of the Berea Delta suggests that the wood was carried in and buried.

SEDIMENTATION OF THE SUNBURY SHALE

As an aid in tracing the areal extent of the Sunbury, a map of this shale was made from the thicknesses noted on logs of wells drilled to the Berea sand or deeper rocks throughout Ohio, West Virginia, western Pennsylvania, and Kentucky. This map (fig. 56) shows wide variations in thickness of the black shale. In general the Sunbury is thin through northern Kentucky, West Virginia, and southern Ohio. In two areas, one in northern Ohio and the other in southern Kentucky, the drillers record abnormal thicknesses of Sunbury shale (fig. 57). In each area the drillers include with the Sunbury a black shale that is not of Sunbury age. In southern Kentucky the silts and shales of the Bedford and Berea disappear and the Sunbury lies on the Ohio shale. This sequence is recorded by the driller as "Sunbury," "brown," or "coffee shale." In northern Ohio the Orangeville shale above the Sunbury member is dark gray and contains thin beds or stringers of black shale. The drillers usually record "Sunbury", "black", "brown", or "coffee shale", beginning with the first black shale noted in the Orangeville and continuing to the Berea sand.

If black shales are regarded as deposits in shallow stagnant seas, then the data obtained from well records indicate that the longest period of complete stagnation during Sunbury time lay in eastern Kentucky, western West Virginia, and southern Ohio. In this area the Sunbury shale reached a maximum thickness of nearly 20 feet and makes a sharp contact with the Berea sand below and the Cuyahoga shale above. In northern Ohio, although the contact between the Sunbury and Berea is sharp, the basal few inches are a black sandy shale, which probably means that the Sunbury sea was slightly agitated by currents from the drowned and dying streams which brought in the Berea sediments. During the deposition of the Sunbury and Orangeville, however, spasmodic but slight upwarping took place in the north; for a local siltstone, the Aurora siltstone member, was deposited over the Sunbury in the vicinity of Cleveland. Occasional thin stringers of siltstone and gray shale alternating with thin black shales show that sediments were brought in from the north during early Orangeville time.

At the end of Sunbury time a warping of the area in West Virginia apparently took place; for gray mud was carried into the area and was laid down in sharp contact with the Sunbury shale. The gray mud was followed by and interstratified with sandy mud and sand in central West Virginia and eastern Ohio. The streams from the upwarped areas in West Virginia and possibly Pennsylvania added little sediment and had but slight effect on the reducing environment of that part of the central Ohio sea which covered Ashland, Wayne, Holmes, Knox, Coshocton, and other Counties. The Orangeville shale on the outcrop in northern Ohio is in itself a very dark gray shale containing zones of grayish-black shale and is not easily separated from the Sunbury. The dark shale in the Orangeville indicates, therefore, a continuation of Sunbury environment in northern Ohio.

PETROGRAPHIC STUDIES OF THE BEREA SAND

The results of the petrographic examination of many samples of Berea sand were published as Preliminary Map 58 by Gordon Rittenhouse (1946). Rittenhouse's findings on the mineralogy and physical characteristics of the Berea sand are summarized briefly in the following résumé of portions of the text of Preliminary Map 58 and in plate 11, which is adapted from that map.

Mineralogically the Berea sand is composed predominantly of quartz grains, but also contains a few percent each of chert, unaltered feldspar, and rock fragments. Like most sands of Mississippian and early Pennsylvanian age in the Appalachian basin, the Berea contains a very small suite of heavy minerals. Heavy mineral grains of specific gravity of 2.93 or more form less than 1 percent of the rock. Tourmaline and zircon are the dominant heavy minerals. Red and yellow rutile, chromite, apatite, garnet, and anatase occur less commonly. Locally, barite may be the most abundant heavy mineral.

Division of the Berea sand into petrographic provinces is based primarily on differences in the roundness of the heavy mineral grains. Some confirming evidence is given by variations in the relative abundance of a variety of quartz.

The differences in mineralogy and grain characteristics in these provinces reflect differences in sources from which the Berea sand was derived. Together with the data on thickness and areal extent, they aid in interpreting the geologic history and paleogeography, and thus help to delineate the areal extent, shape, and trends of areas favorable for oil and gas exploration.

Although the data are sufficient to bring out many aspects of the broad, regional picture, they are inadequate as yet to fill in many of the details. To solve other regional problems and to provide detailed information, additional work is needed. In part, completion of such work will depend on whether well samples can be obtained from critical localities.

Although many varieties of tourmaline and zircon occur in the Berea, differences in their relative abundance

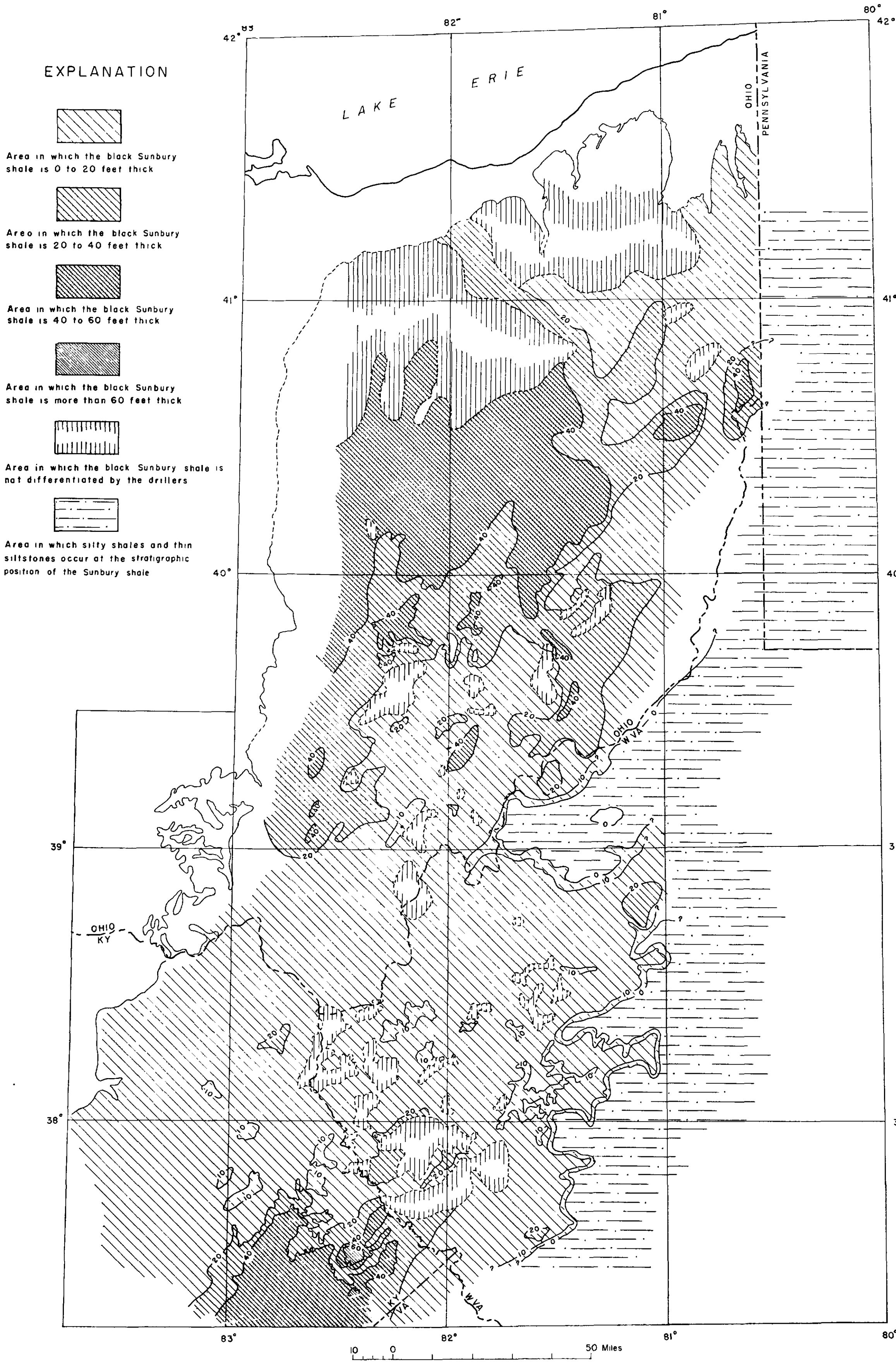


FIGURE 56.—Map showing the thickness of the Sunbury shale as recorded on drillers' logs.

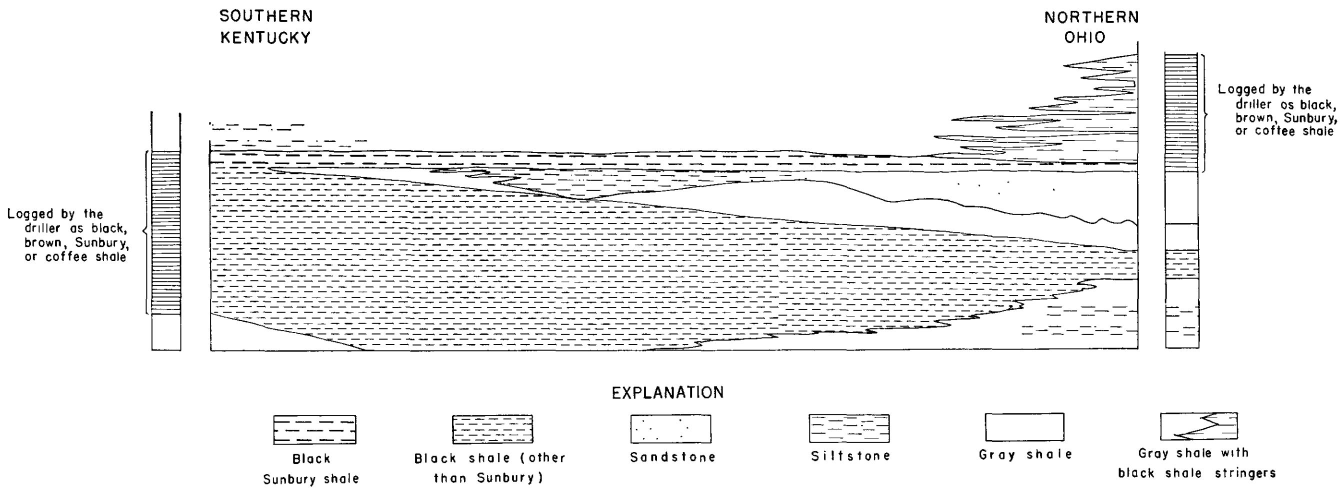


FIGURE 57.—Generalized cross section from southern Kentucky to northern Ohio, which shows the abnormal thickness of Sunbury shale as recorded by drillers. In northern Ohio the Orangeville shale above the Sunbury member contains many stringers of black shale interbedded in a dark-gray shale. In southern Kentucky where the wedge of Bedford and Berea rocks has disappeared, the combined thickness of the Sunbury shale and the Ohio shale is sometimes identified as Sunbury, thus giving a much greater than normal thickness to the Sunbury shale.

are too small to be significant. In contrast, the roundness of the tourmaline and zircon grains does vary systematically in different parts of the mapped area and can be used to outline petrographic provinces. In fact, roundness of heavy minerals is one of the most valuable criteria that have been found, not only for outlining petrographic provinces in the Appalachian basin, but also for identifying producing horizons, and for deciphering geologic history.

The use of roundness as an independent criterion to identify sediments from different sources is based on three kinds of evidence. First, differing degrees of roundness in two or more sands may be associated with differences in mineral composition. Second, in beds of the same age areal variation in roundness may be accompanied by areal variation in mineral composition. Third, in the same lithologic unit, roundness may be essentially constant throughout areas of hundreds or thousands of square miles. At the boundary between petrographic provinces an abrupt change occurs. In the Berea sand of southern West Virginia, for example, roundness of tourmaline changes from about 55 percent round grains to about 20 percent round grains in an east-west distance of a few miles.

The rounding of heavy mineral grains reflects the past history of the grains. A large percentage of angular grains or euhedral crystals usually indicates a relatively short distance of transportation prior to deposition. Such grains were derived from a primary source or from a sediment that had passed through one or possibly two cycles of erosion, transportation, and deposition. In contrast, a large percentage of round grains indicates that the grains have passed through many cycles of erosion, transportation, and deposition, or have been subject to unusually favorable conditions for rounding.

On the basis of mineralogy and grain characteristics the Berea sand may be divided into two main areal units. These units are shown in plate 11 as 1, a long narrow belt extending from the northern panhandle of West Virginia southward through Ohio and West Virginia to Wyoming County, W. Va.; and 2, a large area west and north of area 1. A third area (3 on pl. 11), which may represent a type of Berea sand, lies along the outcrop of Mississippian rocks in eastern West Virginia.

The Berea in area 1 is characterized by the large percentage of round tourmaline grains. On the average about 55 percent are round and about 5 percent are angular. This type of Berea does not crop out and is known only from the analysis of well samples.

The samples from area 2 average about 20 percent round tourmaline and vary from a few percent to about 55 percent angular tourmaline. In part the variation in tourmaline angularity may reflect variation in the average grain size at different localities. Additional work may show that the Berea of area 2 is divisible into two or more units which cannot yet be differentiated.

The boundary between area 1 and area 2 is well-defined in some places but is poorly defined in others. In four wells in southern West Virginia both types of sand occur, always with the eastern, highly rounded type of area 1 overlying the western, less well-rounded type of area 2. In wells a few miles to the east and to the west only one type of Berea sand is present. Farther north the boundary is less well defined, mainly because of the lack of well samples from the locality of the boundary, but in part because of some interfingering or intermixing of the two types of sand.

In area 3 the samples were taken from the first sandstone that crops out above the Catskill redbeds in eastern West Virginia. Because of its position, this sandstone has been called Berea by some geologists. Its identification with the Berea of areas 1 and 2 has not been established by paleontological studies or direct tracing. In this sandstone about 5 percent of the tourmaline are round and about 50 percent are angular. The roundness thus differs greatly from that in the Berea sand of area 1 and from that of many samples from area 2. In contrast, the roundness is essentially the same as that in some of the Devonian beds below. Whether the first sandstone above the Catskill redbeds is Berea or Upper Devonian cannot be determined from the present evidence. If it is Berea, it is of a third type.

In describing the petrographic provinces 1, 2, and 3, the roundness of tourmaline grains was used as the distinguishing characteristic. Differences in the roundness of zircon grains also occur although they are somewhat different in magnitude. The average percentages of euhedral, subangular, and round zircons are as follows: Area 1: 1, 48, and 51; area 2: 6, 69, and 25; and the outcrop in West Virginia, area 3: 10, 76, and 14. In area 2 zircon roundness varies greatly; a few samples are similar to those from area 1.

The relative abundance of what are designated "green grains" for want of a better term also differs in the several provinces of the Berea sand. Most of these green grains appear to be quartz grains containing small, worm-shaped inclusions of chlorite. Some may be chlorite-rich rock fragments.

In area 1 each gram of very fine sand of the light-mineral fraction contains about 100 green grains. In area 2 the Berea sand averages about 500 green grains per gram in the very fine sand size. In one sample from the outcrop in West Virginia, area 3, the very fine sand size contained about 1,100 green grains per gram.

Areas 4, 5, 6, 7, and 8 on plate 11 represent other petrographic provinces as outlined from studies of samples and well records.

In area 4 a thick sand occurs at or very near the horizon of the Berea. At the time Preliminary Map 29 (Pepper and others, 1945a) was published, this sand was interpreted as a deltaic deposit of early Berea age. In the two wells from which samples are available, the tourmaline grains are much less rounded than those in the Berea sand of area 1. In mineralogy and roundness these samples are very similar to those in the Cussewago (Murrysville) sand of southwestern Pennsylvania (area 5). The areal distribution and thickness of the Berea and Cussewago (Murrysville) sands in western Pennsylvania, as shown by Preliminary Map 49 (Demarest, 1946), also suggest that the thick sandstone of area 4 is Cussewago (Murrysville) instead of Berea in age. Additional work on this problem must await the collection of more well samples.

Between areas 1 and 4 in northern West Virginia, and between area 1 and the outcrop of the Pocono sandstone in southern West Virginia, the Berea sand is absent or spotty. This is area 6. Dividing area 6 into northern and southern parts is a long narrow belt of Berea sand known as the Gay-Fink Channel (area 7). At the west end of this channel, the tourmaline grains are of the highly rounded type characteristic of area 1. In the east half of the channel, the tourmaline grains are much less rounded; about 20 percent of the grains are round and about 10 percent are angular. This sediment appears to be a mixture of highly rounded sand similar to that of area 1 and of sand similar to that along the West Virginia outcrop (area 3). Some sand from area 4 may be included.

Petrographic and other evidence shows that most of the Berea sand of area 2 was derived from a northern source. The rounding of the sand grains and the presence of chert and sedimentary rock fragments indicate that the source rocks were predominantly sediments composed in large part of grains which had passed through one or more cycles of erosion, transportation, and deposition. The round grains probably had passed through many cycles. Some of the angular and euhedral grains may have been derived directly from granites or other acid igneous rocks rather than from sedimentary rocks.

The sediment was brought southward by a large river and emptied into the Ohio Bay from several distributaries between Norwalk and Ashtabula, Ohio. In part the sediment was deposited on a large delta that had developed during Bedford time and persisted into Berea time. River-channel deposits, near-shore or fluvial types of cross bedding, decrease in grain size to the east, south, and west, and the areal distribution and thickness of the deposits all substantiate this hypothesis of deltaic accumulation. Fluctuation in water level and major changes in the position of the river channel may have produced several stages of deposition of the Berea.

The thick sandstone and siltstone deposits centering in Tuscarawas County, Ohio, in area 2, probably have a more complicated history than the deposits to the north and northwest. Variations in mineral composition, grain roundness, texture, and thickness suggest, but do not prove, the possibility of interfingering or overlap of sediments that were derived from several sources. In part the deposits in this locality may have accumulated along the west shore of an embayment at the same time the sediments of area 1 were being deposited along the eastern shore. In part the deposits may be a southeastward extension of the deltaic accumulations. Additional samples may provide data to prove or disprove these suggestions.

In southern West Virginia in that part of area 2 just west of area 1, the sediment may represent an early-stage accumulation of debris from the east or south, rather than from the north. In this southern part of area 2 the Berea sand has essentially the same mineralogy and grain roundness as the Berea sand farther north. As yet the sediment in the two parts cannot be differentiated. Despite this similarity, an eastern or southern source is suggested by the texture of the deposits in this southern part of area 2, where the Berea is fine- and very fine-grained sandstone. How this sand could have been transported southward across areas that are thought to be siltstone is difficult to explain. Also, toward the west the sandstone grades into a body of thick siltstone which is separated from the thick Berea deposits of east-central Ohio by an area of thinner Berea.

In area 1 the Berea sandstone contains highly rounded tourmaline and zircon grains that probably have passed through many cycles of erosion, transportation, and deposition. Similarly rounded tourmalines have been reported by Krynine (1940, p. 30–31) from early Paleozoic sands of central Pennsylvania. Early Paleozoic sandstones to the east of the present mapped area are likely sources of the Berea sediment of area 1.

From the evidence now available, the Berea sand of area 1 probably was derived from the east, transported westward through the Gay-Fink Channel (area 7), and spread northward and perhaps southward to accumulate as shore or near-shore deposits in a low-stage Berea sea. The sand in the southern part of area 1 may have been brought westward through the Cabin Creek Channel (area 8) from the same source. Under this hypothesis both Gay-Fink and Cabin Creek are sand bodies which were deposited in river channels that traversed area 6, a westward-sloping land area at the time the sediments of area 1 were accumulating.

All of the sand in the Cabin Creek Channel and in the western end of the Gay Fink Channel is similar to that in area 1. In the eastern half of the Gay-Fink Channel, however, the sand appears to be a mixture of sediment of area 1 type and sand similar to that along the outcrop in West Virginia. The difference in sediment in the eastern and western parts of the Gay-Fink Channel would be expected if orogenetic movements to the east brought deposition in area 1 to a close. The source of highly rounded sand would have been cut off and the Berea sea would have transgressed rapidly eastward. As the Gay-Fink Channel was backfilled, a mixture of sand from old and new sources would have been deposited in it.

PALEOGEOGRAPHY

PALEOGEOGRAPHY OF BEDFORD AND BEREA TIME

THE APPALACHIAN BASIN

Although the Appalachian geosyncline includes all the area between Appalachia and the Cincinnati arch, the axis of the basin in which sediments were deposited within this broad area did not remain constant but shifted east or west throughout the long span of geologic time from the Cambrian period to the Permian period.

Apparently the sediments that were deposited in the Appalachian basin during much of Paleozoic time were derived mainly from land to the east and southeast.

Periodic upwarps of the eastern edge of the Appalachian basin increased the amount of sediments derived by erosion from the land area, and the consequent deposition of vast quantities of these sediments along the eastern border of the geosyncline shifted the axis westward. However, whenever downwarping of the geosyncline was greater in some places than the rate of fill by sediments that were transported into the geosyncline from the eastern land area, the axis of the depositional basin was shifted eastward. Figure 58 shows that the axis of the basin during a part of Ordovician time lay west of the axis during Silurian time. From Silurian through Devonian to early Mississippian time the axis moved progressively westward. From early Mississippian time, when the Bedford and Berea sediments were deposited, the axis again moved eastward through late Mississippian and early Pennsylvanian time, but again shifted westward in Permian time.

The sands and silts of the Bedford and Berea formations were deposited on the western edge of the Appalachian geosyncline at a time when most of the area of the geosyncline was above sea level. The present writers point out that a greater part of the Bedford and Berea sediments in Ohio were derived from the north. The highlands of eastern Canada lying northeast and north of the Ohio Bay, as shown in plate 12, were probably the source area of most of the Bedford and Berea sediments.

Although much of the sand and silt of the Bedford and Berea was derived from the north, perhaps one-fifth was derived from the east. The sand and silt from the eastern source may well have been derived from the Oriskany, the Tuscarora, and other sandstones cropping out on a domed area in Virginia and Maryland. Little in the content of the heavy minerals in this part of the Berea sand as observed by Rittenhouse suggests any first generation sands derived directly from a granite-cored Appalachia.

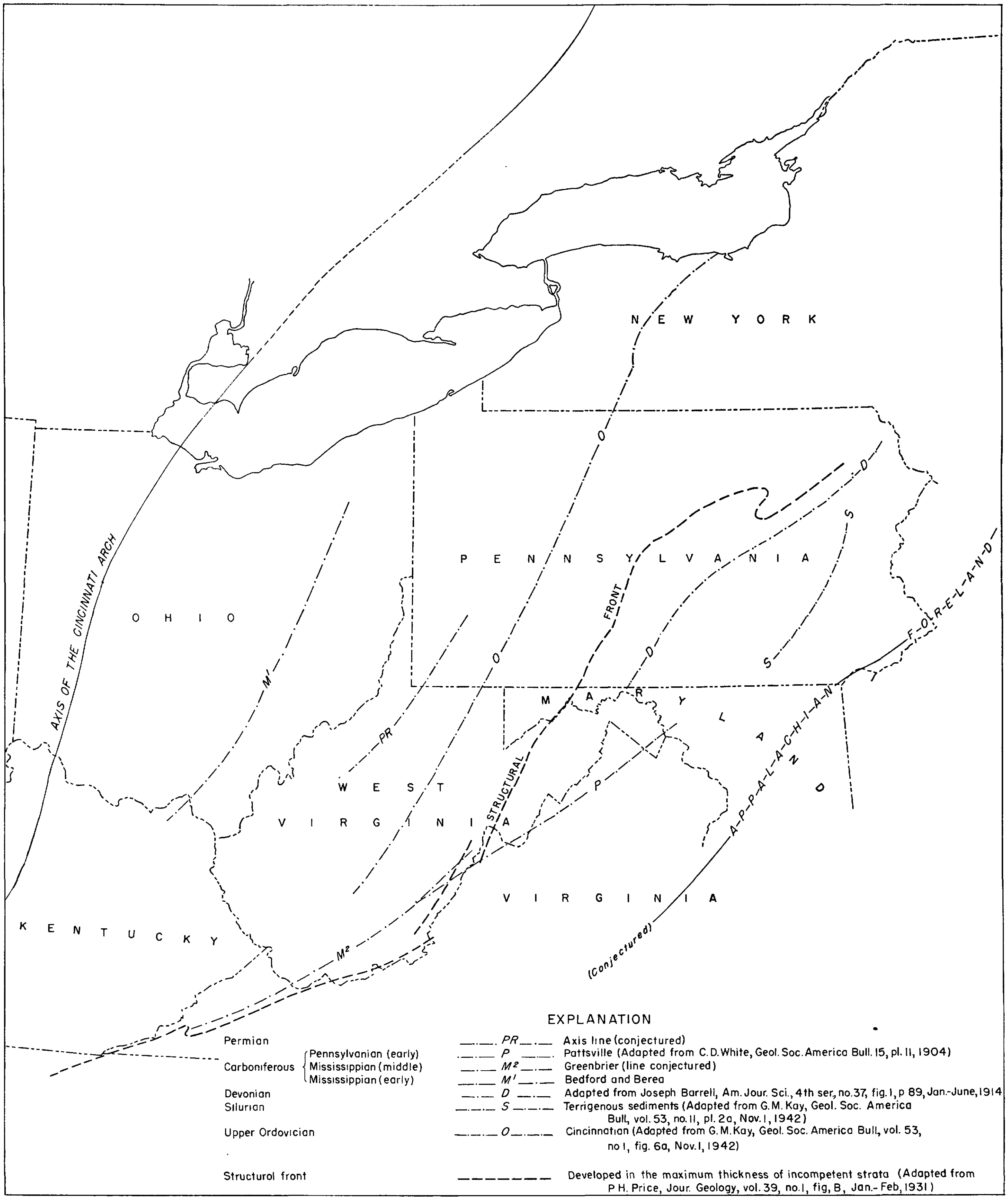


FIGURE 58.—Diagram showing axes of basins in which sediments were deposited from Ordovician to Permian time within the Appalachian geosyncline.

During earliest Bedford time a shallow sea extended from the Cincinnati arch to a low-lying land area in western Maryland and West Virginia. To the north in Canada, the northern rim of the Appalachian basin was already tilted slightly and mud from the Bedford deltaic plain was being carried into the open sea in Ohio. A broad deltaic plain fronted the Ohio Bay on the east and from this mass of sediments which probably make up the basal part of the Pocono rocks, the thin sheet sand of the Cussewago (Murrysville) spread westward across central and western Pennsylvania. A broad shallow sea apparently lay to the southwest and west of the Ohio Bay, covering parts of Alabama, Kentucky, and Tennessee, for according to W. H. Hass (personal communication) in Kentucky south of Irvine, Estill County, the Chattanooga shale contains some black shale of early Mississippian age as well as Late Devonian age. Possibly only a very small amount of fine quartz silt and some carbonaceous material reached this shallow sea in early Mississippian time, for during the deposition of the Bedford and Berea sediments this seaway may have been so shallow as to be essentially an area of nondeposition. The tilting of the edges of the Appalachian basin and the encroachment of the sea were so gradual that no unconformity is visible between the Berea sand and the sands of Devonian age below in western Pennsylvania and central West Virginia.

CINCINNATI ARCH

The Appalachian basin is bounded on the west by the Cincinnati arch, which passes through central Tennessee, Kentucky, western Ohio, and western Lake Erie into Ontario. Although the Cincinnati arch is a positive element which forms a boundary between the Appalachian basin on the east and the Illinois and Michigan basins on the west, many geologists believe that it was not caused by folding.

Stout (1941, p. 13) in describing the arch states that, "This prominent regional feature is only a part of the rock configuration of the interior basin constructed through the action of several agencies operative over a long period of time. The Cincinnati arch is a structure formed primarily by differential lateral deposition of the great formations making up the geological column of western Ohio." Lockett (1947, p. 435) is of the opinion that the Cincinnati arch, together with other positive areas in the northeastern United States, has a crystalline core which represents the remnants of a pre-Cambrian mountain system. The detritus eroded from these mountains was deposited as sediments in the surrounding basins and their added weight caused further sinking of the basins.

At times low islands or larger land masses emerged above water along the crest of the Cincinnati arch in Ohio, Kentucky, and Tennessee. At other times these land areas were submerged. The evidence for these movements was noted in the overlap of sedimentary beds over the arch. Foerste (1902) showed that increasingly older Silurian rocks are found toward the axis of the arch, because the Devonian beds truncate all of the Silurian rocks.

McFarlan (1943, p. 135) believes that the overlap of beds from the Helderberg down to the Maysville seems to indicate that the arch of Middle Devonian time was nearly comparable to the present one. He notes, however,

> That the early "upwarp" does not necessarily mean an early island condition of any great extent or height is shown by the presence of the Ohio and New Providence (lower Waverly) formations locally preserved on the crest of the Arch in downfaulted blocks.

A peninsula or island was present in Middle Devonian time along the axis of the arch in central and southern Ohio as noted by Newberry (1889), Stauffer (1909), and more recently by Wells (1944), who named the island Cincinnatia. This island was low lying and probably nearly submerged during the deposition of the Ohio shale. The present writers believe that an island was in existence in earliest Bedford time in the vicinity of Cincinnati, and that this island slowly emerged to join the northern mainland as a low peninsula in middle Bedford time. The peninsula was again broken into a chain of islands in late Berea time; in the early part of Sunbury time the islands slowly submerged.

The northern continuation of the Cincinnati arch is broken by a downwarp in Ontario known as the Ontario sag. Lockett (1947, p. 433) estimates that this part of the arch has dropped 2,000 feet since Trenton (Ordovician) time. Possibly the sag area was downwarped during Berea time sufficiently to permit the deposition of a continuous belt of sediments from the eastern edge of the Michigan Basin to the northern rim of the Ohio Bay. Whether the sediments extended across the sag during this time is uncertain. The southern end of the Berea sand of Michigan on the west flank of the arch, as shown on the map of Cohee and Underwood (1944), lies 95 miles from the nearest outcrop of Berea sand in northern Ohio on the east flank of the arch. Subsequent erosion has removed all of the sediments which were deposited on the arch in northern Ohio down to the Lower Devonian, but the possibility exists that the Berea sand of Michigan may have been connected across the arch with the Berea sand of Ohio on overlapping flood plains which may or may not have been strictly of the same age.

On the other hand, if the Ontario sag was not depressed enough during early Mississippian time to connect the Michigan and Ohio basins, the Berea sediments of Michigan and Ohio, though probably derived from the same source area, must have been transported by a river system that emptied first into one basin and then into the other.

An analogous recent occurrence is provided by the Hwang-Ho of China, which in 1938 shifted its main channel at a point 300 miles from the mouth, from north of the mountainous Shantung peninsula to a new outlet on the Yellow Sea south of the peninsula. The new outlet is about 300 miles from the previous mouth. The Shantung highlands, which effectively divided the two areas of deposition, control the drainage of the Hwang-Ho in the same way that the northern end of the Cincinnati arch area may have controlled the drainage of the Ontario River in early Mississippian time (fig. 59).

If such a diversion of the Ontario River occurred, as seems likely to the writers of this report, the problem of the sequence of events is somewhat more equivocal. The deposition of the Berea sand of Ohio and of Michigan may have been nearly contemporaneous if the Ontario River switched back and forth from one basin to the other. The chief objection to this supposition, however, is that the Red Bedford Delta, the forerunner of the Berea of Ohio, was deposited only in the Ohio basin. The shale of supposed Bedford age below the Berea of Michigan is predominantly, if not wholly, drab in color. It is difficult to see how the Michigan Basin could have escaped receiving a large quantity of red mud if cycles of deposition took place in the two basins concurrently. Deposition of the Berea of Michigan probably could not have occurred immediately before the deposition of the Berea of Ohio; because erosion in Ohio during deposition of the Berea in Michigan would have enlarged the steep-walled scour channels incised in the Red Bedford Delta, and streams would have removed much of the red beds that make up the delta.

In Michigan, the rocks in the stratigraphic sequence from the Bedford shale through the Berea sandstone, Sunbury shale, and the basal reddish shale of the Coldwater, have not been precisely dated by fossils. If conodonts or other fossils could be recovered from the Sunbury shale of Michigan and compared with the faunas from the Cleveland member of the Ohio shale and the Sunbury shale of Ohio, the problem of the correlation of the rocks in Michigan and the relation of their depositional history to the Bedford shale and the Berea sandstone of Ohio might finally be resolved.

Assuming that the Berea sandstones of Michigan and Ohio were not deposited concurrently and are not temporal equivalents, two alternate hypotheses for the deposition of the Berea sandstone in Michigan are possible.

The present writers favor the hypothesis that the Berea of Michigan is slightly younger than the Berea of Ohio but was derived from the same source area. The Ontario River, which carried the Berea sediments into the Ohio Bay first, was diverted from its course 200 miles or more upstream and discharged into the Michigan Basin on the west side of the Cincinnati arch in post-Berea time. In Sunbury time, black mud accumulated in the Ohio area as the Ontario River carried sand into the Michigan Basin. As the supply of sand decreased, a period of deposition of black mud terminated the accumulation of the Berea sand of Michigan. The writers favor this hypothesis because it fits many of

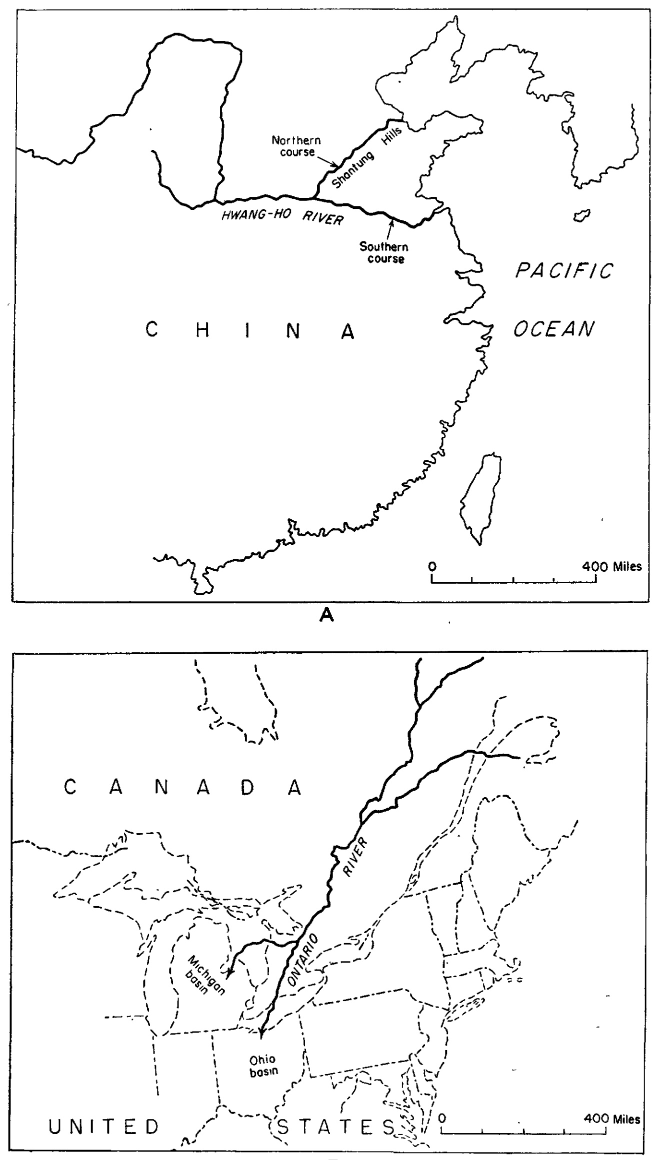


FIGURE 59.—Sketch maps comparing the diversion of the Hwang-Ho of China and the ancient Ontario River. *A*, Part of eastern China showing the two lower courses of the Hwang-Ho or Yellow River. *B*, Part of eastern North America on same scale showing the two probable courses of the Ontario River. The river discharged into the Ohio basin during Bedford and Berea time and was diverted into the Michigan basin in post-Berea time.

the known facts, it is simple, and it requires no diastrophic movement to shift the course of the Ontario River.

If the Sunbury shale of Michigan should prove to be the equivalent of the Cleveland member of the Ohio shale, the Berea sandstone of Michigan would be of Late Devonian age and probably genetically unrelated to the Berea sandstone of Ohio. The writers believe this hypothesis is less plausible because it requires two distinct times of uplift in the source area to produce a period of deposition of mud and sand in each basin, separated by a common time of accumulation of black mud. This is a more complicated diastrophic history than is required in the alternative hypothesis favored by the writers. Also, the hypothesis of a Late Devonian age for the Berea sandstone of Michigan runs counter to the general beliefs held by many geologists acquainted with the area. Until further work is done on the correlation between Michigan and Ohio, the writers believe the burden of proof should rest upon the more complicated hypothesis.

CLIMATE OF BEDFORD AND BEREA TIME

The inferences regarding the climate during Bedford and Berea time are discussed as follows:

Plant remains in the Berea sandstone in the quarries of northern Ohio suggest that the banks of the streams were covered by considerable vegetation and that the climate was mild.

The amount of sediment brought in from the north by the Ontario River indicates abundant precipitation at least in the higher reaches of the stream course.

The presence of red beds in the flood plain of the Red Bedford Delta is of little value as a criterion of climate. Red beds may form in an arid climate by oxidation of iron compounds, or they may form in extremely moist climates and retain their red color provided they are not deoxidized by organic material. As Krynine (1940, p. 78) points out,

> * * * the red color of a sediment due to iron oxide may be preserved in a sediment if there is no organic plant matter to reduce it. But it will be preserved just as well if the organic matter, even if very abundant, is destroyed by intense oxidation and bacterial activity faster than it can accumulate in the soil. In the first case semi-aridity is implied; in the second, a hot and very humid climate.

Oscillation ripple marks which trend about N. 50–55° W. are extremely abundant in some of the siltstones of the Bedford and Berea in the outcrop belt of central Ohio. The presence of these ripples and the almost total absence of current ripples suggest the work of wind and waves. Bucher (1919, p. 249–254) in describing these ripple marks infers from their prevalence and their uniformity of direction that they must have been formed normal to the greatest fetch of seaway by winds that blew periodically from the southwest against a great continental land mass to the northeast. These winds, he concludes, were probably monsoon winds.

The vast amount of sediment derived from the north and the nature of the known areas of Devonian and Mississippian rocks in New Brunswick, Canada, suggest a mountainous region of moderate height and extent in northeast Canada. The writers infer that this mountain area was bounded on the west by a broad plain which sloped in a southwesterly direction at the rate of a few feet to the mile. The monsoon winds from the southwest were cooled as they swept upward across the rising plain and into the mountainous region, thus causing torrential downpours in the mountain and foreland area. The flood water produced by these rains was dissipated in part in the lower reaches of the stream course in much the same manner as the Mississippi River, where uncontrolled by artificial levees, overflows its banks and forms innumerable new channels across its floodplain.

SOURCE OF THE SEDIMENTS OF THE BEDFORD AND BEREA DEPOSITED IN MICHIGAN AND OHIO

Devonian and Mississippian sediments were probably deposited in the region east of Hudson Bay. Certainly the folding in the Appalachian and Acadian regions of Canada including "all Canada east of a line running northeast from the foot of Lake Champlain to the city of Quebec and down the St. Lawrence River" (Young, 1926, p. 83, 92–93) provided a source for the large volumes of Carboniferous rocks of the Maritime Provinces. As Young says of these regions:

> The intense folding and faulting of the Devonian and older rocks presumably gave rise to mountain forms in the Appalachian and Acadian regions, but erosion was so vigorous that in various districts the granite bodies were unroofed by early Carboniferous time and contributed detrital matter to the earliest Carboniferous beds. The greater part of the Acadian region, however mountainous it may have been, appears to have been reduced to a condition of low relief, perhaps in part approximating a plain, for though some of the present uplands, as in southeastern New Brunswick, are relics of hills of pre-Carboniferous or very early Carboniferous time, other upland areas of pre-Carboniferous rocks, which now rise above districts flooded with Carboniferous beds, are due to warping and faulting. No Carboniferous strata occur in the Appalachian region except along the shores of Chaleur bay. Probably this region continued to be an area of denudation rather than of deposition throughout the Carboniferous and later periods of time. * * *
>
> The greater part of the Carboniferous series in the Maritime Provinces is formed of non-marine sediments, which in some districts are thouands of feet thick. They occupy the New Brunswick lowland, practically all of Prince Edward Island, and considerable districts in Nova Scotia. Beds of this age occur in Magdalen islands, lying towards the centre of the gulf of St. Lawrence, and it seems likely that a large part of the area of the

gulf, together with adjacent districts of the Acadian region, were parts of an extensive region over which great volumes of arenaceous and argillaceous beds were laid down. So great an accumulation of clastic material postulates as a source of supply an extensive area or series of areas of upland country subjected to vigorous erosion. The main source of supply of detrital matter could hardly have been the limited upland surfaces now protruding through the Carboniferous areas, nor does it seem likely that it was furnished from the pre-Carboniferous rocks of the Nova Scotia peninsula, for the relations of the areas of these rocks with the early Carboniferous strata and the existence of marine Carboniferous beds on the Atlantic coast on the eastern side of the area, indicate that the greater part of the peninsula had been reduced to a condition of low relief before the close of the Mississippian period. Nor does the main source of supply of the clastic material appear to have lain in the present upland districts of northwestern New Brunswick for, approaching these areas, the Carboniferous sediments decrease in volume.

This source area could well have provided sediments to the east and southeast also. In southern Ohio the Berea is largely a siltstone containing lenses of fine sand, grading laterally northward into fine sands and sand containing a few pebbles. Coarser sands and conglomeratic beds of Berea age probably lay in the area between Hudson Bay and eastern Quebec at the north end of this vast river system and north of the present outcrop. The presence of Mississippian conglomerates in New Brunswick strongly indicates that during the time of their formation large quantities of finer sediments were probably supplied to the river system of early Mississippian time which deposited Berea sediments in Ohio and probably in Michigan. During early Pennsylvanian time the conglomeratic sands of the Sharon conglomerate member of the Pottsville formation of Ohio and the Olean conglomerate member of the Pottsville formation of New York and Pennsylvania were derived from the north and northeast respectively. A logical source of these conglomerates may have been in part from older conglomerates of Berea age in Canada.

THE PALEOGRAPHIC MAP OF BEDFORD AND BEREA TIME

The paleogeography of Bedford and Berea time is the history of the Ohio Bay and its relation to a group of rapidly growing deltas that encroached upon it from the north, east, and southeast. In another sense it represents the dynamic equilibrium between the rate of subsidence of the floor of the Ohio Bay and the volume of sediment transported into the bay by several rivers. Although the transporting power of the waves and currents was sufficient to halt the eastward encroachment of the Red Bedford Delta at the line of the Second Berea bar, this power alone was entirely inadequate to remove detritus from the area of the Ohio Bay. Thus had it not been for the slow subsidence of the bay floor, the entire area would have been dry land at the close of Berea time, because of the great volume of sediment carried into the Ohio Bay. Instead, the gradual sinking of the bay floor provided space for the deposition of the sediment, and the seaway was maintained. Nevertheless, the rate of deposition was greater than the rate of subsidence until the middle of Berea time, when the influx of sediments decreased, and the rate of subsidence finally exceeded the rate of deposition.

The deposition of the Bedford and Berea sediments records one major regression of the sea in early Bedford time, followed by a gradual transgression of the sea throughout late Bedford time. Except for a brief reversal of direction in earliest Berea time this transgression continued to the close of Berea time. Figure 60 shows the relative position of the shoreline throughout the deposition of this series of sediments. The Ohio Bay of Bedford and Berea time, beginning as a stage of submergence, ended in submergence as well, but not until many land forms had been created and partly destroyed, leaving their enduring though fragmentary record in the rocks.

The series of nine paleogeographic maps depicts the most clearly discernible stages of the paleogeography of the Ohio Bay during Bedford and Berea time, as deduced from the geologic record. Insofar as possible, each map presents an instant in geologic time. The maps depict in nine steps the various noteworthy geographic features, most of which undergo some modification from one map to the next. Figure 61 shows the

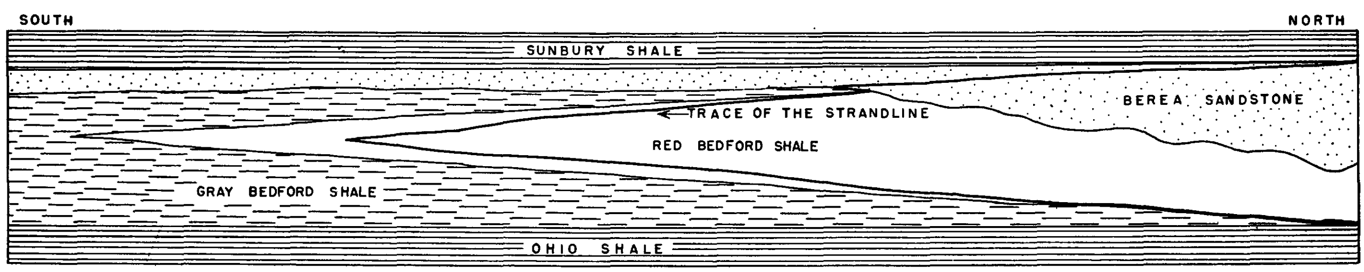


FIGURE 60.—A schematic cross section from Lorain County, Ohio, to Wayne County, W. Va., showing the relative position of the strand during the deposition of the Bedford and the Berea sediments. The heavy black line joins successive points occupied by the strand line; terrestrial and subaerial deposition occurred north of this line.

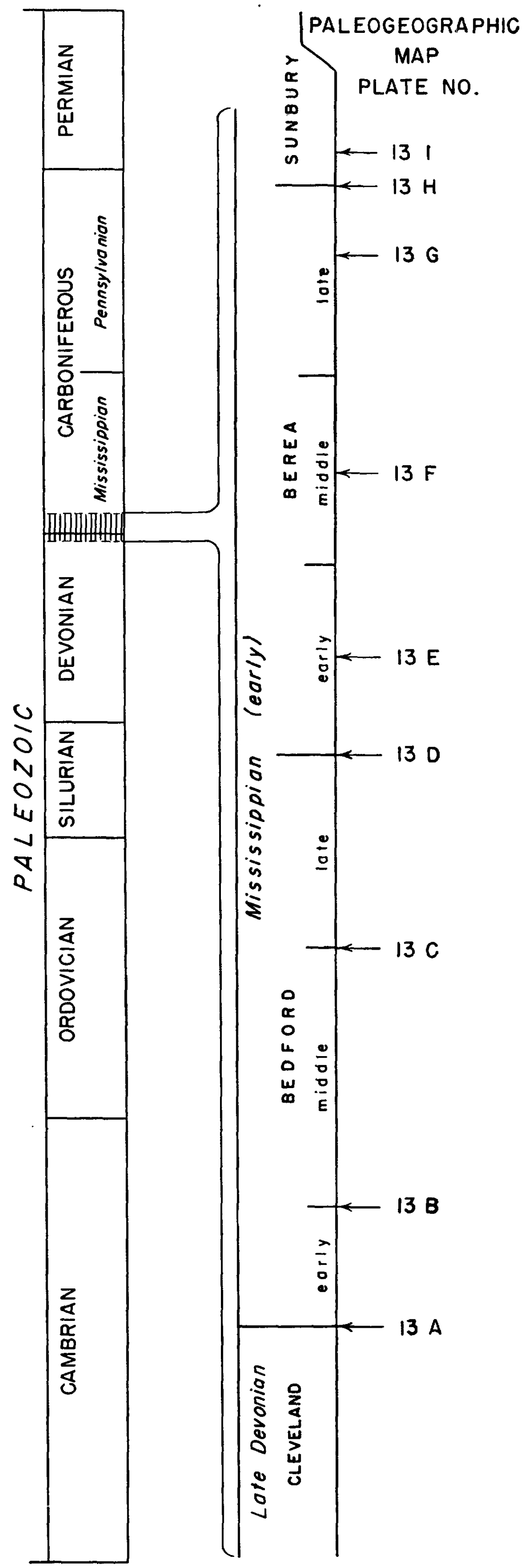


FIGURE 61.—Columnar section showing the relation of the nine paleogeographic maps (early Bedford to early Sunbury) to the Paleozoic time scale.

probable relation of the time covered by these nine maps to the Paleozoic time scale.

The purpose of the maps is to show graphically what the writers believe is the most likely picture of the paleogeography of Bedford and Berea time. These maps, drawn from basic data presented elsewhere in this paper, represent the writers' attempt to coordinate these data into a unified interpretation and to fill in the gaps where necessary with the most reasonable conjectures. Some of the larger features of the maps, most of which appear well substantiated, are Cincinnatia, the Red Bedford Delta, the Cussewago (Murrysville) Delta, the Berea Delta, the Gay-Fink Delta and Channel, the Cabin Creek Channel, the Second Berea bar, and the Ontario River. Other features are less well substantiated, though they appear to be nonetheless real. The Virginia-Carolina Delta and the Virginia-Carolina River (pl. 12) for example, are inferred mainly from the presence of Berea sand in wells in Wise County, Va. and the presence of thick siltstones of the Bedford and Berea projecting northwestward into the Ohio Bay from southwest Virginia. It is difficult to account for these deposits unless a delta and river system are postulated. A similar example is the Ashtabula River. Although the presence of an "Ashtabula River" was doubted in the early part of this investigation, no other way could be found to bring much of the silt and sand into the relatively isolated local basin area in Geauga, Portage, Stark, and Tuscarawas Counties, Ohio. Most of the smaller refinements in the maps are largely hypothetical, but a few, such as some of the channels in northern Ohio, parts of the Second Berea bar, and the main courses of the Gay-Fink and Cabin Creek Channels, are reasonably accurate.

PALEOGEOGRAPHY AT THE BEGINNING OF EARLY BEDFORD TIME

In early Bedford time the sea spread widely across most of Ohio, Kentucky, and West Virginia and into adjacent parts of Pennsylvania, Maryland and Virginia. (See pl. 13 *A*.) The water in the Ohio Bay was deepest in northern Kentucky and southern Ohio, but even here the greatest depth probably was not much in excess of 100 feet, and in much of the bay the water was less than 30 feet deep. The strait between Cincinnati (Wells, 1944, p. 287–289) and the Red Bedford Delta was probably shallow. A broad shoal in northeastern Ohio and northwestern Pennsylvania acted as a barrier to sediments, restricting the eastward spreading of mud and silt of the Bedford.

In early Bedford time the Cincinnati arch was low and was represented by a small low-lying island, Cincinnatia. This small marsh-fringed island separated the broad shallow Ohio Bay from the main epicontinental sea to the west. A wide shallow strait joined the Ohio and the Michigan Bays and separated Cincinnatia from the Red Bedford Delta which formed the northern shore of the Ohio Bay. This delta, which covered most of southwestern Ontario, was being built southward by the Ontario River. The Ontario River had its headwaters in the mountainous Acadian highlands and trended southwestward across Quebec and Ontario to the northern shore of the Ohio Bay. In early Bedford time the Ontario River was in maturity and transported a great amount of silt and mud into the Ohio Bay. Lying about 50 miles east of the Ontario River and essentially paralleling its lower course was the smaller Ashtabula River system. A broad shoal area occurred east of the Ashtabula River in the vicinity of the Ohio-Pennsylvania State line. This shallow area acted as a barrier to sediment and separated the Ohio Bay on the west from the Corry Bay on the east. This small bay was more or less isolated from the main part of the Ohio Bay throughout much of Bedford and Berea time. The Corry Bay covered parts of Chatauqua and Cattaraugus Counties, N. Y., and Crawford, Erie, Forest, McKean, Venango, and Warren Counties, Pa. It was bounded on the south by the Cussewago (Murrysville) Delta, which was being built toward the northwest across western Pennsylvania. The Cussewago (Murrysville) delta was the northernmost of a series of deltas which coalesced to form the eastern and southeastern rim of the Ohio Bay. From north to south the main deltas on the eastern side of the bay were the Cussewago (Murrysville), the Gay-Fink, the Cabin Creek, and the Virginia-Carolina. The Cussewago (Murrysville) River appears to have had its headwaters in Maryland and northern Virginia; the Gay-Fink River in central Virginia; the Cabin Creek River in central Virginia; and the Virginia-Carolina River in southern Virginia and northern North Carolina.

The Ontario River carried large amounts of mud and fine silt into the bay. The earliest Bedford sediments in northern Ohio are composed largely of dark-gray shales and thin intercalated siltstones. The sediment from the Ashtabula River contained more silt than that from the Ontario River, probably because the Ashtabula River was actively removing some of the beds of siltstone of the Chagrin shale north of Lake and Ashtabula Counties, Ohio. The sediment from the Cussewago (Murrysville) River was predominantly medium and coarse sands and some small pebbles. This sediment is coarsest in southern Pennsylvania in the vicinity of Johnstown, and becomes finer grained to the north and west. The rivers south of the Cussewago (Murrysville) Delta were carrying finer-grained sediment into the Ohio Bay. The basal Bedford sediments in southeastern Kentucky were made up almost exclusively of fine silt and silty gray mud.

The lands immediately adjacent to the Ohio Bay were low in early Bedford time, but to the east the hills of Appalachia were undergoing active erosion, as shown by the coarse sediments of central and western Pennsylvania. However, the greater part of these sediments was being derived by the erosion of older Paleozoic sedimentary series, and only a small amount of the rock may have been cut from the crystalline rocks in the core of Appalachia.

PALEOGEOGRAPHY OF EARLY BEDFORD TIME

By the middle of early Bedford time, the sea was greatly reduced in area in the Ohio Bay. Delta building was progressing rapidly and deposition was greatly in excess of subsidence throughout most of the area of the bay. (See pl. 13 *B*.)

Less than one-half of the area of the bay that was flooded at the beginning of Bedford time was covered by the middle of early Bedford time. In the two narrow arms of the bay in northern Ohio, the water was very shallow and in much of the rest of the bay the depth of water probably did not greatly exceed 25 feet. The mouth of the bay in southern Kentucky probably contained the deepest water, for apparently black mud was being deposited there throughout early Bedford time.

Slight upwarp of the edges of the bay occurred, and Cincinnatia was elevated sufficiently to separate the Michigan Bay and the Ohio Bay by a narrow neck of low swampy land. Cincinnatia increased in size and many of the peripheral marshes now formed a broad coastal plain. The Red Bedford Delta was increasing greatly in size, but as yet it had not attained its maximum size. Several offshore or barrier bars were being built along the sides of the Red Bedford Delta and had almost reached their greatest size. Two barrier bars, the Euclid of Cuyahoga County and the Second Berea of southeastern Ohio, have been preserved, but along the eastern side of the Red Bedford Delta post-Bedford scour removed the sand deposited intermediate between the two. The delta formed by the Ashtabula River was much smaller than the Red Bedford Delta.

The Cussewago (Murrysville) Delta reached its maximum size during early Bedford time and extended across the mouth of the Corry Bay to impinge upon the extreme eastern end of the delta of the Ashtabula River. Thus the Corry Bay was temporarily converted into a broad land-locked lake. The Cussewago (Murrysville) Delta extended into northeastern Ohio covering parts of Ashtabula, Carroll, Columbiana, Mahoning, and Trumbull Counties. The delta also expanded to the south in Pennsylvania, and in northwestern West Virginia the southern front of the Cussewago (Murrysville) Delta coalesced with the northern front of the Gay-Fink Delta. The Gay-Fink and Cabin Creek Deltas were smaller than the Cussewago (Murrysville) Delta, probably because their master streams carried less sediment into the bay. The Virginia-Carolina River was actively building its delta northwestward across southwestern Virginia and into southwestern West Virginia.

Because Cincinnatia was relatively low-lying, little sediment was carried eastward from this land area into the Ohio Bay. However, the maximum amount of mud which might possibly be derived from Cincinnatia would be very small compared to the vast quantities of mud and silt carried by the Ontario River. The bulk of this sediment carried into the Ohio Bay by the Ontario River was red mud. Some silt and fine sand were transported along the main distributary channels of this river and were deposited either in the abandoned parts of the distributary channels or in the bay at the channel mouths. Largely along the east side of the Red Bedford Delta the waves and currents winnowed the silt from the mud and constructed offshore or barrier bars essentially parallel to the existing shoreline. Apparently both the Ontario and Ashtabula Rivers supplied silt, for the Euclid member appears to be made up largely of silt carried into the upper end of the bay by the Ashtabula River and transported into the present position by the long-shore current. The silt which composes the Second Berea bar was apparently supplied by the Ontario River. Probably some bar building occurred on the western side of the Red Bedford Delta, but subsequent erosion has cut away the western part of the delta as far south as southern Delaware County, thus removing the sedimentary record of the Bedford in this area.

PALEOGEOGRAPHY AT THE BEGINNING OF LATE BEDFORD TIME

At the beginning of late Bedford time the configuration of the shoreline of the Bedford sea in the Ohio Bay was very similar to that in middle Bedford time. (See pl. 13 *C*.) The greatest change occurred in the northeastern part of the bay where the rate of subsidence of the bay floor exceeded the rate of deposition on the Cussewago (Murrysville) Delta. There the shoreline retreated to the east before a transgressing sea which increased the width of the eastern arm of the bay. The sea flooded a slightly larger amount of the total area than in middle Bedford time. Although the water remained very shallow in much of the northern part of the bay, subsidence in the small basin in Stark and Tuscarawas Counties deepened the water adjacent to the northeastern flank of the Red Bedford Delta. Probably the depth of water covering this small basin did not exceed 100 feet but was greater than the average depth of the Ohio Bay. The western arm of the bay lying between Cincinnatia and the Red Bedford Delta was extremely shallow and at times may have been little more than a vast salt-water marsh.

The general shape and size of Cincinnatia had not changed greatly from middle Bedford time. Continued silting in the northern part of the adjacent arm of the bay and a brief retreat of the sea made the neck of land connecting Cincinnatia and the Bedford land area to the north less swampy. Except for this slight change Cincinnatia remained relatively unaltered. The Red Bedford Delta reached its maximum size in the early part of late Bedford time. It extended southward across Ohio into Boyd County, Ky., and Cabell County, W. Va. Along the eastern side of the delta, the red mud filled the lagoons and covered the fringing offshore bars that formed in early Bedford time. A part of the silt load of the Ontario River filled the abandoned parts of the distributary system which fanned out on the delta surface.

The delta of the Ashtabula River remained small, and most of the mud and silt carried into the Ohio Bay by this smaller river were trapped in the slowly subsiding basin in Stark and Tuscarawas Counties. As a result of the retreat of the Cussewago (Murrysville) Delta front which had been in progress since late middle Bedford time, the late Bedford sea breached the barrier between the Ohio Bay and the Corry Bay, although the water remained very shallow across the connecting strait.

Along the eastern side of the Ohio Bay the delta fronts were driven landward by a transgressing sea, and erosion had begun to destroy the periphery of the deltas.

Although the Ontario River continued to carry vast amounts of red mud and some silt into the bay, the sediments transported by the Ashtabula River contained a great deal more silt. Probably the load of the Ashtabula River was composed of almost equal amounts of mud and quartz silt. The stream that had built the Cussewago (Murrysville) Delta now was supplying only small amounts of sand and silt to the northeastern part of the Ohio Bay, and wave and current erosion was slowly destroying the delta front. The retreat of the fronts of the Gay-Fink and Cabin Creek Deltas was less rapid than the Cussewago (Murrysville), and their major streams continued to transport some sand and silt to the bay.

PALEOGEOGRAPHY AT THE END OF LATE BEDFORD TIME

Near the end of late Bedford time the sea again spread widely across the Ohio Bay because the rate of subsidence of the bay exceeded the rate of deposition. (See pl. 13 *D*.) Excepting the configuration of the Cincinnatia peninsula, the shoreline was changed and driven landward by a transgressing late Bedford sea. The shape of the Red Bedford Delta was greatly changed, for the southern half of the delta was covered by the sea and many estuaries indented the part of the delta remaining above water. The strait joining the Corry Bay to the Ohio Bay was wider, but the water remained shallow in the strait. The eastern shore of the Ohio Bay was straightened by the erosion of the delta fronts as the Bedford sea moved eastward. A slight increase in the average depth of water accompanied the extensive flooding of the bay. However, the ripple-marked siltstones in the upper part of the Bedford in southern Ohio indicate that the depth of water probably did not exceed 150 feet.

The shape of Cincinnatia had not changed greatly from middle Bedford time. A decreasing amount of sediment was carried into the Ohio Bay by the Ontario River, and a large marsh formed which separated Cincinnatia from the Red Bedford Delta. The southern half of the Red Bedford Delta was covered by the transgressing sea, and the Ontario River backfilled with silt and fine sand many of its distributary channels in the northern part of the delta, thus preserving much of the channel system of this vast delta. The Ashtabula River continued to carry some silt and mud into the Ohio Bay but in decreasing amounts. In the eastern part of the Corry Bay the lowest beds of the Corry sandstone were being deposited. Erosion straightened the shoreline along the eastern side of the Ohio Bay, and the Cussewago (Murrysville), Gay-Fink, Cabin Creek, and Virginia-Carolina Deltas were being dissected by the advancing sea in late Bedford time. Most of the sediment cut from these deltas was spread in a thin layer over the eastern part of the Ohio Bay. Very little sediment was being carried into the bay by these eastern rivers.

PALEOGEOGRAPHY OF EARLY BEREA TIME

An upwarp in southern Ontario and northern Ohio in latest Bedford time caused the regression of the widespread late Bedford sea. (See pl. 13 *E*.) The early Berea sea which followed was about two-thirds the size of its immediate predecessor and was bordered by a broad strip of low-lying coastal plain. Adjacent to the newly exposed coastal plain the sea was extremely shallow. In northeastern Ohio sun cracks in the lower part of the Berea sandstone show that at times the sea withdrew and exposed these sand flats. Probably the depth of water did not exceed 10 feet over much of this area. Elsewhere the depth of water probably did not exceed 50 feet, except in the deeper parts of the bay in southeastern Ohio and in the locally subsiding basin area of Stark and Tuscarawas Counties. The shallow strait that connected the Corry Bay to the Ohio Bay throughout much of Bedford time was closed by the upwarp at the end of Bedford time. The Corry Bay was separated from the Ohio Bay by a narrow, low neck of marshy land which in part prevented the mixing of Berea and Corry sediments.

Cincinnatia was a broad low peninsula. A few small hills about 100 feet above sea level were present in the northern part. Small sluggish streams flowed eastward from these hills carrying a little mud into the bay. Most of this mud was derived from the erosion of the Upper Devonian shales which extended across the arch, although some of the sediment may have been derived from the limestones exposed along the crest of Cincinnatia. The volume of sediment derived from Cincinnatia was small when compared to the vast amounts of sand, silt, and mud soon to be carried into the bay by the rejuvenated Ontario River.

Uplift in late Bedford time was sufficient to rejuvenate the Ontario River over much of its lower course. The winding meander-pattern of the distributary channels was incised deeply into and in some places through the Bedford and Cleveland sediments. Rejuvenation and erosion were brought about not only by uplift but also by the Ontario River abandoning its old distributary system on the Red Bedford Delta and breaking into the area of the slowly subsiding basin in the area of Stark and Tuscarawas Counties. This shortening of the river course aided in downcutting the distributary channels north of the break-out and completed the silting up of the old channel system south of the point of rupture. Erosion along the eastern margin of the Red Bedford Delta near the break-out produced a large reentrant (fig. 31) in the configuration of the delta, and completely obliterated any trace of the bar deposits that one time may have linked the Euclid and the Second Berea bars.

Some of the water of the Ontario River was discharged into the Ashtabula River in flood seasons prior to the incisement, and by the time that the rejuvenation and channeling occurred, the lower reaches of Ashtabula River had become a part of the Ontario distributary system.

By early Berea time the period of emergence and scour was completed, and sand was being deposited in the deeper channels as both the Ontario River and the recently captured Ashtabula River built their deltas southward into the Ohio Bay. Silt and sand were being laid down in the eastern part of the Corry Lake, but little sediment was carried into the western part of this lake.

Upwarp occurred in Virginia and eastern West Virginia at the end of Bedford time, pushing the early Berea shoreline far to the west of the position occupied by the late Bedford shoreline. The major streams, which flowed into the Ohio Bay from the east, cut channels in the newly exposed coastal plain. These channels were deepest along the inner side of the coastal belt and merged into normal marine deposition along the shoreline. The Cussewago (Murrysville) River was greatly reduced in size probably as a result of drainage changes in the area of northern Virginia. The Gay-Fink and Cabin Creek Rivers were depositing pebbles, sand, and some silt along their main channels, and the sediment of the Virginia-Carolina delta was predominantly fine sand and silt. The available data do not show the position of the channel of the Virginia-Carolina delta. Presumably it lay in southern West Virginia and the adjacent part of Virginia.

Possibly the uplift in West Virginia beheaded the northwest-trending Cussewago (Murrysville) River while increasing the cutting and carrying power of both the Gay-Fink and Cabin Creek Rivers.

Deposition of sand occurred in northern Ohio along the delta front and the main stream channels on the eastern side of the Ohio Bay; elsewhere throughout much of the bay the sediment of the basal part of the Berea was similar to the sediment of the upper part of the Bedford. At some places the silt in the basal Berea is only slightly coarser grained than the silt in the upper part of the Bedford. Except for peripheral scour and channeling, deposition was continuous in the Ohio Bay from late Bedford through early Berea time.

PALEOGEOGRAPHY OF MIDDLE BEREA TIME

In middle Berea time the sea was larger than it had been in early Berea time. (See pl. 13 *F*.) All the shorelines except the Berea Delta were driven back by the slowly transgressing sea. The lower reaches of most of the streams that emptied into the bay were drowned and the coast lines became more irregular. The peninsula of Cincinnatia decreased in width and many marshes formed along the small water courses of this peninsula. Only along the Berea Delta was the shoreline stable or advancing seaward at a slow rate. The narrow neck of land that separated the Corry Lake from the Ohio Bay vanished, and a narrow marshy pass replaced the land. Slow sinking and valley drowning produced an irregular coast line along the eastern side of the bay. Offshore bars and submerged sand banks formed near the mouths of the Gay-Fink and Cabin Creek Rivers, although elsewhere only small amounts of sand were deposited at the waters' edge. The depth of water in the Ohio Bay increased only slightly. Probably the water was not over 100 feet deep except in the deepest parts of the bay. Oscillation ripple marks observed along the outcrop of the Berea sandstone in southern and central Ohio show that the water covering this part of the bay probably ranged from 5 to 25 feet in depth.

In most of the Ohio Bay during middle Berea time the rate of sinking of the basin exceeded the rate of deposition from the adjacent land areas. The width of Cincinnatia was greatly decreased and a large swampy valley partly separated Cincinnatia from the Berea Delta. The sea drowned most of the lower parts of the small consequent streams that drained Cincinnatia and marshes formed in these small estuaries. Subsidence of Cincinnatia was more rapid in the northern part than in the more stable central and southern parts.

Deposition along the front of the main Berea Delta equaled or exceeded the subsidence of the basin. Thus the size of the delta changed very little. The bays between the distributary channels tended to enlarge headwards slowly until a break-out along the edge of a distributary filled them. Some peripheral sand bars and low shoals similar to the Chandeleur Islands off the present Mississippi Delta formed during this time. Channel filling had been completed except in the northern part of the delta area in Ontario. The distributary streams, having filled their confining channels, meandered across the Berea Delta and deposited the lower part of the sheet sand phase of the Berea in northern Ohio. Some delta lakes formed, and fine silt, mud, and plant debris were deposited on the bottoms of these lakes. These small lakes were in part soon destroyed by the meandering streams.

East of the Berea Delta only slight subsidence occurred. The land barrier between the Ohio and the Corry Bays sank slightly below sea level, and a shallow swamp-bordered strait connected the two bodies of water. South of this pass into the Corry Bay the once relatively smooth eastern shore of the Ohio Bay had become more irregular as the shoreline was driven eastward by the advancing sea, which drowned the mouths of the Gay-Fink and Cabin Creek Rivers. Some of the sand carried into the bay by these rivers was reworked into offshore bars and shoals near the river mouths. In late middle Berea time, the major rivers began to back-fill their channels as the gradient of the rivers decreased.

A little medium and coarse sand was carried into the bay by the Ontario, Gay-Fink, and Cabin Creek Rivers, but most of the sediment deposited in middle Berea time was fine sand and siltstone. Uniform conditions of deposition existed throughout most of the bay. Finer materials were deposited in the deeper waters in eastern Kentucky and southeastern Ohio.

PALEOGEOGRAPHY OF LATE BEREA TIME

Continued subsidence of the Appalachian basin in late Berea time increased the size of the Berea sea. (See pl. 13 *G*.) The water around the periphery of the Ohio Bay remained shallow, but because of the slight elevation of the surrounding lands a small rise in sea level inundated a large area. The shoreline of Cincinnatia became more irregular than it had been in middle Berea time, and although predominantly a shallow marsh, the seaway between the Ohio and Michigan Bays was reestablished. The shoreline of the Berea Delta was driven northward by the sea until only a small area covering parts of Cuyahoga, Lake, and Lorain Counties was exposed. A broad bay lay between the eastern side of the shrinking Berea Delta and the shoal water of northwestern Pennsylvania. The strait that connected the Ohio Bay and the Corry Bay increased in width but remained very shallow. The eastern shoreline of the Ohio Bay continued its retreat to the east as the sea encroached upon the flat land which rimmed the bay on the east.

Late Berea time was one of subsidence and flooding. Cincinnatia was detached from the Berea Delta by a narrow strait which connected the seas in the Ohio and Michigan Bays. Continued sinking of the area of the Ohio Bay subdivided Cincinnatia, over-running the low areas and forming isolated islands of the slightly dissected hills. Decrease in the rate of deposition by the Ontario River resulted in the flooding of much of the Berea Delta. Sufficient fine sand and silt were carried in by the Ontario River to make a shoreline in extreme northern Ohio, but the sea covered most of the once extensive Berea Delta. Little sinking occurred in the shoal area of northwestern Pennsylvania. Although a silt facies of the Berea sandstone was deposited in western Crawford County and sand and silt of the Corry sandstone were deposited at the same time in eastern Crawford County, only a small amount of sediment was deposited in the shoal area. At this time some of the fauna of the Corry spread westward from the vicinity of Corry, Pa., and became established in a small area in northeastern Ohio in the vicinity of Kinsman and Williamsfield. The lower beds of the Hungry Run sandstone member of the Orangeville shale of Erie County, Pa., may have been deposited along the northern shore of the Corry Bay near the end of Berea time, although the exact time of this depostion has not been determined.

The eastern shore of the Ohio Bay changed only in that it was driven farther to the east by the transgressing sea. The Gay-Fink and Cabin Creek Rivers and presumably the Virginia-Carolina River continued to back-fill their channels during this time and only small amounts of sand and silt were carried into the bay from the east. The shallow sea which spread along the eastern part of the bay was an area of little deposition. The sediment that was carried into this area was reworked by waves and carried out to the quieter and deeper waters in eastern Kentucky and southern Ohio. A few incipient sand bars were formed in the shallow-water zone, but the Berea was not deposited as a uniform sheet sand over the area of central West Virginia.

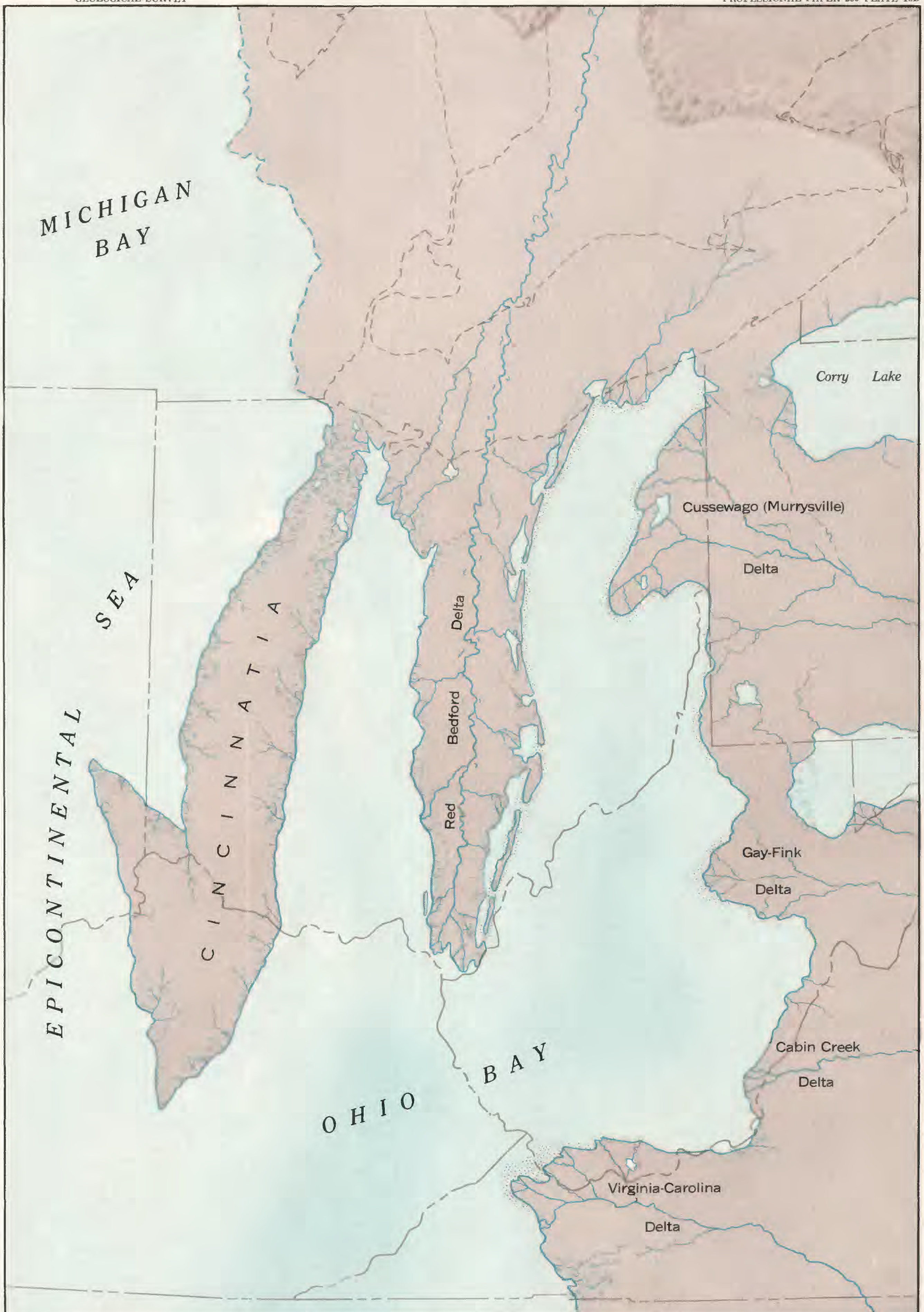
Late Berea time was one of reworking of sediments, and the extensive sheet sand which covers most of central and eastern Ohio, eastern Kentucky, western Pennsylvania, and western West Virginia was reworked and spread at this time. As the Ohio Bay deepened and widened, currents became more effective in shifting sediments, and the increased wave size aided in reworking the existing sediment. The more massive beds of siltstone and the fewer oscillation ripple marks in the outcrops of the Berea in southern Ohio show the change in depositional conditions which occurred in late Berea time.

PALEOGEOGRAPHY OF LATEST BEREA TIME

In latest Berea time the flooding was the greatest of all Bedford and Berea inundations. (See pl. 13 *H*.) Cincinnatia consisted of a chain of low swampy islands separated from the small Berea Delta by a wide but relatively shallow seaway that connected the Ohio and Michigan Bays. The shoreline of the Berea Delta was pushed back farther to the north and the shoal area separating the Corry Bay and the Ohio Bay had increased in width although not in depth. The eastern shoreline of the Ohio Bay, which had been retreating steadily since the end of early Berea time, was driven back to eastern West Virginia. Except for the peripheral shoals around the Berea Delta and the shoal area in northwestern Pennsylvania, the water of the Ohio Bay increased in depth. In the deeper parts of the bay in eastern Kentucky and southeastern Ohio the water was probably more than 150 feet in depth.

Slow sinking of the Cincinnati arch had reduced Cincinnatia to a group of small swampy islands and swamp-covered shoals. The Berea Delta was greatly reduced in size, and the Ontario River carried predominantly fine silt and some mud into the bay. An area characterized by small-scale scour and fill existed along the edge of the Berea Delta in Newburg Township, Cuyahoga County. A broad bay extended from the eastern shore of the rapidly dwindling Berea Delta to the shoal area of northwestern Pennsylvania. The shoal area remained a barrier to the exchange of sediment between the Corry Bay and the Ohio Bay, although the Corry fauna had migrated westward across this area in late Berea time. The rivers along the eastern shore of the Ohio Bay supplied very little sediment to the bay. Some fine sand and silt

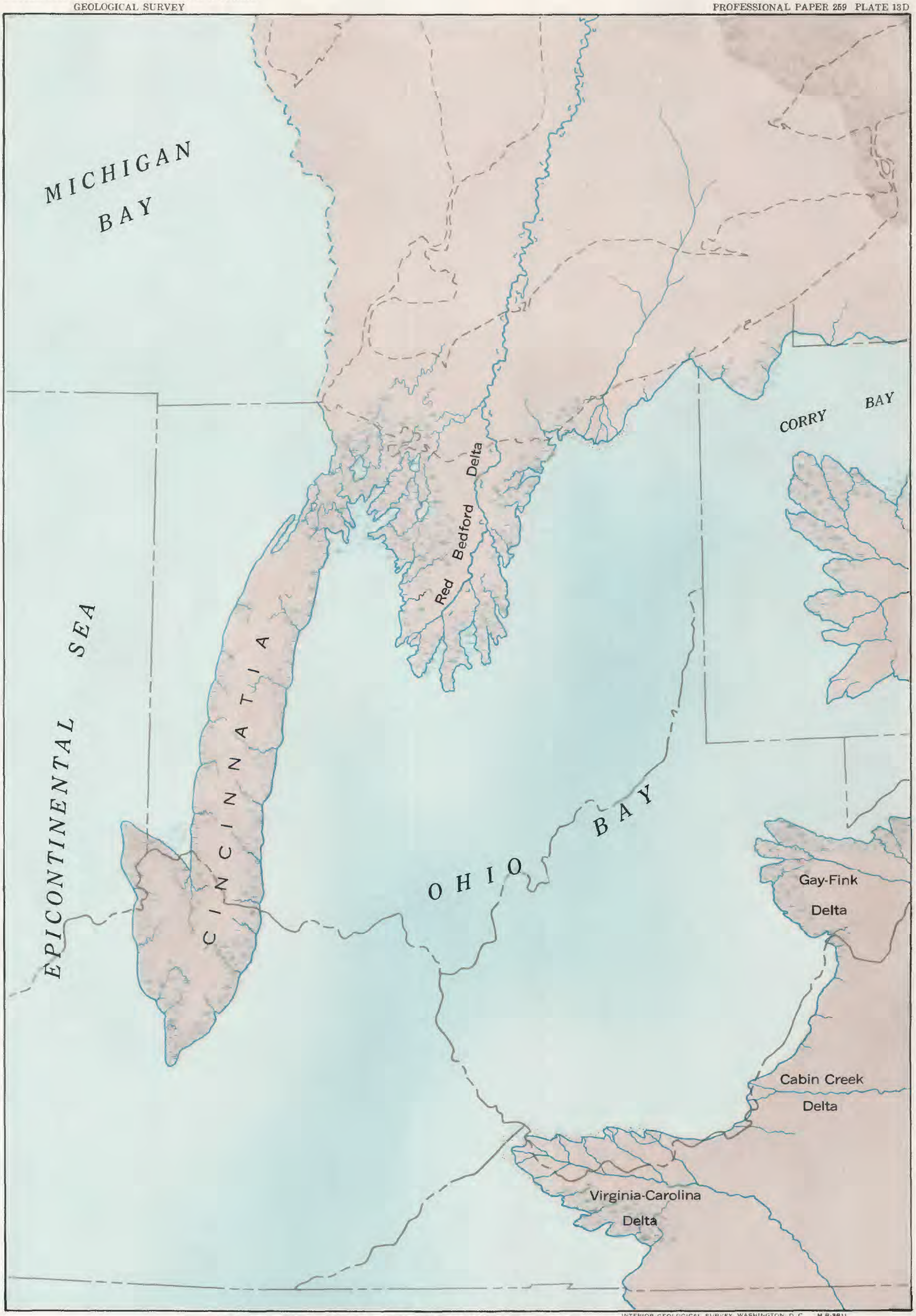
PALEOGEOGRAPHIC MAP OF BEGINNING OF EARLY BEDFORD TIME



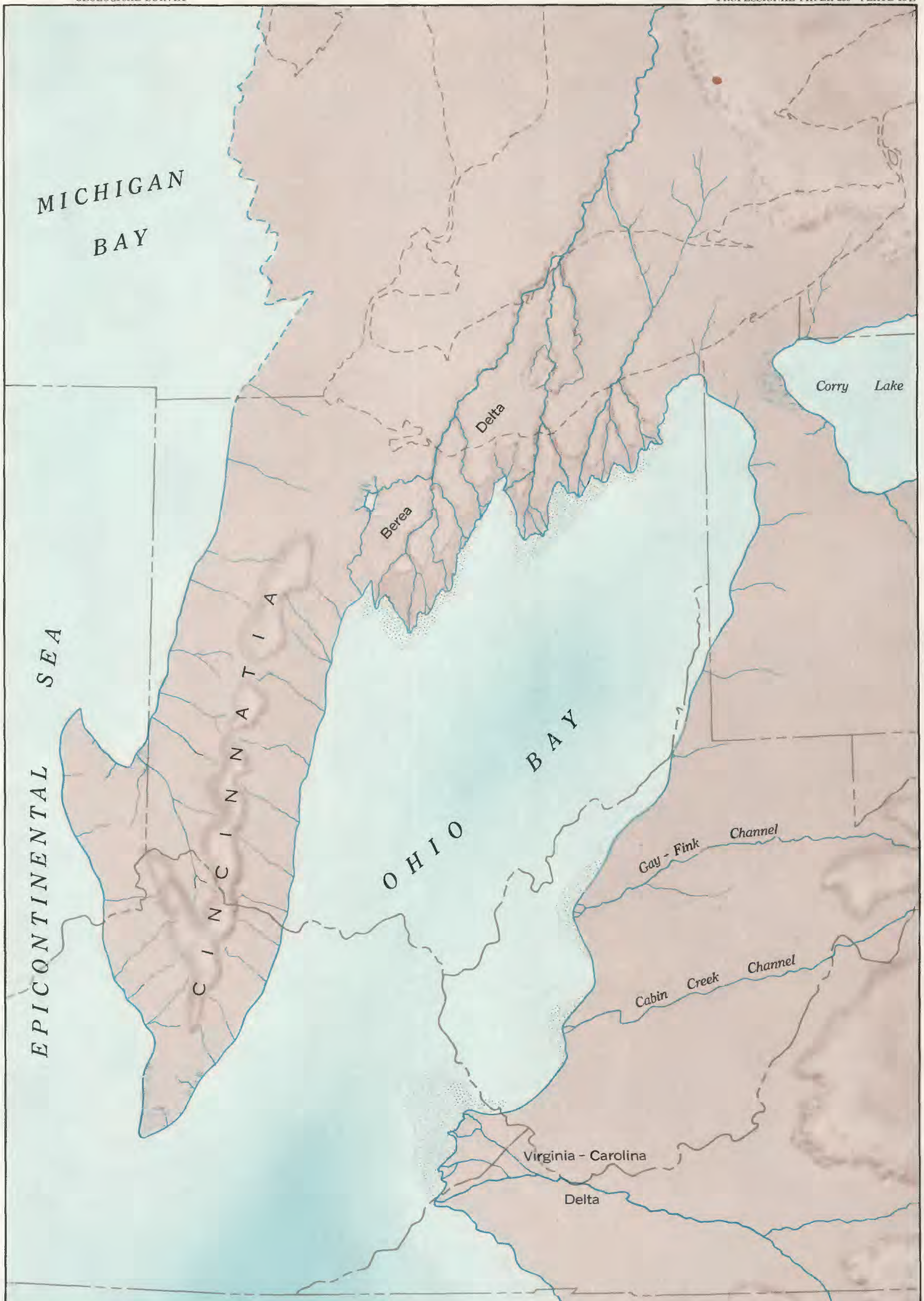
PALEOGEOGRAPHIC MAP OF EARLY BEDFORD TIME

INTERIOR-GEOLOGICAL SURVEY, WASHINGTON, D. C. M R-3811

PALEOGEOGRAPHIC MAP OF BEGINNING OF LATE BEDFORD TIME

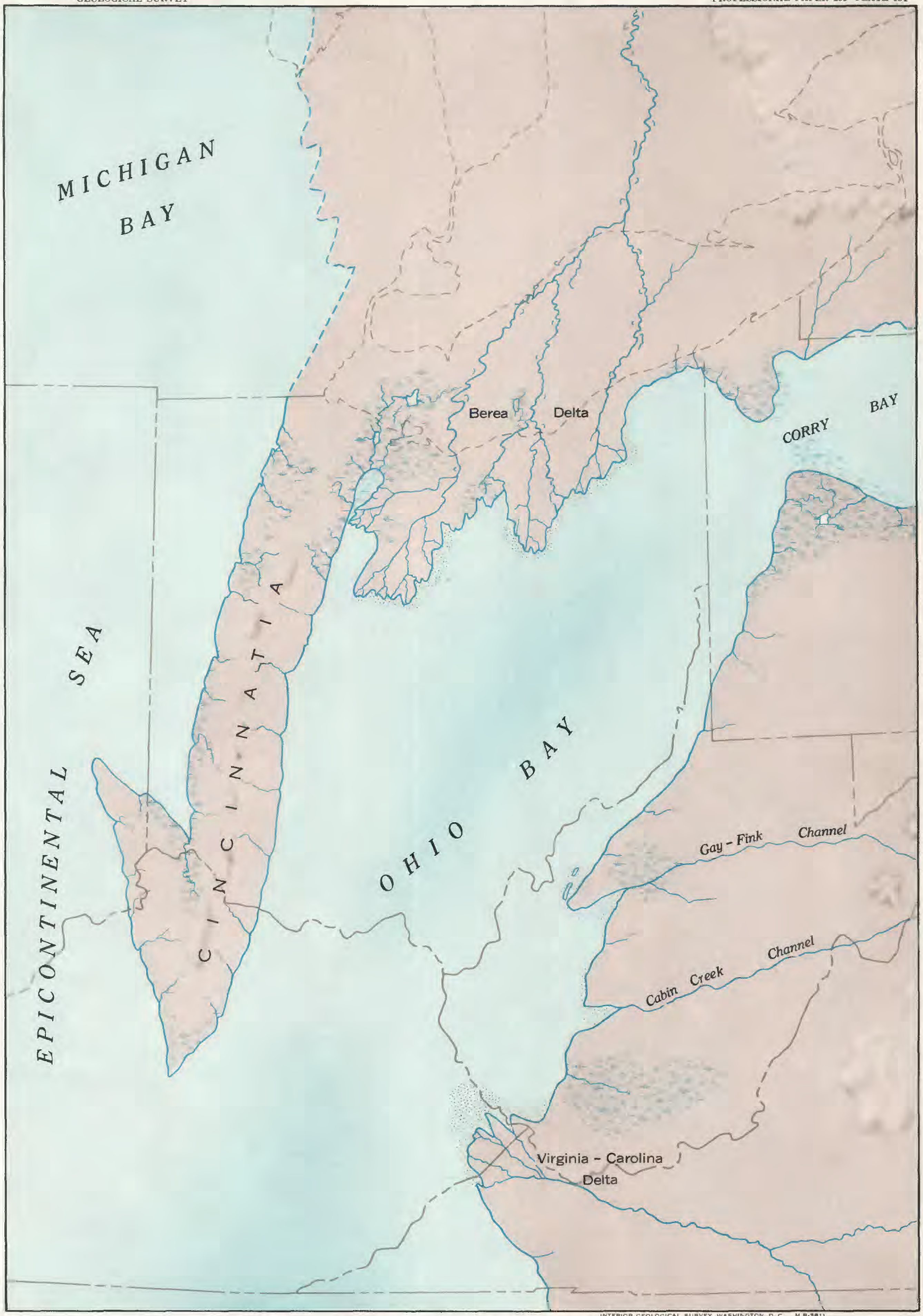


PALEOGEOGRAPHIC MAP OF END OF LATE BEDFORD TIME



INTERIOR-GEOLOGICAL SURVEY, WASHINGTON, D. C. M R-3811

PALEOGEOGRAPHIC MAP OF EARLY BEREA TIME

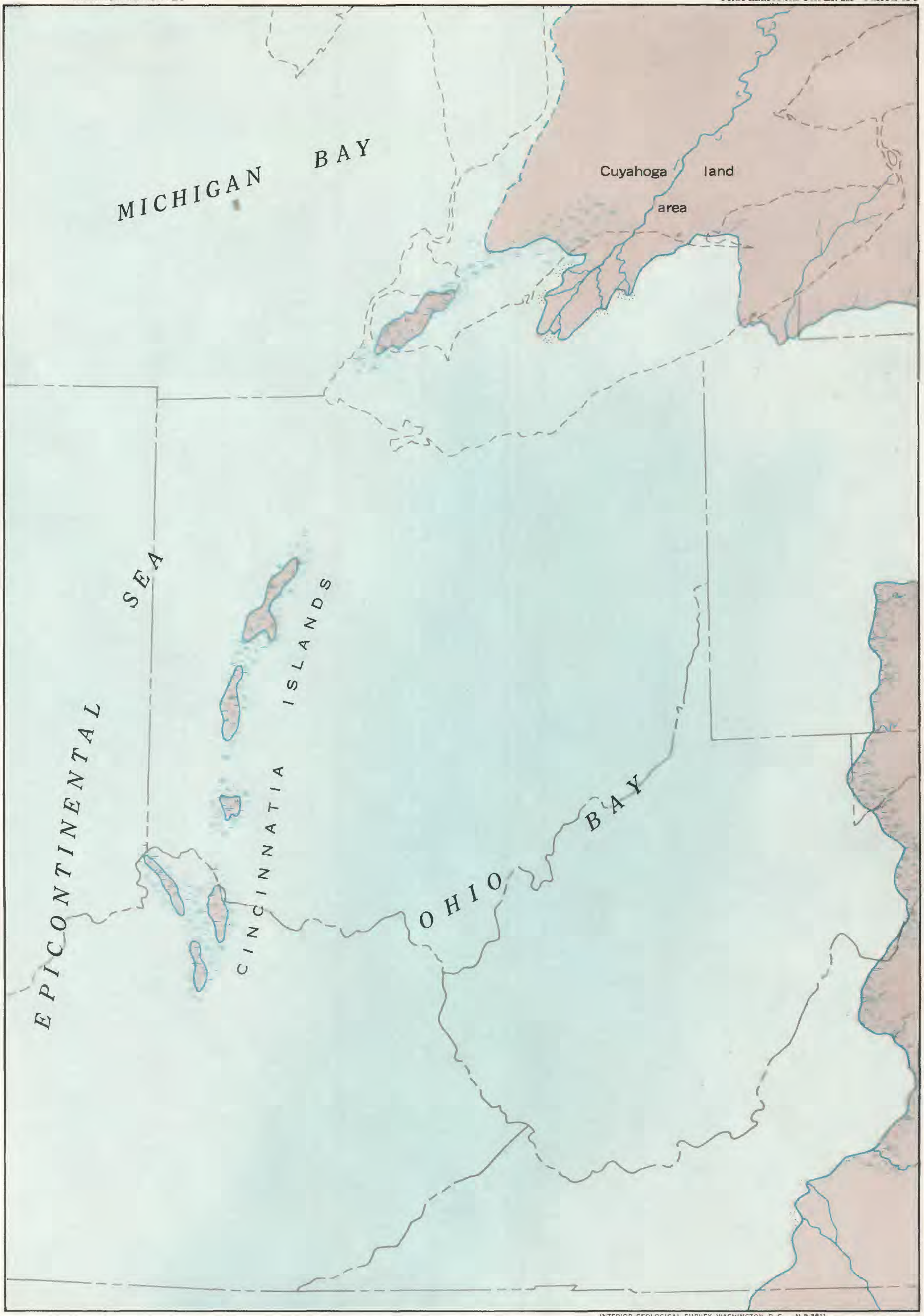


PALEOGEOGRAPHIC MAP OF MIDDLE BEREA TIME

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D. C. M R-3811

PALEOGEOGRAPHIC MAP OF LATE BEREA TIME

PALEOGEOGRAPHIC MAP OF LATEST BEREA TIME



PALEOGEOGRAPHIC MAP OF SUNBURY TIME

were being transported down the river channels, but much of this sediment was trapped in the back-filling of the river channels.

A cap of silt was spread over the Berea sand at many places in latest Berea time. This siltstone cap can be seen in exposures in Newburg Township, Cuyahoga County, and is recorded from many wells in the Chatham-Lodi oil field.

PALEOGEOGRAPHY OF SUNBURY TIME

By early Sunbury time the sea had spread widely across Ohio, Kentucky, West Virginia, and eastern Pennsylvania. (See pl. 13 *I*.) The delta front in West Virginia and the Berea Delta in Ontario were inundated, and the land area of Cincinnatia had been further reduced in size. After the sea reached maximum flood a period of stagnation took place. Little sediment was carried into the sea, and marine plant life apparently flourished. Black mud was deposited over most of the area covered by the Sunbury sea from Kentucky northward across Ohio and into Michigan and from the Cincinnati arch to Pennsylvania and into West Virginia. This deposition of carbonaceous black mud of Sunbury age which followed the Bedford and Berea cycle of deposition indicates a return to a tranquil shallow sea in the Ohio Bay similar to the sea which deposited the black Ohio shale, of Devonian age, just prior to Bedford time.

LITERATURE CITED

Andrews, E. B., 1870, Report of progress in the second district: Ohio Geol. Survey (Rept. Progress, 1869), pt. 2, p. 55–135.

Barrell, Joseph, 1912, Criteria for the recognition of ancient delta deposits: Geol. Soc. America Bull., v. 23, p. 377–446.

Bownocker, J. A., 1915, Building stones of Ohio: Ohio Geol. Survey, 4th ser., Bull. 18.

Briggs, Charles, Jr., 1838, Report (Scioto and Hocking valleys): Ohio Geol. Survey, 1st Ann. Rept., pl. 1, p. 71–98.

Bucher, W. H., 1919, On ripples and related sedimentary surface forms and their paleogeographic interpretation: Am. Jour. Sci., 4th ser., v. 47, p. 149–210, 241–269.

Burroughs, W. G., 1911, The unconformity between the Bedford and Berea formations of northern Ohio: Jour. Geology, v. 19, p. 655–659.

———1913, Economic geology of the Berea sandstone formation of northern Ohio: Econ. Geology, v. 8, p. 469–481.

———1914, Berea sandstone in eroded Cleveland shale: Jour. Geology, v. 22, p. 766–771.

Butts, Charles, 1910, Description of the Warren quadrangle, Pa.-N. Y.: U. S. Geol. Survey Geol. Atlas, folio 172.

———1922, The Mississippian series of eastern Kentucky; a regional interpretation of the stratigraphic relations of the Subcarboniferous group based on new and detailed field examinations: Kentucky Geol. Survey, ser. 6, v. 7.

Carll, J. F., 1890, Seventh report on the oil and gas fields of western Pennsylvania: Pennsylvania 2d Geol. Survey, 15.

Carman, J. E., 1947, Geologic section of the Chillicothe test-core: Ohio Jour. Sci., v. 47, p. 49–54.

Caster, K. E., 1933, Stratigraphic relationships in northwestern Pennsylvania [abs.]: Geol. Soc. America Bull., v. 44, pt. 1, p. 202–203.

———1934, The stratigraphy and paleontology of northwestern Pennsylvania; Part 1, Stratigraphy: Bull. Am. Paleontology, v. 21, no. 71.

Cathcart, S. H., Sherrill, R. E., and Matteson, L. S., 1938, Geology of the oil and gas fields of the Tidioute quadrangle, Pa.: Pa. Topog. and Geol. Survey Bull. 118, Advance rept.

Chadwick, G. H., 1923, Chemung stratigraphy in western New York [abs.]: Geol. Soc. America Bull., v. 34, p. 68–69.

———1925, Chagrin formation of Ohio: Geol. Soc. America Bull., v. 36, p. 455–464.

———1931, Storm rollers [abs.]: Geol. Soc. America Bull., v. 42, p. 242.

———1933a, Great Catskill delta, and revision of late Devonic succession: Pan-Am. Geologist, v. 60, 2, Areal refinements, no. 3, p. 189–204.

———1933b, Great Catskill delta, and revision of late Devonic succession: Pan-Am. Geologist, v. 60, 3, Revised correlations, no. 4, p. 275–286.

Cohee, G. V., and Underwood, L. B., 1944, Maps and sections of the Berea sandstone in eastern Michigan: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 17.

Cooper, G. A., and others, 1942, Correlation of the Devonian sedimentary formations of North America (Chart no. 4): Geol. Soc. America Bull., v. 53, pt. 1, p. 1729–1793.

Cooper, J. R., 1943, Flow structures in the Berea sandstone and Bedford shale of central Ohio: Jour. Geology, v. 51, p. 190–203.

Cushing, H. P., 1888, Notes on the Berea grit in northeastern Ohio: Am. Assoc. Proc. 36, p. 213–215.

——— 1912, The age of the Cleveland shale of Ohio: Am. Jour. Sci., 4th ser., v. 33, p. 581–584.

Cushing, H. P., Leverett, Frank, and Van Horn, F. R., 1931, Geology and mineral resources of the Cleveland district, Ohio: U. S. Geol. Survey Bull. 818.

Demarest, D. F., 1946, Map of the Berea and Murrysville sands of northeastern Ohio, western Pennsylvania, and northernmost West Virginia: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 49.

de Witt, Wallace, Jr., 1946, The stratigraphic relationship of the Berea, Corry, and Cussewago sandstones in northeastern Ohio and northwestern Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Chart 21.

——— 1951, Stratigraphy of the Berea sandstone and associated rocks in northeastern Ohio and northwestern Pennsylvania: Geol. Soc. America Bull., v. 62, p. 1347–1370.

Dickey, P. A., 1941, Oil geology of the Titusville quadrangle, Pa.: Pa. Topog. and Geol. Survey Bull. M-22.

Dickey, P. A., Sherrill, R. E., and Matteson, L. S., 1943, Oil and gas geology of the Oil City quadrangle, Pa.: Pa. Topog. and Geol. Survey Bull. M–25.

Fettke, C. R., 1941, Subsurface sections across western Pennsylvania: Pa. Topog. and Geol. Survey Progress Rept. 127.

Fettke, C. R., and Bayles, R. E., 1945, Conemaugh Gorge section of the Mississippian system southeast of Cramer, Pa.: Pa. Acad. Sci. Proc., v. 19, p. 86–95.

Foerste, A. F., 1902, The Cincinnati anticline in southern Kentucky: Am. Geol., v. 30, p. 359–369.

Girty, G. H., 1905, The relations of some Carboniferous faunas: Washington Acad. Sci. Proc., v. 7, p. 1–26.

——— 1912, Geologic age of the Bedford shale of Ohio: New York Acad. Sci. Annals, v. 22, p. 295–319.

Glenn, L. C., 1903, Devonic and Carbonic formations of southwestern New York: N. Y. State Mus. Bull. 69, p. 967–989.

Hass, W. H., 1947, Conodont zones in Upper Devonian and lower Mississippian formations of Ohio: Jour. Paleontology, v. 21, p. 131–141.

Hayes, C. W., 1891, The overthrust faults of the southern Appalachians (with discussion by C. D. Walcott, W. M. Davis, and Bailey Willis): Geol. Soc. America Bull., v. 2, p. 141–154.

Heck, E. T., 1941, Gay-Spencer-Richardson oil and gas trend, Jackson, Roane, and Calhoun Counties, W. Va., *in* Levorsen, A. I., and others, Stratigraphic type oil fields, p. 806–829: Tulsa, Okla., Am. Assoc. Petroleum Geologists.

Hicks, L. E., 1878, The Waverly group in central Ohio: Am. Jour. Sci., 3d ser., v. 16, p. 216–224.

Hyde, J. E., 1911, The ripples of the Bedford and Berea formations of central and southern Ohio, with notes on the paleogeography of that epoch: Jour. Geology, v. 19, p. 257–269.

——— 1921, Geology of Camp Sherman quadrangle: Ohio Geol. Survey, 4th ser., Bull. 23.

Johnson, D. W., 1919, Shore processes and shoreline development: New York, John Wiley & Sons, Inc.

Kindle, E. M., 1912, The stratigraphic relations of the Devonian shales of northern Ohio: Am. Jour. Sci., 4th ser., v. 34, p. 187–213.

——— 1917a, Recent and fossil ripple mark: Canada, Geol. Survey Museum Bull. 25.

——— 1917b, Deformation of unconsolidated beds in Nova Scotia and southern Ontario: Geol. Soc. America Bull., v. 28, p. 323–334.

Krynine, P. D., 1940, Petrology and genesis of the Third Bradford sand (New York, Pa.): Pa. State College, Min. Industries Exper. Sta. Bull. 29.

Lobeck, A. K., 1939, Geomorphology, an introduction to the study of landscapes: New York, McGraw-Hill Book Co., Inc.

Lockett, J. R., 1947, Development of structures in basin areas of northeastern United States: Am. Assoc. Petroleum Geologists Bull., v. 31, p. 429–446.

Martens, J. H. C., 1940 (May), Interpretation of drilling records in Appalachian region: The Producers Monthly.

Mather, W. W., 1838, First annual report on the Geological Survey of the State of Ohio: Am. Jour. Sci., v. 34.

Matteson, L. S., and Busch, D. A., 1944, Oil-bearing sands in southwestern Pennsylvania (preliminary report): Pa. Geol. Survey, 4th ser., Special Bull. no. 1.

McFarlan, A. C., 1943, Geology of Kentucky: Lexington, Ky., Univ. of Ky.

Morse, W. C., and Foerste, A. F., 1909, The Waverly formations of east central Kentucky: Jour. Geology, v. 17, p. 164–177.

——— 1912, Preliminary report on the Waverlian formations of east central Kentucky and their economic values: Ky. Geol. Survey Bull. 16.

Newberry, J. S., 1870a, The geological survey of Ohio, its progress in 1869; report of an address delivered to the legislature of Ohio, February 7, 1870, 60 p. (Ohio).

——— 1870b, Report on the progress of the Geological Survey of Ohio in 1869: Ohio Geol. Survey (Rept. Prog. 1869), pt. 1, p. 3–53.

——— 1873, Report on the geology of Cuyahoga Co.; . . . Summit County: Ohio Geol. Survey, Rept. 1, pt. 1, Geology, p. 171–222.

——— 1889, The Paleozoic fishes of North America: U. S. Geol. Survey Mon. 16.

Newcombe, R. J. B., 1933, Oil and gas fields of Michigan; a discussion of depositional and structural features of the Michigan Basin: Michigan Geol. Survey Div., Pub. 38 Geol. ser. 32.

Orton, Edward, 1874, Report on third district; geology of Pike Co.; Ross Co.; Greene Co.: Ohio Geol. Survey, Rept. 2, pt. 1, Geology, p. 611–696.

——— 1878, Report on the geology of Franklin County: Ohio Geol. Survey, Rept. 3, pt. 1, p. 596–646.

——— 1879, The Berea sandstone of Ohio, Ohio Secretary of State, Ann. Rept. 1878, p. 591–599.

——— 1882, The Berea grit of Ohio: Am. Assoc. Proc., v. 30, p. 167–174.

——— 1888a, The geology of Ohio considered in its relations to petroleum and natural gas: Ohio Geol. Survey Rept. 6, p. 1–59.

——— 1888b, The Berea grit as a source of oil and gas in Ohio: Ohio Geol. Survey Rept. 6, p. 311–409.

Pepper, J. F., and others, 1945a, Map of the Berea sand of southeastern Ohio, northern West Virginia, and southwestern Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 29.

———1945b, Map of the Berea sand of northern Ohio: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 39.

Prosser, C. S., 1903, The nomenclature of the Ohio geological formations: Jour. Geology, v. 11, p. 519–546.

———1912a, The Devonian and Mississippian formations of northeastern Ohio: Ohio Geol. Survey, 4th ser., Bull. 15.

———1912b, The disconformity between the Bedford and Berea formations in central Ohio: Jour. Geology, v. 20, p. 585–604.

Read, M. C., 1873, Report on the geology of Ashtabula, Trumbull, Lake, and Geauga Counties: Ohio Geol. Survey Rept. 1, pt. 1, p. 481–533.

Rittenhouse, Gordon, 1945, Textural standard for sample log work: Am. Assoc. Petroleum Geologists Bull., v. 29, p. 1195.

———1946, Map showing distribution of several types of Berea sand in West Virginia, eastern Ohio, and western Pennsylvania: U. S. Geol. Survey Oil and Gas Inv., Preliminary Map 58.

Rothrock, H. E., 1949, Mayfield pool, Cuyahoga County, Ohio: Am. Assoc. Petr. Geol. Bull., v. 33, p. 1731–1746.

Schuchert, Charles, 1943, Stratigraphy of the eastern and central United States: New York, John Wiley & Sons, Inc.

Stauffer, C. R., 1909, The Middle Devonian of Ohio: Ohio Geol. Survey, 4th ser., Bull. 10.

Stauffer, C. R., Hubbard, G. D., and Bownocker, J. A., 1913, Geology of the Columbus quadrangle: Ohio Geol. Survey, 4th ser., Bull. 14, v. 11, p. 193–319.

Stout, Wilber, 1941, Dolomites and limestones of western Ohio: Ohio Geol. Survey, 4th ser., Bull. 42.

Ulrich, E. O., 1911, Revision of the Paleozoic systems: Geol. Soc. America Bull., v. 22, p. 281–680.

Van Houten, F. B., 1948, Origin of red-banded early Cenozoic deposits in Rocky Mountain region: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 2083–2126.

Ver Wiebe, W. A., 1916, The Berea formation of Ohio and Pennsylvania: Am. Jour. Sci., 4th ser., v. 42, p. 43–58.

———1917, Correlations of the Mississippian of Ohio and Pennsylvania: Am. Jour. Sci., 4th ser., v. 43, p. 301–318.

Wasson, Theron, and Wasson, Isabel B., 1929, Cabin Creek field, West Virginia, *in* Structure of typical American oil fields, v. 1, p. 462–475: Tulsa, Okla., Am. Assoc. Petroleum Geologists.

Weller, J. M., and others, 1948, Correlations of the Mississippian formations of North America: Geol. Soc. America Bull., v. 59, p. 91–106.

Wells, J. W., 1944, Middle Devonian bone beds of Ohio: Geol. Soc. America Bull., v. 55, p. 273–302.

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Jour. Geology, v. 30, p. 377–392.

White, I. C., 1880, The geology of Mercer County: Pennsylvania 2d Geol. Survey Rept. QQQ.

———1881, The geology of Erie and Crawford Counties: Pennsylvania 2d Geol. Survey Rept. QQQQ.

Winchell, N. H., 1874, Reports on the geology of Ottawa, Crawford, Morrow, Delaware, Van Wert, Union, Paulding, Hardin, Hancock, Wood, Putnam, Allen, Auglaize, Henry, Mercer, and Defiance Counties: Ohio Geol. Survey, Rept. 2, pt. 1, Geology, p. 227–438.

Young, G. A., 1926, Geology and economic minerals of Canada: Canada Geol. Survey, Econ. Geology ser., no. 1 (Pub. no. 2065).

INDEX