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GEOLOGIC SUMMARY OF THE APPALACHIAN BASIN, WITH REFERENCE TO THE SUBSURFACE DISPOSAL OF RADIOACTIVE WASTE SOLUTIONS*

By

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This report is preliminary and has not been edited for conformity with Geological Survey format and nomenclature.

*Prepared on behalf of the U. S. Atomic Energy Commission.

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GEOLOGIC SUMMARY OF THE APPALACHIAN BASIN, WITH REFERENCE TO THE SUBSURFACE DISPOSAL OF RADIOACTIVE WASTE SOLUTIONS

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ABSTRACT

The Appalachian basin is an elongate depression in the crystalline basement complex which contains a great volume of predominantly sedimentary stratified rocks. As defined in this paper it extends from the Adirondack Mountains in New York to central Alabama. From east to west it extends from the west flank of the Blue Ridge Mountains to the crest of the Findlay and Cincinnati arches and the Nashville dome. It encompasses an area of about 207,000 square miles, including all of West Virginia and parts of New York, New Jersey, Pennsylvania, Ohio, Maryland, Virginia, Kentucky, Tennessee, North Carolina, Georgia, and Alabama.

The stratified rocks that occupy the basin constitute a wedge-shaped mass whose axis of greatest thickness lies close to and parallel to the east edge of the basin. The maximum thickness of stratified rocks preserved in any one part of the basin today is between 35,000 and 40,000 feet. The volume of the sedimentary rocks is approximately 510,000 cubic miles and of volcanic rocks is a few thousand cubic miles. The sedimentary rocks are predominantly Paleozoic in age, whereas the volcanic rocks are predominantly Late Precambrian.

On the basis of gross lithology the stratified rocks overlying the crystalline basement complex can be divided into nine vertically sequential units, which are designated "sequences" in this report. The boundaries between contiguous sequences do not necessarily coincide with the commonly recognized boundaries between systems or series. All sequences are grossly wedge shaped, being thickest along the eastern margin of the basin and thinnest along the western margin.

The lowermost unit--the Late Precambrian stratified sequence--is present only along part of the eastern margin of the basin, where it lies unconformably on the basement complex. It consists largely of volcanic tuffs and flows but contains some interbedded sedimentary rocks. The Late Precambrian sequence is overlain by the Early Cambrian clastic sequence. Where the older sequence is absent, the Early Cambrian sequence rests on the basement complex. Interbedded fine- to coarse-grained noncarbonate detrital rocks comprise the bulk of the sequence, but some volcanic and carbonate rocks are included. Next above is the Cambrian-Ordovician carbonate sequence which consists largely of limestone and dolomite. Some quartzose sandstone is present in the lower part in the western half of the basin, and much shale is present in the upper part in the southeast part of the basin. The next higher sequence is the Late Ordovician clastic sequence, which consists largely of shale, siltstone, and sandstone. Coarse-grained light-gray to red rocks are common in the sequence along the eastern side of the basin, whereas fine-grained dark-gray to black calcareous rocks are common along the west side. The Late Ordovician clastic sequence is overlain--unconformably in many places--by the

Early Silurian clastic sequence. The latter comprises a relatively thin wedge of coarse-grained clastic rocks. Some of the most prolific oil- and gas-producing sandstones in the Appalachian basin are included. Among these are the "Clinton" sands of Ohio, the Medina Sandstones of New York and Pennsylvania, and the Keefer or "Big Six" Sandstone of West Virginia and Kentucky. Conformably overlying the Early Silurian clastic sequence is the Silurian-Devonian carbonate sequence, which consists predominantly of limestone and dolomite. It also contains a salt-bearing unit in the north-central part of the basin and a thick wedge of coarse-grained red beds in the northeastern part. The sequence is absent in much of the southern part of the basin. Large volumes of gas and much oil are obtained from some of its rocks, especially from the Oriskany Sandstone and the Huntersville Chert. The Silurian-Devonian carbonate sequence is abruptly overlain by the Devonian clastic sequence--a thick succession of interbedded shale, mudrock, siltstone, and sandstone. Colors range from predominantly purple and red in the northeastern part of the basin to predominantly dark gray and black in the southwestern part. Many rocks in the upper part contain hydrocarbons in commercial quantities. The next higher sequence is a heterogeneous succession that comprises most rocks of Mississippian age in the basin. It is composed largely of fine-grained to very coarse-grained noncalcareous clastic rocks in the northern half of the basin, and largely of carbonate rocks in the southern part. Large quantities of oil and gas are produced from the sequence. The youngest sequence consists of coarse-grained clastic rocks largely of Pennsylvanian age. In the center of the basin a relatively small volume of lithologically similar rocks of Permian age are included. The sequence has been intensively mined for coal throughout most of its extent.

The waste-disposal possibilities of the stratified rocks in the Appalachian basin are considered in terms of the following: 1) gross lithology of the sequences; 2) general lithology of the rock units composing the sequences; and 3) the structural attitude of the sequences in different parts of the basin. The degree of exploitation of economically significant mineral resources is considered briefly where such exploitation may affect waste-disposal possibilities. Hydrologic aspects are not in general considered. Based largely on consideration of the above geologic factors the following types of reservoirs associated with particular geologic environments offer some prospects for the disposal of radioactive waste solutions. They are: 1) artificially created cavities in thick salt beds; 2) artifically fractured thin lenticular sandstone bodies isolated in shale or mudrock sequences; 3) portions of thick noncarbonate clastic sequences possessing appreciable natural porosity and permeability; 4) thin clastic units (with natural or artificially created openings) in the plate of a thrust fault overlain by impermeable strata.

Considered in its entirety the Late Ordovician clastic sequence appears to have a greater number of favorable geologic factors for waste-disposal purposes than the others. The Early Silurian clastic sequence, the Silurian-Devonian carbonate sequence, and the Devonian clastic sequence offer fewer possibilities. The Late Precambrian stratified sequence, Early Cambrian, and the Cambrian-Ordovician carbonate sequence offer few possibilities. The Mississippian and Pennsylvanian sequences appear to be generally unsuitable.

INTRODUCTION

Purpose of report

This summary report of the geology of the Appalachian basin was prepared as part of the Radioactive Waste Disposal Program being conducted by the Geological Survey on behalf of the Division of Reactor Development of the Atomic Energy Commission. It is one of a series of similar reports covering sedimentary basins in the United States. The purpose of this report is to summarize published information about the geology of the Appalachian Basin to aid in evaluating sites considered for the disposal of liquid radioactive wastes in deep wells.

A great many factors will be involved in the selection of a specific site for the disposal of radioactive wastes. The information in this report is not sufficiently detailed or inclusive enough for the location of specific sites. It should serve, however, as a guide for selecting general areas where the type of rock and the structural conditions might warrant more detailed investigation. In this preliminary study of an area covering all of one state and parts of 11 others, only the most general geologic relationships are discussed, namely lithology, stratigraphy, and structural environment. The hydrologic environment is extremely important with respect to radioactive waste disposal, but ground-water hydrology will not be discussed here because time was not available to investigate the literature on this subject. Furthermore, most of the published ground-water studies in the Appalachian basin are concerned only with water that occurs within a few hundred feet of the surface.

Organization of report

The rocks of the Appalachian basin are described from oldest to youngest. For the purposes of this report the stratigraphic column has been subdivided into nine parts, on the basis of gross lithologic composition. The subdivisions are referred to as "sequences" in the text. Word prefixes indicate their general age and gross lithologic composition. For example, throughout most of the basin the Late Ordovician clastic sequence consists largely of clastic rocks (shale, siltstone and sandstone) predominantly of Late Ordovician age. The lithologic composition and the thickness of each of the sequences as well as the stratigraphic relationships and the nomenclature of its component rock units are summarized by means of representative stratigraphic sections, mainly in tabular form. The order of discussion of the representative stratigraphic sections is clockwise around the Appalachian basin. The extent, thickness, and generalized outcrop of most of the sequences are shown on individual maps. The distribution of some of the rock types comprising the sequence is also shown on several of the isopach maps. The structural attitude of each sequence is summarized briefly with the aid of structure-contour maps which show the elevation of the top of the sequence with regard to mean sea level. Finally, the radioactive-waste-disposal possibilities of each sequence in different parts of the basin are considered in terms of the constituent rock types, the stratigraphic relations between constituent rock units, and the structural attitude of the sequence.

Location and extent of area

The Appalachian basin (fig. 1) is an oblong sedimentary basin in the eastern United States which extends from southern Quebec and Ontario Provinces, Canada, southwestward to central Alabama and Mississippi approximately parallel to the North Atlantic coastline. It is not a physiographic basin. On the contrary, much of the basin is occupied by mountains and plateaus. For the purposes of this study the Canadian portion of the basin is excluded. The area occupied by the Champlain Valley of New York and Vermont, and much of eastern New York east of the Hudson River are excluded from the present discussion because: 1) their geologic environments are dissimilar from that of most of the basin; 2) their geology is too complex to be conveniently discussed in this summary report; 3) little subsurface information is available in either area. The west edge of the study area is here defined as a sinuous line that extends from Lake Erie to southwestern Tennessee along the crests of the Findlay and Cincinnati arches, and the Jessamine and Nashville domes. The south edge of the study area is defined to coincide with the boundary between Paleozoic rocks and overlapping Cretaceous strata. It therefore coincides in large part with the boundary between the Appalachian Plateaus and Gulf Coastal Plain provinces.

The line marking the east edge of the study area shown on figures 1 and 2 was adapted from the Tectonic Map of the United States (Cohee, in press). Throughout much of its extent the line marks the surface contact between rocks of Paleozoic age on the west with rocks of Precambrian age on the east and coincides closely with the west flank of the Blue Ridge. In eastern Pennsylvania, northern New Jersey, and southeastern New York, the line coincides closely with the west side of the New Jersey Highlands. The boundary as thus drawn is convenient for most purposes of this study, but it excludes a thick sequence of sedimentary and volcanic rocks of Precambrian age that comprise part of the basin-fill in parts of Virginia, Tennessee, North Carolina, and Georgia. The Precambrian stratified rocks are, however, discussed herein with reference to their waste-disposal possibilities.

In part of southeastern Pennsylvania where Precambrian rocks are not present along the strike of the Blue Ridge, the down-faulted west edges of the Triassic sedimentary basins mark the eastern boundary of the study area. In the Hudson Valley region of New York the west edge of the Taconic klippe is arbitrarily designated as the eastern boundary of the study area. From Barton County, Ga., to the south end of the basin in central Alabama, the eastern boundary of the study area is marked by the contact of unmetamorphosed Paleozoic rocks on the west with metamorphosed Paleozoic rocks on the east. In this area the boundary of the study area coincides with the boundary between the Ridge and Valley physiographic province and the Piedmont province.

Outlined in this manner, the Appalachian basin is about 925 miles long, and about 330 miles wide at its widest point. It covers an area of about 206,864 square miles, including all of West Virginia, large parts of New York, Pennsylvania, Maryland, Ohio, Kentucky, Virginia, Tennessee, Georgia, and Alabama, and small areas in New Jersey and North Carolina.

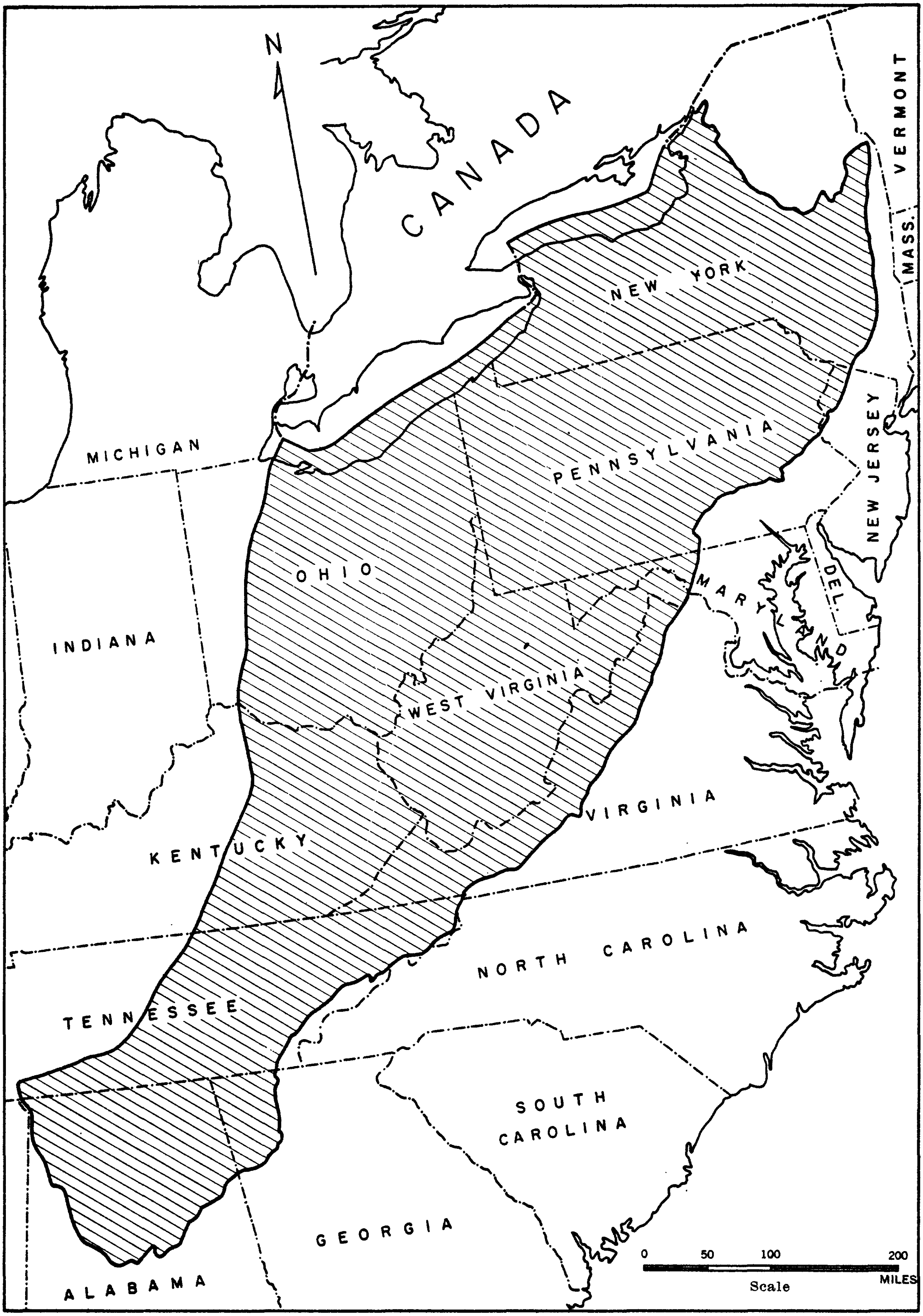

FIGURE 1.—Index map showing extent of study area.

Acknowledgments

This study was facilitated by the help of many people. Special appreciation is expressed to Gail M. Everhart of the U. S. Geological Survey who did much of the preliminary work by reviewing the literature and by compiling published information on base maps from which evolved many of the maps included in this report.

The writer thanks Mr. John T. Miller of the Pennsylvania Department of Forests and Mr. Richard R. Conlin of the Pennsylvania Geological Survey, both of whom supplied information from their unpublished studies in central Pennsylvania. Advice and much helpful information were freely supplied by Wallace de Witt, Jr., J. F. Pepper, G. H. Wood, Jr., H. H. Arndt, J. W. Huddle, L. D. Harris, and K. E. Englund-all of the U. S. Geological Survey.

GEOLOGIC FRAMEWORK

Depositional framework

The Appalachian basin as defined in preceding paragraphs outlines an elongate downwarped segment of the earth's crust in which a great thickness of sediment accumulated. Most of the sediment accumulated in shallow seas that occupied the downwarped area for long periods. Diastrophic processes later uplifted and deformed the sedimentary material that had accumulated and in some areas deformed the Precambrian crystalline floor of the basin. Finally erosional processes which are still active modified the surficial form of the mass of uplifted rock material.

The processes of subsidence and deposition commenced in late Precambrian time in the eastern part of the basin, and continued throughout most of the basin until late Paleozoic or early Mesozoic time. As the basin subsided, sediments derived largely from highland areas to the east were carried westward to accumulate in the seas that occupied the basin. During the early part of the Paleozoic era, when the eastern highland areas contributed relatively little sediment, some sediment was derived from the west. During the later Paleozoic some sediment entered the basin from the north.

The rates of subsidence and of deposition were greatest along the east edge of the basin close to the main source area of most of the sediments. The asymmetry of the basin is evident in figure 3 which shows stratigraphic sections drawn perpendicular to the long axis of the basin. The asymmetry is also shown on figure 4 which shows the approximate configuration of the boundary between Precambrian and Paleozoic rocks by means of structure contours.

Study of stratigraphy and sedimentary structures suggest that most of the sediments were deposited in shallow water and indicate that the rate of deposition closely balanced the rate of subsidence of the sea floor. At times the rate of deposition exceeded the rate of subsidence, and predominantly red, brown, or tan sediments accumulated above sea level. Rocks of these colors are most common near the periphery of the basin, especially in the northeast part. At other times subsidence halted or uplift ensued, resulting in periods of nondeposition or in the erosion of previously deposited sediments. Gaps in the stratigraphic section due to nondeposition or to erosion are most pronounced along the western, northern, and eastern margins of the basin.

Vertical changes in the lithology of the rocks comprising the stratigraphic column at any place in the basin indicate that the environment of deposition changed with time. Lateral changes in a stratigraphic unit indicate that the environment of deposition changed geographically. In general most of the sediments in the eastern part of the basin--especially in the northeastern part--accumulated in a deltaic environment; most of the sediments in the central part of the basin accumulated offshore in the trough of the marine basin; and most of the sediments in the western part accumulated on the shallow platform or shelf bordering the west edge of the basin. The areal distribution of the principal rock types in the Appalachian basin (see figure 5) reflects the geographic location of the predominant environments of deposition. Siltstone and sandstone comprise a relatively high percentage of the stratigraphic columns in the eastern and northeastern parts of the basin where deltaic environments prevailed throughout much of the history of the basin. Argillaceous rocks comprise a higher percentage of the rock sequence in the central part of the basin or the trough of the basin of accumulation than they do elsewhere. Carbonate rocks predominate in the western part of the basin where shelf or platform environments prevailed.

The sediments that accumulated during late Precambrian and Paleozoic time attained a composite maximum total thickness of approximately 60,000 feet. However, the greatest thickness preserved at any one place in the basin is between 35,000 feet and 40,000 feet. This thick sequence, which occurs in east-central Pennsylvania, is composed of rocks ranging in age from Early Cambrian to Early Pennsylvanian. A large but unknown volume of rock has been removed by erosion, largely since late Paleozoic time. The volume of Paleozoic rocks present in the basin today is approximately 510,000 cubic miles. The volume of Precambrian stratified sedimentary and volcanic rocks present in the basin could not be measured because subsurface data are lacking; however, it is probably less than 10,000 cubic miles. The figure of 510,000 cubic miles was obtained by determining the volume (440,000 cubic miles) of the basin below sea level from the structure contours shown on figure 4, and by adding the volume (70,000 cubic miles) of sedimentary rock above sea level. The latter figure is calculated from a basin-wide mass of rock with a uniform thickness of 1,800 feet, which is the approximate average topographic altitude of the basin.

The rocks that comprise the basin fill can be conveniently divided into nine vertically sequential gross lithologic units. Each unit--designated a sequence in this report--accumulated while a more-or-less uniform depositional environment or a suite of closely related environments prevailed throughout much of the basin. Most of the sequences are more or less distinct from those immediately above or below. The contacts between successive units are determined primarily on the basis of vertical change in lithology; precise age relationships are of secondary importance. As a result the contacts between some of them do not coincide with the generally accepted contacts between geologic periods and eras in many parts of the basin. The nine sequences are listed below and are compared with the normal divisions of the time scale.

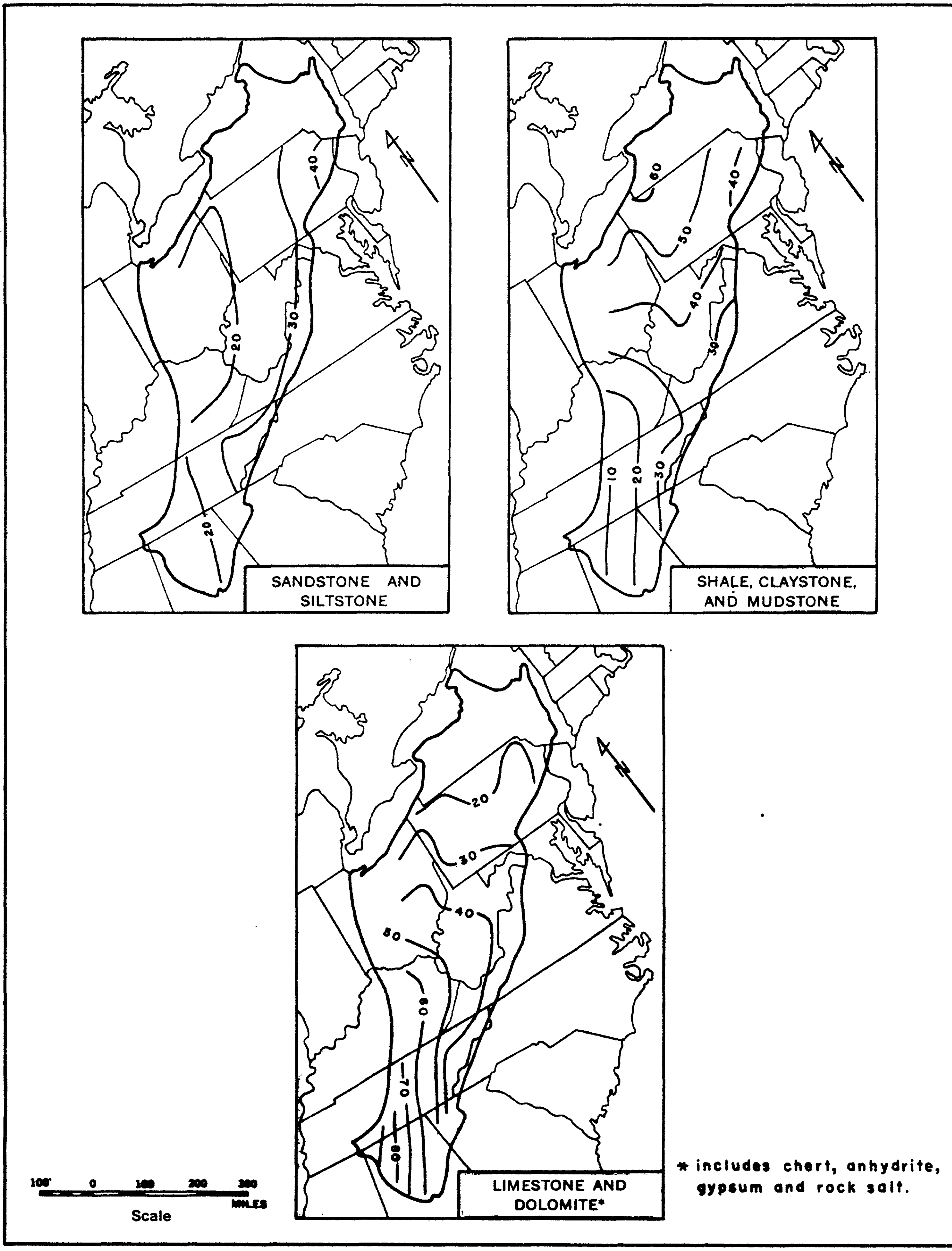

FIGURE 5.—Areal distribution of principal lithologies in the Appalachian basin. Figures show percentage of rock type composing total sedimentary column, exclusive of Pennsylvanian and Permian Systems.

Approximate relationship between the sequences of this report and the divisions of the geologic time scale

<table>
<tr><th>Sequences recognized in this report</th><th>Geologic period</th></tr>
<tr><td rowspan="2">Pennsylvanian sequence</td><td>Permian</td></tr>
<tr><td>Pennsylvanian</td></tr>
<tr><td rowspan="2">Mississippian sequence</td><td>Mississippian</td></tr>
<tr><td rowspan="3">Devonian</td></tr>
<tr><td rowspan="2">Devonian clastic sequence</td></tr>
<tr></tr>
<tr><td>Silurian-Devonian carbonate sequence</td><td rowspan="2">Silurian</td></tr>
<tr><td>Early Silurian clastic sequence</td></tr>
<tr><td>Late Ordovician clastic sequence</td><td rowspan="2">Ordovician</td></tr>
<tr><td rowspan="2">Cambrian-Ordovician carbonate sequence</td></tr>
<tr><td rowspan="2">Cambrian</td></tr>
<tr><td>Early Cambrian clastic sequence</td></tr>
<tr><td>Late Precambrian stratified sequence</td><td rowspan="2">Precambrian</td></tr>
<tr><td>(basement complex)</td></tr>
</table>

Although the two lowest (oldest) sequences are very similar lithologically, they are recognized as distinct units for the following reasons: (1) Precambrian stratified rocks and Lower Cambrian sedimentary rocks are separated by a structural discontinuity in some areas, (2) they have different potentials with reference to the disposal of liquid radioactive wastes. The Precambrian stratified sequence is poorly suited for the disposal of radioactive wastes, whereas the Early Cambrian clastic sequence appears to be better suited. Two sequences near the middle of the section--the Late Ordovician clastic sequence and the Early Silurian clastic sequence--are also somewhat similar to each other lithologically. They are separated partly because of the structural discontinuity between them in some places, but largely for convenience in discussing their suitability for waste disposal. The lower sequence is at present not productive of mineral resources in the subsurface and may be suitable for the disposal of radioactive wastes. The upper sequence is highly productive of oil and gas in many parts of the basin and consequently it appears to be a less likely reservoir for the disposal of radioactive wastes. The Mississippian and Pennsylvanian rocks are also similar to each other in many respects. However, they are separated into two sequences in this report so that their waste-disposal possibilities can be discussed more conveniently. Mississippian rocks are not productive of coal and in some areas may be suitable for waste disposal. Rocks of Pennsylvanian age are thoroughly exploited for coal and clay, and are not likely to be considered as reservoirs for the disposal of liquid radioactive waste products, with the possible exception of one small area.

Structural framework

The structural configuration of the Appalachian basin is primarily the result of two factors: (1) the original shape of the downwarped segment of the earth's crust; (2) diastrophic processes that deformed the Precambrian crystalline floor and the mass of younger sedimentary rock in the basin. The basin was compressed perpendicular to its long axis by forces directed from the east and southeast. Rocks were deformed most severely in the eastern part of the basin. Although the intensity of structural deformation decreases progressively to the west and north, the basin can be divided into two parts on the basis of the type and frequency of occurrence of the resulting structures. The dividing line between the more intensely deformed eastern part and the less intensely deformed western part is marked by the Appalachian structural front (Price, 1931). The trend of the structural front (fig. 2) closely coincides with topographic features known as the Allegheny Front, the Catskill Escarpment, and the Cumberland Escarpment.

The rocks in the eastern part--the area generally included in the Valley and Ridge physiographic province--are characterized by numerous closely spaced folds and many low-angle thrust faults. The axes of the folds and the traces of the faults closely parallel the long axis of the basin. Many of the folds are overturned to the west or oversteepened on their west flanks. Movement of the overthrust blocks along the thrust faults was toward the northwest. Tear faults and high-angle reverse faults are also present in the Valley and Ridge province. Axial plane cleavage is present in some incompetent argillaceous rocks along the eastern margin of the basin. Cleavage is well developed in Precambrian stratified rocks along the west side of the Blue Ridge, which borders the east edge of the Appalachian basin as defined in this report. Within the Valley and Ridge province the folds become progressively gentler and thrust faults become progressively less numerous toward the west.

Structural complexity and insufficient data preclude detailed delineation of the subsurface rocks in the eastern part of the basin. Consequently structure contours are not shown in the area east of the Appalachian structural front on most of the structure maps that accompany this report. Where structure-contour lines are drawn in the eastern part of the basin, they are to be regarded only as an attempt to portray a highly generalized concept of the configuration of the rocks. The details of structure are of course much more complex.

The rocks in the western part of the basin--the area included in the Appalachian Plateaus physiographic province and the easternmost part of the Central Lowlands province--are characterized by gentle, approximately symmetric folds and by the absence of thrust faults. The folds are steeper, more closely spaced, and more commonly parallel to the regional trend near the structural front. Subsurface data show nearly vertical faults along the crests of many anticlines near the front. In general, movement was upward on the west or north side, and downward on the east or south side. Westward the folds become flatter, more widely spaced, more varied in trend, and faults are less numerous. In the westernmost part of the basin deformation is restricted largely to very broad gentle arches and elongate domes. Among these are the Findlay arch, Cincinnati arch, Jessamine dome, and the Nashville dome. A major fault zone--the Kentucky River fault zone--crosses eastern Kentucky oblique to the regional trend of the Appalachian basin (fig. 2). The zone comprises many fault slices bounded by nearly vertical fault planes. Movement is primarily downward on the south. Some of the thickness maps prepared for this report suggest that movement along this zone is more pronounced in the subsurface than on the surface.

The vast number of structures in the Appalachian basin precludes discussion of each one in this paper. Many of the larger structures are shown on figure 2, which was adapted largely from the Tectonic Map of the United States (Cohee, in press) to which the reader is referred for more complete information.

Although the Appalachian basin was subjected to deformation many times throughout its history, several more-or-less distinct episodes of diastrophic activity within the basin have been recognized.

The first episode that resulted in a widespread break in the geologic record occurred in late Precambrian time. As a result of uplift and erosion of the early Precambrian metamorphic and igneous terrane prior to deposition of younger strata, a marked angular unconformity is present between the crystalline basement complex and the overlying sedimentary and volcanic strata.

The next major disturbance--the Blountian of some workers, especially Rodgers (1953, p. 124)--was a gentle epeirogenic uplift that occurred in early Middle Ordovician time. It resulted in an erosional disconformity of basinwide extent between Lower Ordovician and Middle Ordovician rocks.

In parts of the basin there is conclusive evidence of severe diastrophic activity in Late Ordovician time. This disturbance--the Taconic--was strongest in the northeastern part of the Appalachian basin. In parts of eastern Pennsylvania and northwestern New Jersey a pronounced angular unconformity exists between highly deformed fine-grained Upper Ordovician rocks and slightly deformed coarse-grained Lower Silurian rocks. In much of New York, rocks of Late Ordovician age are disconformably overlain by rocks of late Early Silurian age.

The next episode of disturbance--a widespread but gentle epeirogenic uplift--occurred before Late Devonian time. It was strongest in the southeast part of the area and is marked by an erosional disconformity at the base of the predominantly Upper Devonian Chattanooga shale in much of Tennessee, northwestern Georgia, and northern Alabama. The disconformity increases in magnitude from the center of the basin northwestward toward the Nashville dome and southeastward toward the east edge of the basin. In parts of central Tennessee and northeastern Alabama rocks of Late Devonian age rest on rocks of Middle Ordovician age.

In late Mississippian time or in very early Pennsylvanian time, gentle uplift in the northwest part of the basin resulted in an erosional disconformity between the Mississippian and Pennsylvanian Systems. The disconformity is most pronounced along a narrow belt trending south across eastern Ohio into West Virginia and possibly into southern Virginia. In the northern part of the belt, rocks of early Pennsylvanian age are locally channeled into rocks of early Mississippian age. In some areas in the southeastern part of the basin Mississippian and Pennsylvanian rocks are separated by a disconformity.

In late Paleozoic time and probably in early Mesozoic time the Appalachian basin was profoundly affected by deformation commonly referred to as the Appalachian revolution. The deformation may have occurred in two phases: the earlier phase dominated by compressional forces and the later phase by tensional forces. The system of parallel folds that is characteristic of much of the area, as well as most of the longitudinal thrust faults, tear faults and other high-angle faults were formed during this orogeny. The duration of the disturbance can not be accurately determined because of a large gap in the geologic record within the basin. No Paleozoic rocks younger than early Permian, no Mesozoic rocks and no Cenozoic strata except a thin spotty veneer of Quaternary sediments are present. Diastrophism associated with the Appalachian revolution began no earlier than Early Permian time and may have extended at least into Late Triassic time. Downfaulting along parts of the east edge of the Appalachian basin, the rapid accumulation of Late Triassic redbeds in the downfaulted basins, and the subsequent intrusion of many basaltic dikes into the Triassic rocks and into Paleozoic rocks within the Appalachian basin may represent the last phase of the revolution. However, these phenomena of Late Triassic age may represent a later disturbance--the Palisades disturbance of some workers.

Since the end of the Appalachian revolution deformation apparently has been restricted to episodes of relatively mild epeirogenic uplift followed by periods of planation by erosional processes.

STRATIGRAPHY

Late Precambrian stratified sequence

Rocks of Precambrian age crop out (figs. 2 and 4) in the Adirondack Mountains at the north end of the Appalachian basin and along most of the eastern margin of the basin. They are divided into two categories on the basis of stratigraphic position and lithology. The categories are the Precambrian basement complex and the Late Precambrian stratified sequence. As the name implies, the Precambrian basement complex forms the floor or the basement of the Appalachian basin. The generalized configuration of the basement surface in the northern, western, southern, and central parts of the basin is shown on figure 4. Contours in most of the central part are hypothetical and were drawn largely by extrapolation from the northern and western flanks of the basin where data were available. The main outcrop areas (figs. 2 and 4) of the complex are the Adirondack Mountains in northeastern New York; the Jersey Highlands in southeastern New York, northwestern New Jersey, and eastern Pennsylvania; and the central part of the Blue Ridge in Virginia, Tennessee, and North Carolina. Where exposed the complex consists largely of schists and gneisses and various types of igneous intrusives such as granite, quartz syenite, granodiorite, gabbro, and anorthosite. Where the basement complex has been encountered in wells along the northern and western sides of the basin, it is composed of similar gneissic and granitic rocks. Because a study of the crystalline rocks of the basement complex is beyond the scope of this report, they will not be discussed further.

The stratigraphically higher Late Precambrian stratified sequence is a thick succession of interbedded metasedimentary and metavolcanic rocks unconformably overlying the basement complex. The sequence is composed of the Swift Run Formation and Catoctin Greenstone along the Catoctin-Blue Ridge-South Mountain anticlinorium in Pennsylvania, Maryland, and Virginia; the Mount Rogers Volcanics in southern Virginia and northeastern Tennessee; and the Ocoee Series in the southern Appalachians. Along the outcrop, the Precambrian stratified sequence ranges in thickness from a feather edge in Cumberland County, Pa., to probably more than 25,000 feet in the Great Smoky Mountains in Blount and Sevier Counties, Tenn. (King and others, 1952, p. 21-22).

From northwestern Madison County, Va., to southern Amherst County, Va., a thin unit of detrital rock--the Swift Run Formation--unconformably overlies the basement complex. The Swift Run ranges from 0 to 250 feet in thickness and is composed largely of graywacke, subgraywacke, arkosic sandstone, quartzite, and conglomerate. In some places the upper part of the formation contains layers of pyroclastic rock similar in composition to rocks comprising the overlying Catoctin Greenstone.

The Catoctin Greenstone, which unconformably overlies the Swift Run where the latter is present, extends from northern Adams County, Pa., southward to the James River in Amherst County, Va. Where the Swift Run Formation is absent, the Catoctin lies unconformably on the basement complex. The Catoctin consists largely of metamorphosed epidote-rich greenish volcanic flows and tuffs. The composition of the volcanic material changes from predominantly basaltic in Maryland to interbedded basaltic and rhyolitic in southern Pennsylvania to basaltic or andesitic in northern Virginia. In the area north of the James River much graywacke, arkose, and quartzite is interbedded with the volcanic material. The thickness of the Catoctin, like the Swift Run, varies rapidly in short distances. Swartz (1948, p. 1505) estimates a maximum thickness of about 5,000 feet near South Mountain in Pennsylvania and Maryland. King (1950, fig. 12) shows that the Catoctin increases in thickness from 0 feet to approximately 1,500 feet within a distance of less than one mile in southern Page County, Va.

In the northeast corner of Tennessee and in contiguous parts of Virginia and North Carolina, rocks of the Mount Rogers Group unconformably overlie the Precambrian basement complex. The Mount Rogers Group consists mainly of purplish and greenish flows and tuffs of rhyolitic volcanic material but includes layers of conglomerate, sandstone, shale and slate, and layers of basalt flows. Stose and Stose (1944, p. 411) estimate that the Mount Rogers is 1,000 or more feet thick.

In the Great Smoky Mountains in eastern Tennessee and western North Carolina, the Precambrian stratified sequence is represented by the Ocoee Series which is composed entirely of sedimentary rocks with an aggregate thickness of more than 30,000 feet. The Ocoee Series has recently been broadly subdivided into three groups and several unclassified formations (King and others, 1958, esp. table 1, p. 955). The lower Group--The Snowbird--comprises as much as 13,000 feet of feldspathic sandstone, siltstone, and phyllite. It overlies the basement complex unconformably. The upper part of the Ocoee Series is composed of the Walden Creek Group along the northwest flank of the mountains and the Great Smoky Group to the southeast. These two groups may be in part equivalent to each other (King and others, 1958, p. 963). The Walden Creek comprises as much as 8,000 feet of shale and siltstone and some sandstone and conglomerate, and in most places is in fault contact with adjacent formations. The Great Smoky Group--more than 25,000 feet thick--consists largely of fine-grained sandstone, coarse-grained feldspathic sandstone, and dark silty and argillaceous metamorphosed rocks.

The westward extent of the late Precambrian stratified rocks along the floor of the Appalachian basin is unknown. However, King (1950, p. 13) presents evidence that the western extent of the Catoctin Greenstone coincides closely with the west side of the Catoctin-Blue Ridge anticlinorium. He attributes the rapid pinchout of the Catoctin to nondeposition and overlap as the Catoctin accumulated, and to truncation by erosion in post-Catoctin time. Bloomer and Werner (1955, fig. 4) suggest that the Swift Run Formation, as well as the Catoctin, pinches out in the vicinity of the west flank of the Blue Ridge Mountains.

Early Cambrian clastic sequence

The late Precambrian stratified sequence is overlain unconformably in most places by a sequence of predominantly clastic sedimentary rocks which most workers agree is Early Cambrian in age. In some places the contact is conformable (Bloomer and Werner, 1955, p. 589-599, Cloos, 1958,

p. 8) and in other places it is unconformable (King, 1950, p. 13-14). In southeastern New York, much of eastern Pennsylvania, parts of southern Virginia and northeastern Tennessee where stratified rocks of Precambrian age are absent, the Early Cambrian clastic sequence lies unconformably on the basement complex. Lower Cambrian rocks occur as a wedge along the east side of the Appalachian basin from New York to Alabama (fig. 6). They wedge out rapidly to the west and have not been reported in wells drilled to the basement on the west flank of the basin. However, they appear to be present in some deep wells drilled in eastern Kentucky.

Relationships between Lower Cambrian rocks, Upper Precambrian stratified rocks and rocks of the basement complex are not known with certainty in parts of the Appalachian basin. Stose and Stose (1944, p. 412-413) state that the Upper Precambrian Ocoee Series extends southwestward across Georgia into Alabama, and is equivalent to the Talladega Series, which continues across Alabama to the southern end of the Piedmont region. However, the Tectonic Map of the United States (Cohee, in press) shows metamorphic rocks of Paleozoic age occupying the southern part of the belt designated as Ocoee and Talladega by the Stoses. Griffin (1951, p. 43-48) summarized the data regarding the age of the Talladega Series in eastern Alabama and concluded that the upper part of the Talladega was late Paleozoic in age.

Along the lower part of the Hudson River Valley in southeastern New York the Lower Cambrian Series consists of the Poughquag Quartzite and probably some of the lower part of the overlying Wappinger Limestone (Swartz, 1948, p. 1521). The Poughquag consists of about 125 feet of well-cemented, resistant, light-colored quartzite. It is not known how much, if any, of the Wappinger Limestone is Early Cambrian in age. However, for the purpose of this paper, the Early Cambrian clastic sequence in this area is restricted to the Poughquag Quartzite and the entire Wappinger is assigned to the overlying Cambrian-Ordovician carbonate sequence.

In northwestern New Jersey (Lewis and Kummel, 1950, rev.) and eastern Pennsylvania (Willard, 1955, p. 821) the Lower Cambrian is represented by the Hardyston Quartzite, which lies unconformably on the Precambrian basement complex. The Hardyston is a massive vitreous gray quartzite or arkosic sandstone, with layers of sandy shale and conglomerate. In eastern Pennsylvania it ranges from 25 to 300 feet in thickness.

The number of mappable units in the Early Cambrian clastic sequence increases southwestward along the east edge of the basin. Along the west side of the South Mountain uplift in southern Pennsylvania and Maryland, and along the west side of the Catoctin-Blue Ridge anticlinorium in northern Virginia, the Early Cambrian sequence is composed of six formations. From bottom to top the units are: the Loudoun Formation, Weverton and Harpers Formations, the Antietam Quartzite, Tomstown Dolomite, and the Waynesboro Formation. In much of Virginia the four formations below the Tomstown--or the equivalent Shady Dolomite--have been placed in the Chilhowee Group.

The Loudoun Formation is composed of ferruginous, dark-purple to gray sandy phyllite, tuffaceous slate, and arkosic quartzite. It contains some layers of pyroclastic conglomerate and breccia, and some layers of amygdaloidal lava. The Loudoun may be as thick as 500 feet but is much thinner in most places. It is not recognized in central Virginia or in Pennsylvania north of South Mountain.

The Weverton Formation is composed of conglomerate and arkosic sandstone in the lower part, micaceous shale or phyllite in the middle, and vitreous to granular quartzite in the upper part. The Weverton thickens from 200-300 feet along the Potomac River to a maximum thickness of about 1,500 feet in southern Page County, Va.

Along the Potomac River the Harpers Formation consists largely of gray phyllite and slate with thin layers of quartzite. In southern Page County, Va., it consists largely of thin-bedded dark-gray to greenish siltstone. Well-developed axial plane cleavage is characteristic of the Harpers in most places. The formation thins from about 2,500 feet in southern Pennsylvania to about 900 feet in southern Page County, Va.

In southern Pennsylvania, Maryland, and northern Virginia the Antietam Quartzite is divisible into two parts. The lower part consists of thick beds of white to light-gray quartzite composed largely of well-rounded, well-sorted grains of quartz. The upper part consists of thinner beds of ferruginous, calcareous, and dolomitic sandstone, and some layers of quartzite and shale. In this area the Antietam ranges from 300 to 1,000 feet in thickness.

The Tomstown Dolomite overlies the Antietam Quartzite--the upper formation of the Chilhowee Group of Virginia. The Tomstown consists largely of dark argillaceous to saccharoidal, irregularly bedded dolomite with chert concretions and some interbedded shale. Its contacts with the formations above and below are gradational. In southern Pennsylvania, Maryland, and northern Virginia, the Tomstown is reported to be about 1,000 feet thick.

The uppermost unit of Early Cambrian age along the west side of the South Mountain and Catoctin-Blue Ridge anticlinoriums is the Waynesboro Formation. The Waynesboro is a soft nonresistant unit composed largely of red and brown shale, siltstone, and sandstone. Some beds of limestone in the upper part of the formation suggest that the contact of the Waynesboro with the overlying Elbrook Limestone of Middle Cambrian age is gradational. The Waynesboro thickens southward from about 300 feet in Maryland to approximately 1,700 feet in southern Page County, Va.

Clastic rocks of Early Cambrian age extend southwestward along the east side of the Shenandoah Valley. In southern Virginia the sequence totals slightly more than 10,000 feet in thickness. The following table summarizes the stratigraphic succession in this area.

Generalized section, Early Cambrian clastic sequence exposed in the Glade Mountain district, Smyth and Wythe Counties, Va. (after Miller, 1944, table 1).

Series	Formation	Thickness (feet)	Character
Lower Cambrian	Rome	2,000	Red, gray, and green shale and red sandstone with layers of dolomite.
	Shady Dolomite	1,930	Gray to white, even, massive-bedded dolomite; small amount of shale above; a dolomitic sandstone at base.
	Erwin Quartzite	1,500-2,000	Resistant thick-bedded quartzite, quartzitic sandstone, and non-resistant shaly sandstone.
	Hampton Shale	2,000	Dark-gray shaly sandstone and shale.
	Unicoi	2,600±	Conglomerate, arkosic sandstone, quartzose sandstone; some shale and several amygdaloidal lava flows.

The Early Cambrian clastic sequence can be traced from southern Virginia southwestward along the east side of the Appalachian basin to Alabama. The names applied to the units comprising the sequence change. Recent work in Blount and Sevier Counties, Tenn., has resulted in recognition of the stratigraphic sequence shown in the following table.

Generalized section, Early Cambrian clastic sequence,
Blount County, Tenn.
(from King and others, 1952, p. 10-11

Series		Formation	Thickness (feet)	Character
Lower Cambrian		Rome	900	Red silty shale with thin-bedded sandstone.
		Shady Dolomite	1,000	Massive gray dolomite with some beds of shale in upper half.
	Chilhowee Group	Hesse Sandstone	400	Massive white quartzose sandstone and quartzite; upper part thin bedded.
		Murray Shale	300	Greenish-blue silty shale.
		Nebo Sandstone	200	Thin-bedded to massive quartzose sandstone and quartzite.
		Nichols Shale	500	Greenish-blue silty shale.
		Cochran unconformity	1,000	Feldspathic sandstone; upper part quartzitic; conglomerate and red shale in lower part.

Thickness and depth.--As can be seen from figure 6, the Lower Cambrian rocks constitute an elongate wedge-shaped body that extends nearly the full length of the Appalachian basin and pinches out rapidly to the northwest and west. The area of greatest thickness is centered in southern Smyth County, Va., where Miller (1944, table 1) reported approximately 10,000 feet of Lower Cambrian strata. The extent and thickness of the Early Cambrian clastic sequence west and northwest of the outcrop area is not known in many areas because subsurface data are lacking. The thickness lines (fig. 6) in West Virginia are based in part on work by Woodward (1949, p. 209, fig. 7) and in Pennsylvania on work by Swartz (Swartz, F. M., 1948, p. 1528, fig. 12). Thick sequences of clastic rocks above the basement complex and below a thick sequence of carbonate rocks of Cambrian and Ordovician age were reported in several wells recently drilled in eastern Kentucky. Some of these clastic rocks may be Middle Cambrian in age. For convenience, however, the entire clastic sequence is included in the Early Cambrian clastic sequence of this report. No rocks of Early Cambrian age were reported in a well drilled to the basement complex in Wood County, W. Va. (Woodward, 1959). Rocks of Early Cambrian age have not been reported in wells drilled to the basement in western and north-central Ohio, northwestern Pennsylvania, and in New York.

Insufficient data were available to compile a structure-contour map on the Early Cambrian clastic sequence. However, the approximate elevation at the top of the sequence in most places can be estimated by adding the thickness of the Early Cambrian sequence shown on figure 6 to the elevation below sea level at the same point of the Precambrian basement complex shown on figure 4. This method should not be applied along the eastern margin of the Appalachian basin because of complications due to intense folding and thrusting. It is apparent from comparing figures 4 and 6 that the top of the Early Cambrian sequence occurs at depths considerably greater than 5,000 feet below sea level in most of the Appalachian basin. The approximate elevations on the top of the sequence range from approximately 2,000 feet below sea level in the vicinity of Adams County, Ohio, to perhaps 35,000 feet or more in the vicinity of Schuylkill County, Pa.

Cambrian-Ordovician carbonate sequence

A sequence composed largely of limestone and dolomite overlies the Early Cambrian clastic sequence in most of the Appalachian basin. In the western part of the basin, where the Early Cambrian clastic sequence is absent, the carbonate sequence unconformably overlies the Precambrian basement complex. Rocks of the carbonate sequence are predominantly Middle and Late Cambrian, and Early and Middle Ordovician in age. Among the thicker more extensive carbonate rock units included in the sequence are the Elbrook Limestone, the Conococheague Limestone, the Beekmantown Limestone or Group and the Trenton Group of the central and northern Appalachians; and the Knox Group in the southern Appalachians. In eastern Tennessee and parts of contiguous states, thick wedges of noncarbonate clastic rock are included in the lower and upper parts of the carbonate sequence. The clastic rocks in the lower part constitute part of the Conasauga Group. Most of the clastic rocks in the upper part constitute the Tellico, Sevier, and Bays Formations.

In north-central Ohio the Cambrian-Ordovician carbonate sequence of this report unconformably overlies the gneissic basement complex and includes the rocks from the top of the basement complex to the top of the Trenton Limestone of Middle Ordovician age. The sequence is approximately 1,500 feet thick. In this area rocks of Early Cambrian, Middle Cambrian, and Early Ordovician age are absent.

The lower part of the sequence consists largely of interbedded dolomite, sandy dolomite, dolomitic quartz sandstone, and very pure quartz sandstone. Strong flows of salt water occur at several horizons. Two sandstone units are commonly reported in the lower part—the Mt. Simon Sandstone directly above the basement complex and the Franconia-Dresbach Sandstone about 300-500 feet higher. The upper part of the carbonate sequence consists largely of limestone and impure argillaceous limestone. A thin unit of greenish shale—the Glenwood Shale—separates the lower dolomitic part of the sequence from the upper nondolomitic part. The Glenwood marks the approximate position of the St. Peter Sandstone, which occurs in places along the Cincinnati arch and in many areas west of the Appalachian basin. The lithology and chemical composition of the rocks composing the Cambrian-Ordovician carbonate sequence are described in detail by Stout and Lamey (1940, p. 672-692) from samples obtained from a well drilled in Delaware County, Ohio. The stratigraphic relationship of these rocks in the subsurface across Ohio is shown and more modern nomenclature is applied in recent studies by Shearrow (1957, p. 3, pl. 1; 1959, p. 4).

The Cambrian-Ordovician carbonate sequence (approximately 3,750 feet thick) encountered in a deep well in western West Virginia (Woodward, 1959, p. 23-26, pl. 1) is similar to that in north-central Ohio, except that some dolomite rocks of Early Ordovician age are present. The lithology, thickness, and nomenclature of the rock units comprising the Cambrian-Ordovician carbonate sequence in north-central Ohio and in western West Virginia are compared below.

Generalized sections of the Cambrian-Ordovician carbonate sequence encountered in wells in Ohio and West Virginia.

North-central Ohio		Western West Virginia
Trenton Limestone (150 feet): light- to dark-colored limestone; shaly in part.	Middle Ordovician	Trenton Limestone (630 feet): light- to medium dark gray coquinoid and argillaceous limestone.
Black River Limestone (430 feet): light-gray pure limestone; some shale below.	Middle Ordovician	Black River Limestone (255 feet): medium-gray stylolitic limestone; argillaceous in part.
Glenwood Shale (5 feet): greenish glauconitic shale. unconformity	Middle Ordovician	Chazy Limestone (500 feet): medium dark gray limestone; some shaly limestone and shale.
	Middle Ordovician	St. Peter Sandstone (18 feet): light-colored quartz sandstone; heavy flows of salt water. unconformity
Lower Ordovician series missing. unconformity	Lower Ord.	Beekmantown Dolomite (980 feet): fine- to coarse-crystalline dolomite; a sandstone at base. unconformity
Trempealeau Formation (525 feet): light siliceous dolomite and dolomitic sandstone; flow of salt water.	Upper Cambrian	Trempealeau Formation (500 feet): light-gray silty dolomite; in part oolitic; flow of salt water.
Franconia-Dresbach (60 feet): very light gray pure quartz sandstone; flow of salt water.	Upper Cambrian	Franconia-Dresbach Sandstone (220 feet): sandy dolomite and dolomitic sandstone.
Eau Claire (200 feet): green sandy dolomite and pure quartz sandstone.	Upper Cambrian	Eau Claire Formation (505 feet): crystalline dolomite with shale and sandstone streaks.
Mt. Simon Sandstone (135 feet): very pure quartz sandstone; flow of salt water.	Upper Cambrian	Mt. Simon Sandstone (280 feet): reddish, medium- to coarse-grained sandstone; flow of salt water.

Rocks included in the Cambrian-Ordovician carbonate sequence of this report crop out (fig. 7) in a belt bordering the southwest and south sides of the Adirondack Mountains. Because of the complex stratigraphic picture that has resulted from many detailed studies in this area, it is more convenient for the purposes of this report to discuss rocks of similar age encountered in a deep well drilled in northeastern Chenango County (Donnerstag and others, 1950, p. 8-12) about 45 miles southwest of the outcrop belt. The rock sequence--approximately 1,300 feet thick--in the well is summarized below.

Generalized section, Cambrian-Ordovician sequence, northeastern Chenango County, N. Y.

Series	Formation	Thickness (feet)	Character
Middle Ordovician	Trenton-Black River Formations	434	Light- to medium-gray limestone with some dolomite.
	unconformity		
Lower Ordovician	Beekmantown	321	White to light-gray crystalline dolomite with some quartz fragments.
	unconformity		
	Tribes Hill	185	White to light-gray dolomite; some chert above; quartz grains below.
Upper Cambrian	Little Falls Dolomite	255	White to light-gray dolomite; some quartz grains.
	Theresa	26	Dolomitic sandstone and sandy dolomite.
	Potsdam Sandstone	37	Quartzitic sandstone with some feldspar grains.

The Cambrian-Ordovician carbonate sequence thickens to the southeast and the lithology changes. In east-central Pennsylvania the sequence is about 3,800 feet thick, and is composed largely of dolomitic limestone. Rocks of Middle Cambrian age are present in contrast to the previously described sections in New York, West Virginia, and Ohio. However, the presence of several unconformities in the sequence in northeastern Pennsylvania indicates that parts of the Cambrian and Ordovician systems are not represented. The following section is believed to be typical of the carbonate sequence in much of eastern Pennsylvania.

Generalized section, Cambrian-Ordovician carbonate sequence exposed along the Delaware River Valley in northern Northampton County, Pa., and contiguous parts of New Jersey
(From Willard, 1955, p. 821; Johnson and Willard, 1957, p. 128, 129)

Series	Formation	Thickness (feet)	Character
Middle Ordovician	Jacksonburg Limestone unconformity	150-200	Pure to argillaceous, high-calcium limestone; used for cement.
Lower Ordovician	Beekmantown unconformity	1,000-1,500	Blue-gray massive-bedded dolomitic limestone.
Upper Cambrian	Allentown	500	Blue-gray massive-bedded dolomitic limestone with stromatolite biostromes.
	Limeport	900	Blue-gray massive-bedded dolomitic limestone with oolites and quartz grains.
Middle Cambrian	Leithsville	900	Dark-gray dolomitic thin-bedded limestone alternating with gray to brown sericitic shale.

The Cambrian-Ordovician sequence thickens southwestward along the outcrop in Pennsylvania, and the proportion of limestone relative to dolomite increases. In Franklin County, Pa., and in Washington County, Md., the 8,400 feet of rocks assigned to the carbonate sequence consist largely of limestone. Dolomite occurs only in the upper part of the Beekmantown group. The following section is typical of central Maryland and contiguous parts of south-central Pennsylvania, northern Virginia, and West Virginia.

Generalized section, Cambrian-Ordovician carbonate sequence exposed in Washington County, Md. (after Cloos, 1958, p. 6-7)

Series	Group	Formation	Thickness (feet)	Character
Middle Ordovician		Chambersburg Limestone	100-600	Dark-gray, pure to argillaceous thin-bedded limestone.
	St. Paul Group	unconformity	500-1,000	Very pure to dolomitic limestone containing some chert.
Lower Ordovician	Beekmantown Group	Bellefonte? Nittany? Stonehenge?	3,250	Largely light-gray finely crystalline thick-bedded limestone with some chert near base: upper 400 feet largely massive-bedded dolomite.
Upper Cambrian		Conococheague limestone	1,600	Dark-blue laminated limestone with shaly partings; some oolites and quartz sandstone layers near base.
Middle Cambrian		Elbrook limestone	3,000	Interbedded light-gray thin-bedded shaly limestone and calcareous shale; some massive-bedded limestone and dolomite near middle.

The Cambrian-Ordovician carbonate sequence thins from 8,400 feet in southern Pennsylvania and central Maryland to about 8,200 feet (King, 1950, p. 6-7) in Page and Rockingham Counties, Va. The thinning is accompanied by a gradual increase in the proportion of dolomite to limestone. As the Cambrian-Ordovician sequence thins from northern Virginia to the southwest corner of Virginia, the stratigraphy becomes more complex, and more formations are recognized. The writer had difficulty in locating a convenient boundary between the Cambrian-Ordovician carbonate sequence and the underlying Early Cambrian clastic sequence in southwestern Virginia and southeastern Kentucky. In most of the Appalachian basin the boundary coincides closely with the Lower Cambrian-Middle Cambrian boundary. In the only records available to the writer of the deep test wells recently drilled in eastern Kentucky, a contact was shown between a thick sequence of carbonate rocks above and a shale section below that was designated as the Rome shale. The writer believes that this contact occurs well up in the Middle Cambrian

Series and is most nearly equivalent to the top of the Conasauga Group of Middle Cambrian age in outcrop sections in nearby southwestern Virginia. Consequently, the base of the Cambrian-Ordovician carbonate sequence in southwest Virginia is placed at the top of the Conasauga Group in order that the boundary will be reasonably consistent with the only contact shown in this general part of the stratigraphic section in available logs of the Kentucky deep wells. On lithologic criteria the Conasauga could be placed in either sequence with equal justification because it consists of nearly equal amounts of carbonate and noncarbonate rocks. Recent work in Lee County, Va. (Miller and Fuller, 1954, pl. 9; Harris and Miller, 1958) resulted in the terminology shown in the following table.

Generalized section, Cambrian-Ordovician carbonate sequence exposed in Lee County, Va.
(after Miller and Fuller, 1954, Pl. 9; Harris and Miller, 1958)

Series	Group	Formation	Thickness (feet)	Character
Middle Ordovician		Trenton Limestone	600	Light-gray fossiliferous limestone with some shale; a bentonite bed near base.
Middle Ordovician		Eggleston	165	Light olive-gray calcareous mudstone with some limestone; two bentonite beds in upper part.
Middle Ordovician		Hardy Creek Limestone	130	Light olive-gray fine-grained limestone; argillaceous in part; some chert.
Middle Ordovician		Ben Hur Limestone	145	Light olive-gray fine-grained well laminated limestone.
Middle Ordovician		Woodway Limestone	375	Light olive-gray to olive-black fine-grained limestone; chert nodules below.
Middle Ordovician		Unnamed limestone	270	Light olive-gray fine-grained limestone.
Middle Ordovician		Unnamed limestone	130	Brownish-gray to olive-black fine-grained limestone; chert nodules below.
Middle Ordovician		Dot Dolomite unconformity	150	Light-gray fine-grained dolomite with calcareous shale; chert in base.
Lower Ordovician	Knox Group	Mascot Dolomite	520	Light- to medium-gray fine-grained dolomite; much chert; beds and lenses of quartz sand.
Lower Ordovician	Knox Group	Kingsport Dolomite Longview Dolomite	195	Very light gray dolomite with scattered quartz grains; some fine-grained limestone in upper part.
Lower Ordovician	Knox Group	Chepultepec Dolomite	700	Light-gray argillaceous dolomite above; light-gray fine-grained dolomite with sand lenses below.
Upper Cambrian	Knox Group	Copper Ridge Dolomite	630	Thin-bedded brownish-gray dolomite above; massive-bedded brownish-gray coarser-grained dolomite below.
Upper Cambrian		Maynardville Limestone	200	Upper part is medium gray with chert and sand lenses. Lower part is medium-gray fine-grained limestone.

Rocks of the Cambrian-Ordovician carbonate sequence are well exposed in several belts in the eastern part of the Valley and Ridge province in east-central Tennessee. In this area thick wedges of noncarbonate rocks occur in the lower and upper parts of the Cambrian-Ordovician sequence. The total thickness of the carbonate and noncarbonate rocks comprising the sequence is approximately 12,600 feet in Blount County, Tenn., the greatest thickness reported in the Appalachian basin. Recent detailed studies in southern Knox County and the northern half of Blount County, Tenn., resulted in recognition of the stratigraphic sequence shown in the following table.

Generalized section, Cambrian-Ordovician carbonate sequence in Knox and Blount Counties, Tenn.
(from Cattermole, 1955, and Neuman and Wilson (in press)

Series	Group	Formation	Thickness (feet)	Character
		unconformity		
Middle Ordovician		Bays	900	Calcareous red mudrock and siltstone: some sandstone and quartzite.
		Sevier	2,100	Silty gray shale, gray to reddish-gray sandstone, and some gray to maroon calcarenite.
		Chota	700-1,000	Quartzose dark-gray and reddish-gray calcarenite with some argillaceous limestone.
		Tellico	3,875	Calcareous sandy gray shale and fine- to medium-grained gray sandstone; some limestone in upper part.
		Blockhouse Shale unconformity	410	Calcareous dark-gray shale.
		Lenoir unconformity	100	Upper part, dark-gray argillaceous or silty limestone: lower part, light-gray aphanitic limestone: unconformity separates two parts.
Lower Ordovician	Knox	Mascot Dolomite	750	Dark-gray dolomite and light-gray limestone with layers and beds of chert.
		Kingsport	350	Light- to dark-gray dolomite and brown limestone with some chert.
		Longview Dolomite	300	Light-colored fine-grained dolomite with some doloclastic chert.
		Chepultepec Dolomite	800	Light-colored dolomite with chert: much limestone above: some sandstone below.
Upper Cambrian		Copper Ridge Dolomite	900	Crystalline slightly asphaltic light- to dark-gray dolomite and granular gray dolomite: some chert.
	Conasauga	Maynardville Limestone	250	Upper part largely dark-gray dolomite: lower part limestone and shale.
		Nolichucky Shale	750	Light- to dark-colored shale and calcareous shale: lenses of limestone.
Middle Cambrian		Maryville Limestone	670	Thick-bedded blue-gray limestone.
		Rogersville Shale	200	Green shale with some thin beds of limestone in upper part.
		Rutledge Limestone*	210	Banded dark-blue limestone.

The Rutledge Limestone is underlain by the Pumpkin Valley Shale of Middle Cambrian age. For reasons of convenience the Pumpkin Valley is considered here as the uppermost unit of the Lower Cambrian clastic sequence.

The lower part of the Paleozoic sequence in the Valley and Ridge province in northwest Georgia and northeast Alabama has received relatively little recent study. Consequently the stratigraphic relationships are uncertain. The Cambrian-Ordovician carbonate sequence appears to thin from Blount and Monroe Counties, Tenn., as it is traced southwestward across Georgia and Alabama. Most of the thinning can be attributed to unconformities between the carbonate formations in the sequence, and to the abrupt thinning of the noncarbonate clastic formations in the upper part of the sequence from their area of greatest thickness in southeastern Tennessee. In the vicinity of Birmingham, Ala., Butts (1910, columnar section) reported only 4,300 feet of rocks assignable to the present Cambrian-Ordovician carbonate sequence. The thinness of the carbonate sequence was attributed by Butts (1926, p. 115, 117-118, pl. 27) to restricted deposition and to erosion during parts of Cambrian and Ordovician time in an area of gentle uplift in the vicinity of Birmingham. The average thickness, however, of the carbonate sequence in northeastern Alabama is closer to 6,000 feet. The following table summarizes the stratigraphy of the sequence recognized by Butts (1926, p. 67-133) in northeast Alabama.

Highly generalized composite section, Cambrian-Ordovician carbonate sequence recognized by Butts (1926, p. 67-133) in the Valley and Ridge province of northeastern Alabama

Series	Formation	Thickness (feet)	Character
	unconformity		
Upper Ordovician	Chickamauga Limestone	200-500	Medium- to thick-bedded fine-grained blue limestone; some shale and bentonite beds in upper part.
	unconformity		
Middle Ordovician	Little Oak Limestone	0-500	Thick-bedded argillaceous coarsely crystalline dark limestone with chert nodules: two bentonite beds near top.
	Athens Shale	15-300	Fissile highly calcareous black shale with layers of impure very dark-gray limestone.
	unconformity?		
	Lenoir Limestone	500	Finely crystalline dark limestone.
	Mosheim Limestone	20-50	Dense bluish-gray aphanitic limestone.
	unconformity		
Lower Ordovician	Odenville Limestone	50	Argillaceous siliceous fine-grained dark cherty limestone.
	Newala Limestone	1,000	Aphanitic pearl-gray to dark-gray limestone with layers of dolomite.
	Longview Limestone	500	Light-gray limestone with chert and much dolomite.
	unconformity		
	Chepultepec Dolomite	1,000	Lower part, dense light-gray limestone; upper part, coarsely crystalline dark bluish dolomite.
Upper Cambrian	Copper Ridge Dolomite	1,000	Coarse-grained siliceous light-gray dolomite with much chert in weathered exposures.
	Bibb Dolomite	250-500	Coarsely crystalline highly siliceous dolomite.
Middle Cambrian	Ketona Dolomite	250-600	Coarsely crystalline light-gray nearly pure dolomite.
	unconformity		
	Brierfield Dolomite	1,500	Coarse-grained steel-blue highly siliceous dolomite
	Conasauga Formation	* 500-1,900	Alternating beds of limestone, dolomite and shale with some chert.

*Howell and others (1944, chart no. 1) show that the most of the Conasauga is laterally equivalent to the Brierfield, Ketona, and Bibb Dolomites. Consequently the total average thickness of the Cambrian-Ordovician carbonate sequence may be as much as 2,000 to 2,300 feet less than the total of 9,250 feet that is obtained by adding the average thickness of individual rock units reported by Butts.

The Cambrian-Ordovician carbonate sequence thins northwestward across Alabama and eastern Tennessee toward the crest of the Nashville dome. The thinning is caused by the pinchout along the flanks and crest of the dome of some carbonate rock units, and by the rapid wedging out of clastic units in the lower and upper parts of the sequence. A deep well in Giles County, Tenn. (Dott and Murray, 1954), about 18 miles south of the crest of the Nashville dome, penetrated about 5,600 feet of carbonate rocks above the basement complex. The figure of 5,600 feet is very nearly the full thickness of the Cambrian-Ordovician sequence in this area. The rocks penetrated consist, from the surface downward, of 650 feet of limestone, 1,800 feet of cherty and sandy dolomite, 1,800 feet of cherty dolomite, 1,350 feet of dolomite, and 80 feet of arkosic sandstone immediately above the basement complex.

The carbonate sequence thins northward along the elongate arches and domes that mark the west edge of the Appalachian basin. In the vicinity of Lake Erie the sequence is slightly less than 1,500 feet thick (fig. 7). In Powell County, Ky., approximately halfway between Giles County, Tenn., and Lake Erie, the sequence is about 4,650 feet thick in the subsurface and is divided into the following units:

Generalized section, Cambrian-Ordovician carbonate sequence recognized by Freeman (1953, p. 254-260) in the No. 1 James Hall well, western Powell County, Ky.

Series	Formation	Thickness (feet)	Character
Middle Ordovician	Cynthiana-Million	236	Dark-gray argillaceous to coarsely crystalline fossiliferous limestone; some shale in lower part.
	Lexington	203	Light-gray to brown argillaceous, fossiliferous phosphatic limestone.
	Chazy-Black River	659	Tan to brown lithographic dolomitic limestone; some dolomite in lower part.
?	St. Peter unconformity	18	Sandstone composed of coarse, rounded, and frosted grains.
Upper Cambrian	Eminence	177	Cream to gray fine- to coarse-crystalline dolomite with white chert.
	Potosi	429	White to light-gray medium-crystalline dolomite with much chert, some quartz sand and glauconite.
	Elvins	387	Light-tan to gray medium-crystalline dolomite with much quartz sandstone near middle and some in basal part.
	Bonneterre	1,414	Brown finely crystalline dolomite with some shale and limestone near base.
Middle Cambrian	Elbrook(?)	1,126	Greenish-gray to red shale with much interbedded limestone, some siltstone and calcareous sandstone; scattered glauconite throughout.

Freeman reported an additional 765 feet of Elbrook extending to the bottom of the hole. However, the basal 765 feet of rock, consisting largely of shale, quartz siltstone, and sandstone, is excluded from the carbonate sequence, and is included in the underlying Early Cambrian clastic sequence by the present writer. In the above section the boundaries between series were determined by comparing the formation names used by Freeman with the stratigraphic position of rock units bearing the same name shown on the Cambrian correlation chart (Howell and others, 1944, chart no. 1) and the Ordovician correlation chart (Twenhofel, 1954, chart). The writer feels that the absence of the Lower Ordovician series does not indicate an unconformity in the carbonate sequence in this area, but is due to errors in extending names of rocks that crop out west of Kentucky into the subsurface in eastern Kentucky.

Thickness and depth.--The Cambrian-Ordovician carbonate sequence ranges in thickness from about 800 feet in northern New York to slightly more than 12,000 feet in southeastern Tennessee. The axis of greatest thickness extends from southeast New York to northeast Alabama approximately parallel to the east edge of the Appalachian basin (fig. 7). The sequence thins rapidly east of the axis of greatest thickness and thins gradually westward toward the Findlay arch, Cincinnati arch, and Nashville dome. A secondary axis of greatest thickness parallels the Kentucky River fault system in east-central Kentucky. An area of thick predominantly noncarbonate clastic rocks in the lower and especially in the upper parts of the carbonate sequence is centered in southeastern Tennessee and extends outward into contiguous States.

The top of the Cambrian-Ordovician carbonate sequence lies at depths less than 5,000 feet below sea level in large areas around the periphery of the Appalachian basin (fig. 8). In much of the central part of the basin the top is more than 5,000 feet below sea level, and in southwest Pennsylvania and north-central West Virginia the top of the carbonate sequence is more than 12,000 feet below sea level. Within the basin the sequence occurs above sea level and is exposed at the surface along the south flank of the Adirondack uplift (fig. 2) in northeastern New York, at many places in the Valley and Ridge province, along much of the eastern margin of the basin, along the southeast flank of the Nashville dome in Tennessee, and along the east flank of the Jessamine dome in Kentucky.

Late Ordovician clastic sequence

A relatively thin sequence of predominantly noncalcareous clastic rocks overlies the Cambrian-Ordovician carbonate sequence. The contact is conformable throughout most of the basin. The rocks consist largely of shale, ranging from black to red in color, and of siltstone and sandstone ranging from gray to red. The bulk of the clastic sequence is Late Ordovician in age. However, in parts of the Appalachian basin, especially in eastern New York, some rocks of Middle Ordovician age are included in this report, in order that the boundary between the two sequences will coincide with an easily recognized major change in lithology from carbonate rocks below to noncarbonate rocks above.

The Late Ordovician clastic sequence is present throughout most of the basin. The sequence thins rather uniformly to the north, west, and southwest from its area of greatest thickness in eastern Pennsylvania (fig. 9). In most parts of the basin, the basal part consists largely of dark-gray to black shale composing units such as the Martinsburg, Utica, and Reedsville Shales. In the northeast part of the basin where the sequence is thickest, the upper part consists largely of red and light-gray coarse-grained rocks that accumulated on or in front of a large delta. The coarse-grained rocks--the Oswego Sandstone below and the Juniata Formation above--grade westward into finer-grained predominantly red rocks of the Queenston Shale. Along the flanks of the arches and domes marking the west edge of the basin, the Late Ordovician sequence consists largely of interbedded gray to black limestone and shale.

The Late Ordovician clastic sequence has not been productive of oil and gas in commercial quantities, and in general is of little economic significance, especially in the subsurface. Overlying it is a relatively thin sequence of clastic rocks, composed largely of shale, sandstone, and conglomerate, here referred to as the Early Silurian clastic sequence. It is separated from the Upper Ordovician succession largely because it is highly productive of oil and gas in large areas of the basin. Furthermore Lower Silurian rocks are used for the underground storage of hydrocarbons in many places, whereas Upper Ordovician rocks have not been utilized for this purpose.

As Figure 9 shows, Upper Ordovician rocks are not exposed along the northwest margin of the basin. In the subsurface in northwestern Ohio the Late Ordovician clastic sequence consists of 1,000 feet or less of interbedded argillaceous limestone and calcareous shale. The lower two units--the Utica and Eden Groups--consist largely of dark-brown and grayish-black slightly calcareous shale. The upper two units--the Maysville and Richmond Groups--consist of gray to green highly calcareous shale and interbedded limestone. A few thin beds of red shale near the top of the sequence represent the thin western edge of the thick wedge of deltaic red sediments composing the Queenston Shale and the Juniata Formation. The Queenston or the equivalent Juniata underlie much of New York and Pennsylvania, and parts of Maryland, West Virginia, and Virginia.

In northwest Pennsylvania and in contiguous parts of Ohio and New York the Late Ordovician clastic sequence is composed of about 2,000 feet of noncalcareous rocks. The generalized section that follows was encountered between 4,866 feet and 6,749 feet below the surface, and is typical of the Late Ordovician sequence in the subsurface in northwest Pennsylvania, northeast Ohio, and southwest New York.

Generalized section, Late Ordovician clastic sequence in the Emma McKnight no. 1 well, Mercer County, Pa. (Wagner, 1958, p. 20-25)

Series	Formation	Thickness (feet)	Character
Upper Ordovician	Queenston Shale	854	Brick-red partly silty slightly calcareous shale with much greenish-gray shale.
	Oswego Sandstone	70-	Greenish-gray argillaceous siltstone and sandstone with some greenish-gray silty shale.
	Reedsville Shale	830	Dark greenish-gray to gray slightly calcareous shale with thin layers of siltstone and limestone.
	Utica Shale	199	Dark-gray to grayish-black shale; grades downward into the Trenton limestone.

The Late Ordovician sequence in western and central New York is similar in lithology and thickness to the sequence in northwestern Pennsylvania. However, rapid changes occur in eastern New York in the area south of the Adirondack uplift. The section is thinner and is composed of different kinds of rocks. The changes are due largely to the absence of the Queenston (red) Shale and the Oswego (gray) Sandstone in the upper part, and to facies changes in the lower part. The Queenston and Oswego either were not deposited in this area or they were removed by erosion subsequent to deposition. Changes in the lower part are due to the fact that the contact between carbonate rocks below and clastic rocks above descends to progressively lower stratigraphic positions eastward. Consequently in eastern New York rocks of late Middle Ordovician age consist of shale and are included in the lower part of the clastic sequence. To the west stratigraphically equivalent rocks of late Middle Ordovician age consist of limestone and are included in the upper part of the underlying Cambrian-Ordovician carbonate sequence. The changes in the Late Ordovician sequence are shown by a comparison of the section that follows with the section in northwestern Pennsylvania.

Generalized section, Late Ordovician clastic sequence in C. C. Lobdell no. 1 well, northeastern Chenango County, N. Y., on the southwest flank of the Adirondack uplift (Donnerstag and others, 1950, p. 8 and chart).

Series	Formation	Thickness (feet)	Character
	unconformity?		
Upper Ordovician	Pulaski	444	Medium-gray siltstone and interbedded dark-gray shale.
	Frankfort	386	Silty gray shale above; light-gray siltstone and shale below.
?			
Middle Ordovician	Utica	371	Dark-gray shale.

According to Donnerstag the Late Ordovician clastic sequence of this report is overlain, probably unconformably, by conglomerate and sandstone of the Clinton Formation of Early Silurian age. Eastward from northeastern Chenango County to Albany County, additional changes occur in the underlying Middle Ordovician carbonate rocks and in the Upper Ordovician clastic rocks. The upper part of the carbonate sequence interfingers to the east at progressively lower stratigraphic positions with an expanding wedge of grayish-black shale that contains beds of siltstone and sandstone. As previously stated the boundary between the Late Ordovician clastic sequence and the Cambrian-Ordovician carbonate sequence also descends to the east to separate clastic rocks above from carbonate rocks below. This clastic wedge, the Canajoharie Shale, is about 2,000 feet thick in eastern Montgomery County, N. Y. As the clastic wedge of Middle Ordovician rocks thickens toward the Hudson River Valley, the black shale is replaced by gray shale and the content of siltstone and sandstone increases. In Albany County two formations constitute the expanded sequence--the Snake Hill Formation below and the Schenectady Formation above. The Utica, Frankfurt, and Pulaski Formations thin rapidly east of Chenango County. In much of Schoharie and Albany Counties, rocks of Late Ordovician age seem to be absent. In other parts of Albany County a thin sequence of interbedded shale and sandstone appears to be the only rock unit of Late Ordovician age in eastern New York. This unit, the Indian Ladder Shale, ranges in thickness along the outcrop from 0 feet to about 410 feet. The absence of Upper Ordovician rocks in most of eastern New York is attributed to nondeposition and to uplift and erosion during Late Ordovician time. In many places in eastern New York the pyritiferous Brayman Shale of Late Silurian age (Fisher and Rickard, 1953, p. 5-13) unconformably overlies shales of Middle Ordovician age.

In much of northeastern Pennsylvania and northwestern New Jersey the Late Ordovician clastic sequence is composed entirely of the Martinsburg Shale. The Martinsburg is an incompetent homogeneous sequence consisting largely of alternating layers of dark-gray to black shale or slate and thin even beds of gray siltstone and sandstone. Because it has been complexly folded, sheared, and faulted, its thickness cannot be measured accurately. Estimates of its thickness usually range from 4,000 feet to 8,000 feet. In some areas (Johnson and Willard, 1957, p. 129) a 500-foot sequence consisting largely of sandstone is present at the top. In other areas the sandstone unit is cut out by the Late Ordovician unconformity. Twenhofel (1954, chart 2) shows that the lower part of the Ordovician in eastern Pennsylvania and northwestern New Jersey is Middle Ordovician in age. It rests conformably upon the Jacksonburg Limestone--the uppermost unit of the Cambrian-Ordovician carbonate sequence--and is overlain by the Shawangunk Formation of Early Silurian age. The upper contact is unconformable and Johnson and Willard (1957, p. 129) report that Martinsburg strata may lie at angles as high as 90° with the Shawangunk strata. Rocks equivalent to the Oswego Sandstone, and Queenston Shale farther west are absent in most of eastern Pennsylvania and adjoining parts of New Jersey, although they are present in central Pennsylvania. The absence of the higher Upper Ordovician rocks along the eastern outcrop belts and the sharp angular unconformity at the Martinsburg-Shawangunk contact are evidence of diastrophic activity at the end of Ordovician time.

The Martinsburg crops out across Pennsylvania in a broad belt parallel to and immediately east of the folded Appalachian mountains. In Lehigh and Berks Counties the belt is as much as 14 miles in width. In Lebanon County the Martinsburg is more heterogeneous than in most other parts of the Appalachian basin. According to Mosely (1952, p. 79-80) the Martinsburg contains shale ranging in color from light gray to black, red, and green. Much of the shale has been metamorphosed to phyllite. Quartzose sandstone, thick-bedded argillaceous sandstone, conglomerate, impure quartzitic limestone, and several layers of basaltic lava are also present.

In Washington County, Md., and in adjacent counties in Pennsylvania, West Virginia, and Virginia, the Martinsburg is overlain by the Oswego Sandstone, which is overlain by the Juniata Formation. Both the Oswego and the Juniata are thin in this area, and both are absent a short distance to the east. Cloos (1951, p. 66-69) tentatively classifies 77 feet of gray and gray-green sandstone overlying the Martinsburg in Washington County as Oswego Sandstone. The Oswego is overlain by 92 feet of predominantly red sandstone which is assigned to the Juniata Formation. In this area the Late Ordovician clastic sequence is overlain by the Tuscarora Sandstone of Early Silurian age. In southern Page County, Va., King (1950, p. 6) shows that the Martinsburg Shale (approximately 2,800 feet thick) is directly overlain by sandstone of Silurian age.

The Martinsburg extends the length of the Shenandoah Valley in the western part of Virginia. In most places it is overlain by red sandstone, red shale, and mudrock of the Juniata Formation. However, in parts of southwest Virginia facies changes in the Late Ordovician clastic sequence have resulted in the recognition of additional formation names. The stratigraphic sequence recognized by Harris and Miller (1958) is summarized in the following table.

Generalized sections, Late Ordovician clastic sequence exposed in the Duffield 7½-minute quadrangle, Lee and Scott Counties, Va. (from Harris and Miller, 1958)

Northwest part	Series	Southeast part
Sequatchie Formation (260): interbedded calcareous grayish-red siltstone and grayish-red to greenish-gray argillaceous limestone.	Upper Ordovician	Sequatchie Formation (325): grayish-red calcareous siltstone with some interbedded greenish-gray argillaceous limestone and shale.
Reedsville Shale (375): interbedded olive-gray limestone and grayish-yellow shale; overlies Trenton limestone of Middle Ordovician age.		Martinsburg Shale (1200): upper part, interbedded medium-gray argillaceous very fine-grained limestone and olive-gray shale; lower part (Middle Ordovician in age) interbedded grayish-yellow shale and light-gray sandy textured limestone; overlies Moccasin Formation of Middle Ordovician age.
	Middle Ordovician	

For the purpose of this report, the base of the clastic sequence of predominantly Late Ordovician age is designated as the top of the Trenton Limestone in the northwest part of the Duffield quadrangle, and the top of the Moccasin Formation in the southeast part. In this area the nonmarine Juniata Formation is represented by the marine Sequatchie Formation. The lower part of the Martinsburg Shale interfingers westward across the quadrangle with the Trenton Limestone of Middle Ordovician age, and the upper part of the Martinsburg interfingers westward into the Reedsville Shale of early Late Ordovician age. A similar facies relationship between the Middle and Upper Ordovician rocks in east-central Tennessee is well shown diagrammatically by Rodgers (1953, fig. 4). The Late Ordovician clastic sequence is overlain by the Clinch Sandstone—the lowest unit of the Early Silurian clastic sequence of this report.

The Late Ordovician clastic sequence is absent along much of the eastern part of the Tennessee Valley in Tennessee. In some places, as in central Blount County between Maryville and the west slope of Chilhowee Mountain (Neuman, in King and others, 1952), the late Middle Ordovician Bays Formation is unconformably overlain by the Chattanooga Shale of Middle and Late Devonian age. The large gap in the rock sequence is attributed to uplift and erosion in the eastern part of the Tennessee Valley in pre-Chattanooga time. In much of the central part of the Tennessee Valley the Late Ordovician clastic sequence is composed largely of the Martinsburg Shale. In much of the western part of the Valley, the Late Ordovician sequence consists largely of the Chickamauga Limestone and calcareous shale and argillaceous limestone of the Reedsville Shale and the Sequatchie Formation.

The percentage of calcium-carbonate in the Late Ordovician sequence appears to increase southwestward from eastern Tennessee across Georgia into northeastern Alabama. In the vicinity of Birmingham, Jefferson County, Ala., Butts (1926, p. 119-133) includes all rocks of Late Ordovician age in the Chickamauga Limestone. The Chickamauga includes rocks of Early, Middle, and Late Ordovician age, as well as several unconformities. An unconformity at the top of the Chickamauga results in the absence of rocks equivalent to the Oswego, Sequatchie, Juniata, and Queenston in parts of the Appalachian basin north of Alabama. The unconformity increases in magnitude to the southeast. Data presented by Butts (1940) in southern Shelby County indicate that rocks of late Middle Ordovician, Late Ordovician, Silurian, and Early Devonian ages are absent. In this area the Middle Ordovician Little Oak Limestone is unconformably overlain by the Frog Mountain Sandstone of Early or Middle Devonian age. In northeastern Alabama the Chickamauga is composed largely of medium to thick-bedded fine-grained blue limestone. A conglomerate of chert gravel occurs at the base of the formation, and some greenish clay shale and red limestone are present a short distance above the conglomerate.

It is extremely difficult to trace Upper Ordovician strata from the outcrop belt in northeast Alabama into the subsurface in northwest Alabama. Sample studies of recent wells drilled for oil and gas in the northwest part of Alabama (McGlamery, 1955) indicate that the Chattanooga shale is underlain by 100 feet to 400 feet of interbedded greenish-gray to red limestone and sandy limestone, green and red shale, and some fine-grained sandstone. This sequence was considered by McGlamery to be Silurian in age. The Silurian rocks are underlain by a thick sequence of gray limestone designated by the same writer as Ordovician in age. If there is no unconformity between these strata, then part of the gray limestone sequence may be Upper Ordovician in age. If an unconformity is present, none of the gray limestone may be Late Ordovician in age. Because the exact relationships of these rocks are not known, the isopach lines in northern Alabama (on fig. 9) are highly generalized and are speculative.

Rocks of Late Ordovician age crop out along the flanks of the Nashville dome in central Tennessee. They range in thickness from 0 to about 150 feet, and are composed largely of calcareous shale and argillaceous limestone. A series of thickness maps by Wilson (1949, figs. 50, 54, 62, 63, 64, and 65) show that many of the formations comprising the Late Ordovician sequence thin toward the crest of the Nashville dome and are absent in Rutherford County and parts of contiguous counties on the crest of the dome. The sequence unconformably overlies the Catheys Formation of Middle Ordovician age and unconformably underlies the Brassfield Limestone of Early Silurian age. The stratigraphy of the Late Ordovician sequence in central Tennessee is summarized in the following table.

Generalized section, Late Ordovician clastic sequence exposed in central Tennessee (from Wilson, 1949)

Series	Group	Formation	Thickness (feet)	Character and distribution
		unconformity		
Upper Ordovician	Richmond	Mannie Shale	0-50	Heterogeneous sequence of greenish argillaceous limestone, calcareous shale and noncalcareous shale; absent on crest of Nashville dome; interfingers eastward with upper part of Sequatchie.
		Fernvale Limestone (Sequatchie formation)	0-45	Massive and irregularly bedded, very coarse crystalline light-colored limestone; red locally; absent on crest of dome: intertongues eastward with Sequatchie formation.
		Sequatchie (Sequatchie formation)	0-20	Greenish-gray to red calcareous and dolomitic mudstone, argillaceous limestone, shale and sandstone; absent on crest of dome.
		unconformity		
		Arnheim (Sequatchie formation)	0-20	Heterogeneous limestone sequence like Leipers below; present on northwest flank of dome; absent on southeast flank.
		unconformity		
	Maysville	Leipers	0-150	Heterogeneous sequence of blue-gray thin-bedded nodular limestone, massive dark-blue coarse-grained limestone, massive argillaceous limestone, blue-gray calcareous shale, light-gray to bluish-gray mudstone and siltstone; absent on crest of Nashville dome.
		unconformity		
	Eden	Inman	0-50	Interbedded greenish-gray calcareous shale and fine-grained laminated limestone in thin beds; some layers of red shale; present on southeast flank of arch.
		unconformity		

Lithologically the Late Ordovician rocks of eastern Kentucky closely resemble those of central Tennessee. However, the nomenclature is different. The writer had difficulty in placing the contact in Kentucky between rocks to be included in the Cambrian-Ordovician carbonate sequence of this report and the predominantly noncarbonate Late Ordovician sequence that overlies it. Freeman (1953, p. 26) reports that there is no sharp faunal or lithologic break between rocks of Middle Ordovician and Late Ordovician age in surface exposures or in the subsurface. The present writer used the horizon designated as the top of the Cynthiana Formation by Freeman. In places where Freeman grouped the Cynthiana with the overlying Million Shale, the present writer used the base of the lowest shale bed of appreciable thickness in the Million to separate the Middle from the Upper Ordovician series as well as the carbonate sequence below from the clastic sequence above. As a result of the uncertainty of placing this horizon in the eastern half of Kentucky there may be discrepancies in the structure-contour map (fig. 8) and the isopach maps of the Cambrian-Ordovician carbonate sequence (fig. 7) and the Late Ordovician clastic sequence (fig. 9). The following table briefly describes the stratigraphic sequence in eastern Kentucky.

Generalized section, Late Ordovician clastic sequence in the No. 2 Prewitt, Miller and Goff well, Powell County, Ky.
(adapted from Freeman, 1953, p. 245-253)

Series	Group	Formation	Thickness (feet)	Character
Upper Ordovician	Richmond		120	Gray-green shale at bottom and top; gray, gray-green fine-grained argillaceous limestone, gray-green silty argillaceous dolomite, and trace brownish-red dolomite in middle.
	Maysville	Gilbert	20	Dark-gray slightly phosphatic, slightly argillaceous limestone.
		Tate	134	Greenish-gray fine-grained argillaceous limestone; some reddish limestone.
		Fairmount	72	White to gray, argillaceous to crystalline phosphatic very fossiliferous limestone.
	Eden	Garrard	98	Gray limestone as above.
		Million Shale and Cynthiana Formation		Upper part gray fossiliferous phosphatic crystalline limestone with some dark calcareous shale.
?	?			
Middle Ordovician				Lower part limestone as above with small amount of chert and very small amount of gray shale.

Thickness and depth.--From the area of greatest thickness (slightly more than 4,000 feet) in eastern Pennsylvania the Late Ordovician clastic sequence thins to the northwest and southwest. It is less than 1,000 feet thick along the crests of the Findlay arch in northwest Ohio, and less than 400 feet thick along the crest of the Cincinnati arch in Kentucky. As previously mentioned, it is absent on the crest of the Nashville dome in central Tennessee and is thin on the flanks of the dome. The writer considers the thickness map of the Late Ordovician clastic sequence (fig. 9) to be least accurate along the east margin of the Appalachian basin and in the southern extremity of the basin south of the southern border of Tennessee. Few accurate thickness measurements are available along the structurally complex eastern part of the basin. In Alabama and Georgia facies changes and uncertainty of age relationships made it difficult to determine the base of the Upper Ordovician series accurately and consistently. In eastern Kentucky also, where the rocks are not exposed, it was difficult to determine the base of the Upper Ordovician series with accuracy and consistency.

A map showing the structural configuration of the Late Ordovician clastic sequence was not prepared. However, in much of the Appalachian basin the elevation of the top of the sequence can be determined approximately by referring to figures 10 and 11. Figure 10 shows the thickness of the Early Silurian clastic sequence, which immediately overlies the Late Ordovician sequence, and figure 11 shows the elevation of the top of the Early Silurian clastic sequence with reference to mean sea level. In areas of gentle structure the Late Ordovician sequence is deeper than the Early Silurian sequence by an amount equal to the thickness of the latter. In areas of steeply dipping rock, the Late Ordovician sequence may be deeper than the Early Silurian sequence by an amount much greater than the thickness of the Early Silurian sequence.

By comparing figures 10 and 11 it can be seen that the Ordovician sequence is deepest (more than 25,000 feet below sea level) in a small narrow trough in Schuylkill and Carbon Counties, Pa. It is moderately deep (5,000-11,000 feet below sea level) in a broad trough approximately parallel to the Appalachian structural front, extending from northeastern Pennsylvania to southernmost West Virginia. From the axis of this trough the sequence rises to the west, north, and east toward outcrop areas. Consequently the top of the Late Ordovician clastic sequence occurs at depths less than 5,000 feet in most peripheral parts of the Appalachian basin.

Early Silurian clastic sequence

The Late Ordovician clastic sequence is overlain by a thin sequence of predominantly clastic rocks, mainly of Early Silurian age, that extends throughout most of the Appalachian basin (fig. 10). The Early Silurian sequence underlies a thick sequence of predominantly calcareous rocks of Middle and Late Silurian and early Devonian age, the Silurian-Devonian carbonate sequence of the report. Like the underlying Late Ordovician sequence, the Early Silurian clastic sequence is thickest and coarsest grained in the northeastern part of the basin where it consists largely of sandstone and conglomerate. It thins to the north, west, and southwest. In the central part of the basin it is composed largely of shale, siltstone, and sandstone. Along the western part of the Appalachian basin it is composed largely of limestone and dolomite. In general the sequence is divisible into a lower sandy part and an upper shaly part. Among the better known and more extensive units in the lower part are the sandstones comprising the Albion Group, the Tuscarora Quartzite or Sandstone, and the Clinch Sandstone. In northwestern New Jersey and contiguous parts of New York and Pennsylvania, the Shawangunk or the Green Pond Conglomerate comprises the entire sequence. In northeastern Alabama the Red Mountain Formation (largely sandstone) comprises the entire sequence. Among the better known and more extensive units in the upper shaly part are the Clinton Shale or Group, the Rochester Shale, and the Rose Hill Formation (largely shale).

Some of the sandstones most productive of oil and gas in the Appalachian basin occur in the Early Silurian sequence. Among the productive sandstones are the "Clinton sands" of the eastern half of Ohio, the "Medina sands" of the Albion Group of the western half of New York and the northwest corner of Pennsylvania, the "Big Six" sand in parts of eastern Kentucky and southwestern West Virginia, and the Tuscarora Sandstone in parts of western West Virginia. The Tuscarora and equivalent rocks are largely untested potential reservoirs of gas in much of Pennsylvania, south-central New York, eastern Ohio, and much of West Virginia.

The stratigraphic relationships of the Early Silurian rocks in Ohio and parts of contiguous States are well described by Rittenhouse (1949). In eastern Ohio the Early Silurian clastic sequence of this report includes some rocks (the Dayton Limestone and Alger or Rochester Shale at the top) of early Middle Silurian age. The sequence conformably overlies the Queenston Shale of Late Ordovician age and is overlain conformably by the Lockport Dolomite of Middle Silurian age. It is composed largely of clastic rocks in the eastern half of the State, and in most areas includes at least three more-or-less distinct layers of sandstone. Westward toward the outcrop on the east flank of the Findlay arch, the sandstones and interbedded shale interfinger with dolomite and limestone of the Brassfield Limestone. The following section is typical of the Early Silurian sequence in the subsurface in eastern Ohio:

Generalized section, Early Silurian clastic sequence in wells in Stark and Wayne Counties, Ohio (after Pepper and others, 1954, p. 4-8)

Series	Formation or drillers' name	Thickness (feet)	Character
Middle Silurian	Alger Shale-Rochester Shale	45	Light-gray shale with interbedded limestone; some dolomite near top.
	Dayton Limestone "Packer Shell"	30	White to light-gray limestone with interbedded shale; some chert near top.
Lower Silurian		30	Greenish-gray shale with interbedded white to grayish-green siltstone and light-gray limestone.
	"Stray Clinton"	10	White siltstone; some light-gray to greenish-gray shale.
	"Red Clinton"	48	White to grayish-red fine-grained sandstone with some grayish siltstone and light-gray to purplish shale: some bands of hematite.
	"White Clinton"	50	White to greenish-gray fine-grained sandstone, with some light-gray to greenish-gray siltstone.
	Unnamed	60	Interbedded light-gray to greenish-gray siltstone and shale.

Rocks comprising the Early Silurian clastic sequence of this report crop out along the Niagara Gorge a short distance below Niagara Falls.

Generalized section, Early Silurian clastic sequence exposed in the Niagara quadrangle, New York (adapted from Kindle and Taylor, 1913, p. 6; Gillette, 1947, p. 13; Fisher, 1960)

Series	Group	Formation or drillers' name	Thickness (feet)	Lithology
Middle Silurian	Clinton	Rochester Shale	60	Olive to bluish calcareous clay shale.
		Irondequoit Limestone	15	Light-gray coarsely crystalline crinoidal limestone.
		Reynales Limestone	12	Dark-gray fine- to coarse-grained dolomitic limestone; basal part phosphatic and pyritic.
		Neahga Shale	5	Olive-green slightly calcareous silty shale.
Lower Silurian	Medina	Thorold Sandstone ("Gray Medina sand")	6	Light-gray fine-grained highly argillaceous well-cemented sandstone.
		Grimsby Sandstone ("Red Medina sand")	53	Interbedded gray to red sandstone and red to bluish-gray sandy shale
		Whirlpool Sandstone ("White Medina sand")	22	White crossbedded sandstone.

The Early Silurian clastic sequence increases in thickness and becomes coarser grained from the Niagara Gorge eastward to central New York. The stratigraphic relationships of some rock units in the present Early Silurian sequence across the western two-thirds of New York are shown diagrammatically by Gillette (1947, p. 13). Limestone units grade eastward into shale; shale and sandstone units grade eastward into conglomeratic sandstones. The only part of this sequence reported to be present in a well drilled in northeastern Chenango County, N. Y. (Donnerstag and others, 1950, p. 7-8) is the Clinton Formation, consisting of 397 feet of sandstone, conglomerate, shale, limestone, and hematite. Quartz conglomerate in the basal part of this sandstone sequence abruptly overlies shale and siltstone of Late Ordovician age. The Lower Silurian Medina Group is absent, indicating an unconformity at the base of the conglomeratic Clinton Formation. The sandstones of the Clinton Formation are overlain by shales designated by Donnerstag and others (1950) as the Lockport Formation.

The Early Silurian clastic sequence thins rapidly east of Chenango and Madison Counties (fig. 10). It is very thin or absent along the Helderberg escarpment in Montgomery, Schoharie, Albany, Green, and northern Ulster Counties. In much of this area shale and limestone of the Late Silurian Brayman Shale rest unconformably on shales of Ordovician age (Fisher and Rickard, 1953, p. 10).

In southeastern New York, northeastern Pennsylvania, and northwestern New Jersey the Early Silurian clastic sequence of this report is represented solely by the Shawangunk Conglomerate. The Shawangunk expands in thickness along the outcrop from about 270 feet near High Falls in east-central Ulster County, N. Y., to between 1,500 and 1,800 feet on the Delaware River east of Stroudsburg. The bulk of the Shawangunk is composed of white to greenish-gray, crossbedded, lenticularly bedded conglomeratic quartzite and arkosic sandstone. It contains some interbedded arenaceous gray and black shale, and is commonly stained buff to brown by limonite. The contact of the Shawangunk with the underlying Martinsburg Shale of the Late Ordovician sequence is an angular unconformity in much of this area. The contact of the Shawangunk with the overlying Bloomsburg red beds—considered as the basal unit of the Silurian-Devonian carbonate sequence in this area—is transitional.

The relationships of the Shawangunk in northeastern Pennsylvania with stratigraphically equivalent rocks along the outcrop belts in south-central and east-central Pennsylvania are well shown by Swartz and Swartz (1931, p. 660, fig. 2). The lower part of the Shawangunk grades southwestward into the Tuscarora Sandstone, the middle part into the Rose Hill Formation, and the upper part grades westward into the Keefer Sandstone, Rochester Shale, and perhaps the lower part of the McKenzie Formation. In Ohio and in much of New York the top of the Rochester Shale is designated as the top of the Early Silurian clastic sequence. In northeastern Pennsylvania the top of the Shawangunk Conglomerate conveniently marks the top of the clastic sequence. However, in much of eastern Pennsylvania, Maryland, and northern West Virginia, a stratigraphically lower horizon—the base of the Rochester or the top of the Keefer Sandstone—is designated as the top of the Early Silurian clastic sequence. The boundary was shifted for the following reasons: 1) in much of the central part of the Appalachian basin, the calcareous Rochester Shale is more closely related to the rocks of the Silurian-Devonian carbonate sequence above than to the Early Silurian sequence below; 2) the contact between the Rochester and the overlying McKenzie Formation is indistinct, whereas the contact between the Rochester and the underlying Keefer Sandstone is sharp; 3) the Keefer Sandstone correlates to the west (Lafferty, 1941, p. 815 and fig. 6) with the "Big Six" Sand in Kentucky which directly underlies and sharply defines the base of the succession of calcareous rocks of the Silurian-Devonian carbonate sequence. In summary, the boundary between the Early Silurian clastic sequence and the overlying Silurian-Devonian carbonate sequence is most conveniently placed at the contact between the Rochester Shale and the Keefer Sandstone in much of the central part of the Appalachian basin. The following table summarizes the stratigraphy of the Early Silurian clastic sequence exposed in the vicinity of Cumberland, Md., where it is about 970 feet thick. The sequence in this area is typical of much of Maryland and adjacent parts of Pennsylvania and West Virginia.

Generalized section, Early Silurian clastic sequence exposed in the Evitts Creek quadrangle, Allegany County, Md.

Series	Group	Formation	Thickness (feet)	Character
Middle Silurian	Clinton (lower part)	Keefer Sandstone	10-25	Light-gray resistant lenticular to massive-bedded, conglomeratic quartz sandstone, with a bed of sandy hematite at top; abruptly overlain by calcareous gray shale of the Rochester.
		Rose Hill	550	Olive-gray to purplish-gray silty mudrock and shale; many thin beds of sandstone in lower part; a 3-foot bed of very sandy oolitic hematite ore in lower third.
Lower Silurian		Tuscarora quartzite	400	White to light-gray medium- to massive-bedded quartzose sandstone or quartzite; gradational contact with Juniata Formation below.

The Early Silurian clastic sequence thins gradually southward from Maryland along the outcrop in eastern West Virginia and western Virginia. Price and Heck (1939, p. 335-341) estimated about 600 feet from the base of the Tuscarora to the top of the Keefer in eastern Greenbrier County, W. Va., where the stratigraphic sequence is very similar to that in Maryland. In the southwest part of Virginia different names have been applied to the rocks here included in the Early Silurian clastic sequence. The following table based on recent studies in Lee and Scott Counties in the southwest corner of Virginia summarizes the succession of rocks comprising the sequence. The sequence is underlain by the Sequatchie Formation of Late Ordovician age.

Comparison of Early Silurian clastic sequences exposed in western Lee County and western Scott County, Va.

	Western Lee County (Miller and Fuller, 1954, p. 140-154)	Western Scott County (Harris and Miller, 1958)
Series	Formation, character, and thickness	Formation, character, and thickness
Middle Silurian	Clinton Shale (325 feet): interbedded gray, blue, purple, and red shales, containing fine-grained very light-gray to greenish-gray sandstone; some medium-grained sandstone in upper part, some thin beds of hematitic iron in lower two-thirds.	Clinton Formation and Clinch Sandstone undivided (450 feet): very light-gray silica-cemented medium-grained sandstone with some very coarse-grained sandstone and conglomerate lentils.
Lower Silurian	Clinch Sandstone (102-183 feet): upper part (Poor Valley Ridge Member) largely light-colored massive-bedded medium-grained sandstone; lower part (Hagen Shale Member) largely greenish-gray shale with some thin beds of sandy limestone and some layers of hematitic iron ore.	

In eastern Tennessee the Late Silurian clastic sequence crops out in several belts that extend from Cumberland Mountain and Sequatchie Valley on the west to Clinch and Whiteoak Mountains on the east. The sequence is not exposed in many places along the several belts because it has been covered by overthrust older rocks. It is absent in some places along the east edge of the Valley and Ridge province because it was removed by pre-Middle(?) Devonian erosion. The regional stratigraphic relationships of the Lower Silurian rock units are discussed briefly by Rodgers (1953, p. 98-103). In general the Early Silurian sequence is represented by the Rockwood Formation in the western outcrop belts. The Rockwood is composed largely of greenish to brownish calcareous shale containing thin beds of reddish shale, some siltstone and limestone, and hematitic iron ore. In many places beds of sandstone are present near the base. It averages between 250 and 350 feet in thickness. The Rockwood overlies the Sequatchie Formation and is overlain by the Hancock Limestone or Dolomite, which is included in the overlying Silurian-Devonian carbonate sequence in this area. Along the eastern outcrop belts in Tennessee the Early Silurian sequence is represented solely by the Clinch Sandstone. The Clinch is composed largely of thick- to massive-bedded white quartz sandstone that is commonly iron stained in weathered exposures. The upper part of the Clinch sandstone in much of northeast Tennessee includes rocks of Middle Silurian age. In the Sequatchie Valley in Marion and Sequatchie Counties, Tenn., and in some of the counties along the southern boundary of Tennessee west of Sequatchie Valley, different names were applied to rocks in the lower part of the Silurian System by Wilson (1949, p. 239-248, fig. 82). The predominantly calcareous and argillaceous rocks in this area were divided into the Brassfield Limestone below and the Niagaran(?) Shale above. The Brassfield consists of approximately 30 feet of thin-bedded blue-gray limestone with interbedded siltstone and shale. A bed of iron ore is present near the top. The Niagaran(?) Shale of Wilson consists of approximately 45 feet of unfossiliferous greenish clay-shale. Although its correlation is uncertain (Wilson, 1949, p. 246), this shale is included in the upper part of the Early Silurian clastic sequence of this report. It is disconformably overlain by the Chattanooga Shale in Sequatchie Valley and in the southern tier of counties in Tennessee west of Sequatchie Valley. The stratigraphic relationship of the rocks comprising the Early Silurian clastic sequence in eastern Tennessee is shown diagrammatically below.

	Sequatchie Valley Marion County	Whiteoak Mountain, Hamilton and Bradley Counties	Elk Valley, western Campbell County	Powell Mountain Hancock and Claiborne Counties	Clinch Mountain Hawkins County
	unconf.				
Middle Silurian	Niagaran(?) Shale	Rockwood Formation	Rockwood Formation	Rockwood Formation	Clinch Sandstone
Lower Silurian	Brassfield Limestone			Clinch Sandstone	

Throughout the Appalachian Valley in northwestern Georgia and northeastern Alabama the Silurian system is represented only by the Red Mountain Formation. According to Butts (1926, p. 133) the Red Mountain unconformably overlies rocks ranging in age from Late Cambrian to Late Ordovician. The magnitude of the unconformity increases from the north to the south. Along the outcrop belts southeast of the Cahaba and Coosa Rivers, the Red Mountain is present only in western Calhoun, eastern Otowah, and central Cherokee Counties (fig. 10). In most places in northeast Alabama, the Red Mountain is unconformably overlain by the Frog Mountain Sandstone of Middle Devonian age. In the vicinity of Birmingham, Jefferson County, the Red Mountain consists of 300 to 500 feet of thin- to thick-bedded greenish-gray to red sandstone, much interbedded sandy shale, layers of iron ore, and some lenses of quartz conglomerate. Two layers of fossiliferous and oolitic hematite ore, the Big Seam and Irondale Seam, have supplied most of the ore for the iron industry at Birmingham. On the basis of fossil studies the lower part of the Red Mountain is Early Silurian in age and the upper part is Middle Silurian. Little is known about the Red Mountain in the subsurface northwest of the outcrop belts in the Appalachian Valley. Sample studies of wells drilled in the northwest part of Alabama (McGlamery, 1955) show a sequence of interbedded shale, siltstone, sandstone, and limestone overlying limestones of Ordovician age and underlying black shale of Devonian age. The content of limestone increases northward toward the Alabama-Tennessee border. Part of the heterogeneous sequence in north-central Alabama probably is equivalent to the Red Mountain Formation, and consequently is included in the Early Silurian sequence of this report.

Rock units comprising the Early Silurian clastic sequence thin to the northwest across north-central Alabama into Tennessee. They are absent at the surface along much of the crest of the Nashville dome in central Tennessee and southern Kentucky. Subsurface data indicate that they are absent along a narrow belt coinciding with the "southern arm" of the Nashville dome in northwestern Alabama. In Wayne and Hardin Counties, Tenn., in the area between the "southern" and "western arms" of the Nashville dome, the sequence consists of about 20 feet of limestone (the Brassfield) and shale (the Osgood). In Kentucky the Early Silurian sequence grades eastward from a thin sequence of dolomitic shale and dolomite exposed along the east flank of the Jessamine dome into a thicker sequence of shale and sandstone in the subsurface near the eastern edge of the State. In a well drilled in Powell County, Ky., about 50 miles east of the crest of the dome, Freeman (1951, p. 51-52) reports 55 feet of dolomite (Brassfield) overlain by 165 feet of gray, green, and red dolomitic shale (Clinton). In wells drilled in Floyd and Pike Counties, Ky., about 70 miles farther east Freeman reports (1951, p. 313-317) approximately 400 feet of stratigraphically equivalent rocks. The sequence is underlain by the Richmond Group in the top of the Late Ordovician clastic sequence, and is overlain by the Lockport Dolomite in the base of the Silurian-Devonian carbonate sequence. In this area the Early Silurian clastic sequence of this report consists of a white quartzitic sandstone (88 feet thick) at the base, a dark-green to red shale (310 feet thick) containing oolitic hematite in the middle, and a tan coarse-grained sandstone (10-15 feet thick) at the top. The sandstone--known as the "Big Six" Sand--yields large amounts of gas in many parts of eastern Kentucky. The occurrence of gas in the "Big Six" Sand has been discussed in detail by Young (1949, p. 34-56).

Thickness and depth.--As can be seen from figure 10, the Early Silurian clastic sequence underlies most of the Appalachian basin within the limits of its outcrops. The sequence is thin compared to the sequences above and below. From an area of maximum thickness (approximately 1,800 feet) in Monroe County in east-central Pennsylvania, it thins to the north, west, and southwest. A secondary area of maximum thickness (approximately 1,200 feet) is centered in Bradley County, Tenn., near the southeast corner of the State. As previously stated it is absent in east-central New York, along the eastern part of the basin in parts of Tennessee, Georgia, and Alabama, and along the flanks of the Nashville dome in parts of northwestern Alabama, central Tennessee, and south-central Kentucky.

The structural configuration of the Early Silurian sequence in the Appalachian basin is shown on figure 11. The sequence is deepest in parts of northeastern Pennsylvania. In the vicinity of the southern Anthracite field in Schuylkill and Carbon Counties, Pa., the top of the sequence is probably more than 25,000 feet below sea level. The top of the sequence ranges in depth from 6,000 feet to 10,000 feet in a long trough extending from northeastern Pennsylvania to southernmost West Virginia. The trough is parallel to and a short distance west of the Appalachian structural front. From the axis of the trough the sequence rises rapidly southeastward and is exposed at the surface in many belts in the Valley and Ridge province. The sequence rises gradually northwestward from the axis of the trough toward the outcrop belt along the northern and western margins of the basin. In most of New York and eastern Ohio, in parts of westernmost West Virginia, and in all of eastern Kentucky, the Early Silurian clastic sequence occurs at depths less than 5,000 feet below sea level. The sequence lies above sea level in much of central Tennessee and northern Alabama and in many places in the folded Appalachian Mountains of the Valley and Ridge physiographic province. However, because of the lack of subsurface data and the complexity of the structure in the Valley and Ridge province, the structural attitude of the sequence in the eastern part of the basin could not be shown at the scale of the maps accompanying this report.

SILURIAN-DEVONIAN CARBONATE SEQUENCE

A moderately thick succession of carbonate rocks of Middle and Late Silurian and Early Devonian age and some of early Middle Devonian age underlies most of the Appalachian basin except the periphery and much of the southern part. Like the underlying sequences it is wedge shaped, being thick on the east and thin on the west (fig. 12). It is thickest—approximately 3,400 feet--in northeastern Pennsylvania. The carbonate sequence thins toward the southern part of the Appalachian basin, and is absent in most of Tennessee, all of Georgia, and much of Alabama. In northeastern Pennsylvania and adjacent parts of New Jersey the Silurian-Devonian carbonate sequence is composed largely of a thick wedge of red sandstone, siltstone, and shale, the Bloomsburg Red Beds. A succession of interbedded salt (halite), gypsum, anhydrite, and shale of Late Silurian age occupies the central part of the carbonate sequence in southern New York, the northwestern half of Pennsylvania, northeastern Ohio, and north-central West Virginia. As the Late Silurian evaporite succession of the Appalachiam basin has been discussed by Griggs (1958), it will be referred to only briefly in this report. Among its more extensive and better known units are the Lockport Dolomite, Salina Group, Bloomsburg Red Beds, Helderberg Group, Oriskany Sandstone, the Onondaga Limestone and the Hancock (formerly Cayuga) Limestone or Dolomite. The Oriskany Sandstone, which occurs in the upper part of the carbonate sequence, is a prolific gas-producing formation in parts of Ohio, New York, Pennsylvania, Maryland, and West Virginia. The Onondaga and the equivalent Huntersville Chert also contain gas in parts of Pennsylvania, Maryland, and West Virginia. Oil and gas have been obtained in commercial quantities from other parts of the Silurian-Devonian carbonate sequence in the basin, especially from thin quartz sandstones and other permeable layers in the lower part of the sequence in eastern Ohio and eastern Kentucky.

The Silurian-Devonian carbonate sequence overlies the Early Silurian clastic sequence. The contact is conformable in most of the basin. The carbonate sequence is overlain by a sequence of predominantly clastic rocks of Middle and Late Devonian age, which comprise the Devonian clastic sequence of this report. The contact is sharp in most parts of the basin, ranging from conformable to markedly disconformable.

Rather than discuss the lithology, stratigraphy, and extent of the many formations composing the carbonate sequence, stratigraphic successions representative of various parts of the Appalachian basin are summarized briefly. The geographic order of discussion of the stratigraphic successions is clockwise about the basin, beginning in north-central Ohio.

In north-central Ohio the Silurian-Devonian sequence consists almost entirely of dolomite and limestone and ranges from 900-1,000 feet in thickness. The following stratigraphic succession is typical of much of north-central Ohio. The sequence is also shown in figure 13, which shows in graphic form some of the rocks encountered in drilling to the "Clinton" Sands in the underlying Early Silurian clastic sequence.

Generalized section, Silurian-Devonian carbonate sequence encountered in wells drilled in Ashland and Richland Counties, Ohio

System	Series	Formation	Thickness (feet)	Character
		unconformity		
	Middle and Lower Devonian	Columbus-Onondaga	150-200	Medium- to light-gray fine-grained fossiliferous limestone with much nodular chert: upper few feet argillaceous, chert free —may be Dundee or Delaware limestone; salt water at base.
		unconformity?		
			40	Medium- to light-gray fine-grained limestone with chert.
		unconformity?		
		Oriskany Sandstone?	0-5	Very light-brown to white calcareous sandstone grading to porous sandy dolomite; heavy flow of salt water.
Silurian	Upper Silurian	Bass Island—Salina Formation undifferentiated	500-600	Medium- to light-brown fine-grained saccharoidal dolomite with some thin layers of shale, anhydrite and rock salt; upper 30-40 feet largely limestone —probably Bass Island equivalent.
		unconformity		
	Middle Silurian	Lockport-Guelph Dolomites undifferentiated	150-300	Light-gray to white finely crystalline dolomite with some limestone; fossil reefs in upper part; "Newburg sand" of drillers at top - a salt-water-bearing horizon.

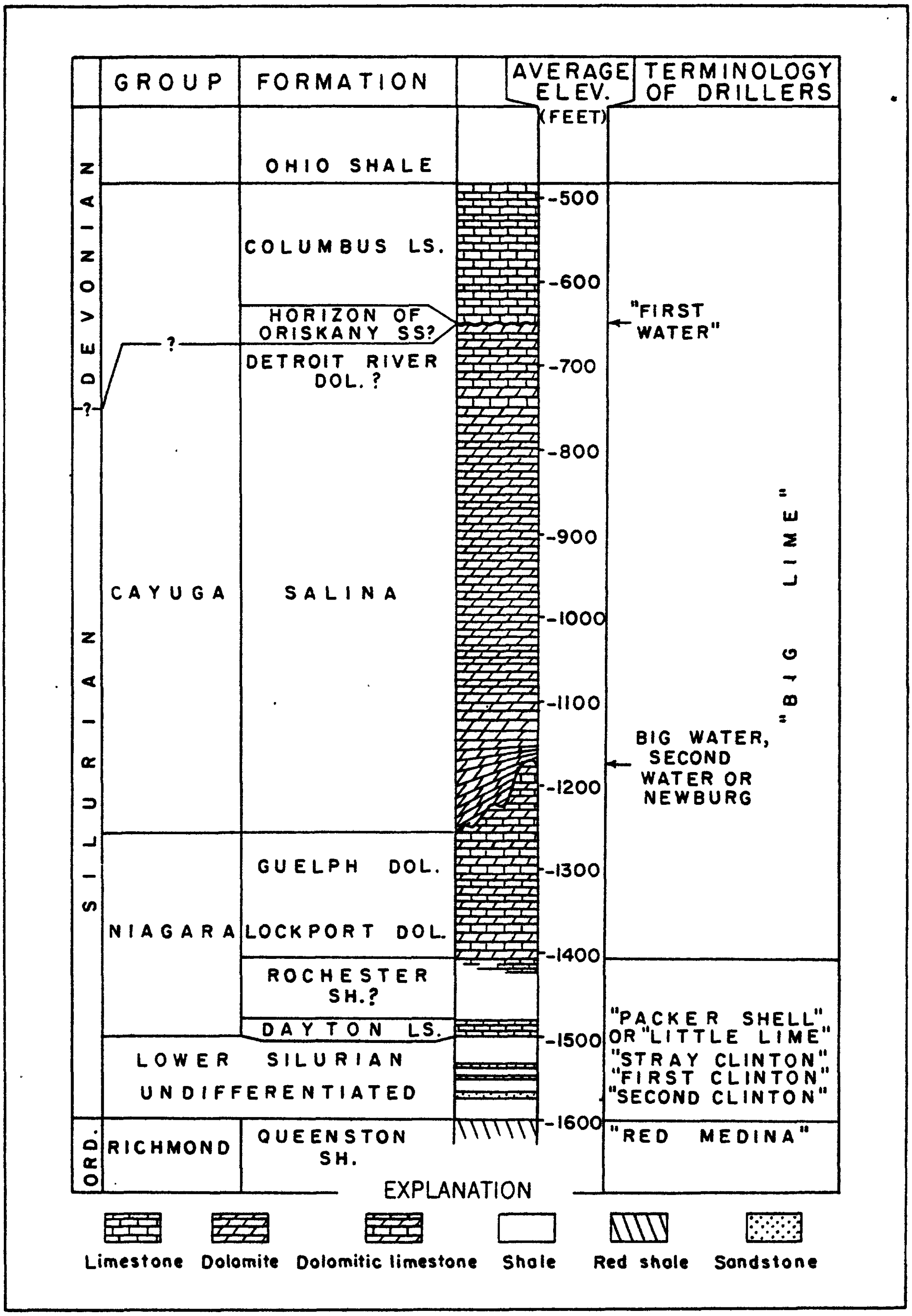

FIGURE 13.—Generalized columnar section showing part of the Paleozoic section encountered in the subsurface in north-central Ohio.

The Silurian-Devonian carbonate sequence thickens east of north-central Ohio. In northwestern Pennsylvania, where the sequence ranges from 1,000 to 1,400 feet in thickness, appreciable amounts of shale, anhydrite, and rock salt are present in the Salina Group. Limestones of the Helderberg Group, which are absent in much of Ohio, are present between the Oriskany Sandstone and the Salina. The sequence thins from northwestern Pennsylvania to about 750 feet in the outcrop area in western New York. The following succession is exposed in the Niagara Gorge, and is typical of much of western New York and contiguous parts of Ontario Province, Canada.

Generalized section, Silurian-Devonian carbonate sequence exposed in the Niagara Gorge, Niagara County, N. Y.
(modified from Kindle and Taylor, 1913, p. 7-9, and Fisher, 1960)

System	Series	Group or Formation	Thickness (feet)	Character
Devonian	Middle Devonian and Lower Devonian(?)	Onondaga Limestone	150	Light- to medium-gray, nearly pure limestone with lentils and nodules of gray to blackish chert; lentils of sand and shale at base--Springvale Sandstone Member and Oriskany Sandstone.
		unconformity		
Silurian	Upper Silurian	Akron Dolomite	5	Ash-gray massive bed of dolomite.
		Bertie Group	440	Interbedded shale, dolomitic and argillaceous limestone (waterlime) and dolomite; subdivided into four formations by some.
		Salina Group		Interbedded bluish-gray shale and argillaceous magnesium limestone, dolomite and some gypsum.
	Middle Silurian	Lockport Group	143	Dark-gray to brown saccharoidal dolomite; basal 9 to 20 feet (Gasport Limestone) light-gray to white crinoidal limestone; group subdivided into six formations.
		unconformity		
		Decew Dolomite	6-8	Bluish-gray fine-grained nonresistant argillaceous limestone.

The thickness of the carbonate sequence remains relatively constant along the outcrop from Niagara County to the meridian of Herkimer in Herkimer County, N. Y. East of this area the sequence thins abruptly as most rocks of Middle Silurian age and some of Late Silurian age wedge out against an unconformity at the base of the sequence. The eastward thinning and disappearance of Silurian rocks in the lower part of the sequence is partly compensated for by an increase in the number and thickness of Devonian rock units in the upper part of the sequence. The stratigraphic succession (approximately 440 feet thick) in part of Schoharie County, N. Y., is summarized in the following table.

Generalized section, Silurian-Devonian carbonate sequence exposed in the Berne quadrangle, Schoharie County, N. Y. (from Goldring, 1935, p. 78-148)

System	Series	Formation	Thickness (feet)	Character
Devonian	Middle Devonian ?	Onondaga Limestone	100	Light-bluish massively bedded resistant limestone with lenticular chert layers; reef structures in lower part.
	Lower Devonian	Schoharie Grit	0-8	Dark bluish-gray highly fossiliferous very sandy (siliceous) limestone.
		Esopus Grit	80-90	Dark-gray to blackish brittle (highly fractured) siliceous siltstone or silty shale.
		Oriskany Sandstone	0-6	Very dark bluish-gray to blackish resistant calcareous quartzose sandstone.
		unconformity		
		Becraft Limestone	15-30	Light-gray to light pinkish-gray, very coarsely crystalline, fossiliferous, massive-bedded very pure limestone.
		New Scotland Limestone	75-100	Dark bluish-gray fossiliferous thin-bedded, shaly limestone; some black chert.
		Coeymans Limestone	50±	Dark brownish-gray, massive-bedded, coarse-crystalline, highly fossiliferous resistant limestone.
	?	Manlius Limestone	50±	Dark blue-gray thin-bedded brittle fossiliferous limestone: a cement rock.
Silurian	Upper Silurian	Rondout Limestone	2-20+	Dark thin-bedded fine-grained limestone and limy shale: a cement rock.
		Cobbleskill Limestone	6-12	Dark thick-bedded very fossiliferous (especially corals) sandy dolomitic limestone.
		unconformity		

The Silurian-Devonian carbonate sequence undergoes some remarkably rapid facies changes as it crops out southward along the Helderberg escarpment to east-central Ulster County, then southwestward along the trend of the Shawangunk Mountains to the vicinity of the Delaware Gap near

Stroudsburg, Pa. In the area about the Delaware Gap the Silurian-Devonian sequence consists of approximately 3,400 feet of rock of which the lower 2,000 feet is composed of red sandstone, shale, and mudrock. The following section is typical of northeastern Pennsylvania, northwestern New Jersey, and southern New York.

Generalized section, Silurian-Devonian carbonate sequence exposed in the vicinity of the Delaware Water Gap, Monroe County, Pa. (modified slightly from Willard, 1939; Swartz, 1939; Cleaves, 1939; and Johnson and Willard, 1957, p. 129-130)

Series	Group	Formation	Thickness (feet)	Character
Middle Devonian	Onondaga	Buttermilk Falls Limestone	475	Upper 200 feet (Buttermilk Falls Limestone) massive, dark bluish-gray limestone with lentils and nodules of chert; middle 25 feet (Schoharie Formation), limy shale with crinoid columns: lower 250 feet (Esopus Shale), dark ash-brown gnarly sandy shale.
		Schoharie		
		Esopus Shale unconformity		
Lower Devonian	Oriskany	unconformity?	118	Upper half calcareous sandstone with layers and nodules of black chert and siliceous gray limestone: lower half interbedded dark-gray sandy shale, siliceous shale and black chert.
	Helderberg	Port Ewen Shale	150	Ash-gray shale with well-developed cleavage.
		Becraft Limestone	14	Bluish-gray thick-bedded crystalline limestone.
		New Scotland Limestone	88	Largely slightly calcareous fossiliferous shale with siliceous, argillaceous limestone with much dark-gray chert in large part.
		Coeymans Limestone unconformity	77	Gray, thick-bedded, crystalline, highly fossiliferous sandy limestone grading to calcareous sandstone: "Stormville" Sandstone at top.
Upper Silurian		Manlius Limestone	32	Dark bluish-gray thick-bedded fine-grained limestone.
		Rondout Limestone	25	Thinly laminated limestone.
		Decker Sandstone	75	Thick-bedded calcareous sandstone with some limestone.
		Bossardville Limestone	100	Bluish-gray fine-grained quite pure laminated "ribbon" limestone.
		Poxino Island Shale	200	Buff to greenish irregularly-bedded calcareous shale.
Middle Silurian		Bloomsburg Red Beds (High Falls Conglomerate)	2,000	Interbedded red shale, sandstone, and mudrock; some greenish-gray sandstone and shale in lower part; some conglomerate.

The Silurian-Devonian sequence crops out in several belts following the trend of the folded Appalachian Mountains southwestward across Pennsylvania into Maryland and other states to the south. The numerous facies changes in the sequence are well shown diagrammatically by Swartz (1939, fig. 17), Cleaves (1939, fig. 29), and Swartz and Swartz (1931, fig. 2, p. 660). The sequence thins toward the southern Appalachians, due in large part to the rapid thinning of the Bloomsburg Red Beds, and to the disapperance of some of the limestone units. The following section, in western Maryland, is typical of the Silurian-Devonian carbonate sequence in much of the central Appalachians.

Generalized section, Silurian-Devonian carbonate sequence exposed in the vicinity of Cumberland, Allegany County, Md.

Series	Group	Formation	Thickness (feet)	Character
Middle Devonian		Needmore Shale	150	Interbedded greenish-gray to black nonresistant shale with thin beds of nodular limestone and layers of limestone concretions.
Lower Devonian	Oriskany	Ridgeley Sandstone	160	Light- to medium-gray, calcareous, fossiliferous, fine- to very coarse-grained quartz sandstone with conglomerate lenses.
		Shriver Chert	165	Medium dark-gray calcareous and siliceous shale with much chert and silty shale in lower part.
	Helderberg	Mandata	19	Gray slightly calcareous soft easily weathered shale.
		New Scotland Limestone	27	Irregularly interbedded medium light-gray limestone and light-gray to pink chert.
?		Coeymans Limestone	9	Medium dark-gray thick-bedded coarsely crystalline bioclastic limestone with some chert.
Upper Silurian		Keyser Limestone	290	Medium-gray thick-bedded coarsely crystalline bioclastic limestone: some very dark gray chert in upper part.
		Tonoloway Limestone	575	Very dark-gray laminated argillaceous limestone with some interbedded shale.
		Wills Creek Shale	475	Medium- to dark-gray calcareous mudrock and shale with thin beds of argillaceous limestone.
		Bloomsburg Red Beds	25-50	Interbedded greenish-gray and purplish red sandstone, siltstone, mudrock and shale: a thin limestone in center.
Middle Silurian		McKenzie	330	Greenish-gray and gray calcareous shale with thin beds of limestone.
	Clinton	Rochester Shale	30	Medium-gray calcareous shale with thin beds of argillaceous limestone.

The Silurian-Devonian sequence thins along the outcrop belts in eastern West Virginia and western Virginia. In Greenbrier County, the sequence is about 900 feet thick (Price and Heck, 1939, p. 314-338) and includes virtually the same rock units that are present in Allegany County. The stratigraphic relationships of the upper part of the sequence in the subsurface west of Greenbrier County are shown diagrammatically by Martens (1939, figs. 7, 8). In much of West Virginia the position of the Onondaga Limestone or the Needmore Shale is occupied by a unit composed of interbedded chert and shale--the Huntersville Chert. In Lee and Scott Counties in the southwest corner of Virginia, the Silurian-Devonian carbonate sequence of this report ranges from 19 to 185 feet in thickness and consists of one formation, the Hancock Dolomite or the Hancock Limestone. The Hancock consists largely of light-brown massively bedded dolomite to the west (Miller and Fuller, 1954, p. 155-158) and of interbedded limestone and dolomite to the east (Harris and Miller, 1958). In both counties some beds of fine- to coarse-grained calcareous sandstone occur in the base of the formation. In part of Scott County and in parts of contiguous counties in Tennessee, a thin sandstone containing fossils of early Middle Devonian age overlies the Hancock. The sandstone is equivalent in age to the upper part of the Silurian-Devonian carbonate sequence in areas to the north. However, because of its lithology it is included in the overlying Devonian clastic sequence of this report. The Hancock extends a short distance into Tennessee and appears to be absent in most of the State south of Claiborne County.

A thin unit of argillaceous limestone and calcareous shale belonging to the carbonate sequence is present in the northwest corner of Alabama and in contiguous counties in southern Tennessee. The rocks occupy the interval between the top of the Osgood Shale (the upper unit of the Early Silurian clastic sequence) and the base of the Chattanooga Shale (the basal unit of the Devonian clastic sequence). In this area rocks of the carbonate sequence may total as much as 225 feet in thickness, but generally are much thinner. They may represent an accumulation of predominantly fine-grained carbonaceous rocks preserved within an embayment formed by the "western" and "southern arms" of the Nashville dome. With this exception, rocks of the Silurian-Devonian carbonate sequence are absent along the crest and much of the flanks of the Nashville dome of Tennessee and the Jessamine dome of Kentucky. The absence of this sequence on the domes is due to a combination of nondeposition, erosion during Middle and Late Silurian time and during Early Devonian time, and erosion a short time before the overlying Chattanooga Shale was deposited.

The Silurian-Devonian carbonate sequence is present in the subsurface in most of eastern Kentucky. It expands in thickness from a feather edge on the east flank of the Jessamine dome to about 350 feet in Pike County along the Kentucky-West Virginia boundary line. The following succession is typical of the Silurian-Devonian sequence in the subsurface in eastern Kentucky.

Generalized section, Silurian-Devonian carbonate sequence in the No. 5458 L. F. Burpee well in Floyd County, Ky. (after Freeman, 1951, p. 313)

System	Group	Formation	Thickness (feet)	Character
Devonian		Huntersville Chert	45	Black shale with interbedded limestone above; very light tan fine-grained limestone with some chert below.
		Oriskany Sandstone	10	Slightly calcareous fine- to coarse-grained sandstone.
	Helderberg		55	Dark-brown limestone with brown chert.
Silurian	Salina		252	Brown very fine- to medium-grained crystalline dolomite with gypsum and anhydrite in lower half.
		Lockport*	78	Gray-brown to nearly black medium-crystalline dolomite with sand grains at top.

*An additional 20 feet of rock consisting of fine-grained sandstone was included in the base of the Lockport by Freeman. This sandstone--the "Big Six" Sand of the drillers--is included in the underlying Early Silurian clastic sequence of this report, as was stated earlier (p.

Thickness and depth.--The Silurian-Devonian carbonate sequence is thickest (more than 3,400 feet thick) in the vicinity of Bradford, Tioga, Lycoming, and Sullivan Counties in northeastern Pennsylvania (fig. 12). It is apparent from figure 12 that the area of greatest thickness lies approximately midway between the areas of greatest thickness of salt beds on the northwest and of the Bloomsburg Red Beds on the southeast. The sequence is quite thick in north-central West Virginia and westernmost Maryland. An area in which the carbonate sequence is relatively thin extends northwestward across Pennsylvania between the two areas in which the sequence is thick. The carbonate sequence thins very rapidly toward the northern and eastern margins of the Appalachian basin, and thins gradually toward the western and southern margins.

The structural configuration of the top of the Silurian-Devonian carbonate sequence (fig. 14) is similar to that of the underlying Early Silurian clastic sequence. The carbonate sequence is deepest in the vicinity of Schuylkill and Carbon Counties, Pa., where it is about 20,000 feet below sea level. The top of the sequence lies more than 6,000 feet below the surface in many places along a broad belt parallel to and a short distance west of the Appalachian structural front in Pennsylvania, western Maryland, and central West Virginia. In most of New York, Ohio, all of Kentucky, and in parts of Tennessee and Alabama where the carbonate sequence is present, the top of the sequence is less than 5,000 feet below sea level. The sequence occurs at shallow depths in most of the Valley and Ridge province, and crops out at the surface in many places in the province.

Devonian clastic sequence

The Devonian clastic sequence is a moderately thick sequence composed largely of shale, mudrock, siltstone, and sandstone, primarily of Middle and Late Devonian age. It extends throughout most of the Appalachian basin, but is absent in the vicinity of Jefferson County, Ala., and in a narrow belt in part of north-central Alabama and south-central Tennessee (fig. 15). In all but the southern part of the basin it overlies the Silurian-Devonian carbonate sequence. The contact is conformable in most areas, but is commonly sharply defined. In the southern part of the basin it disconformably overlies rocks older than those comprising the Silurian-Devonian carbonate sequence. Throughout its extent the Devonian sequence is overlain by coarse-grained clastic rocks of the Mississippian system. The Devonian sequence is wedge-shaped, being thickest near the east margin of the Appalachian basin and thinnest near the west margin. It ranges in thickness from slightly more than 11,000 feet in northeastern Pennsylvania to a feather edge in parts of Alabama and Tennessee. Relatively coarse-grained sedimentary rocks, including red rocks deposited in a subaerial environment, predominate in the northeastern part of the basin where the sequence is thickest. Medium-grained gray rocks deposited in a marine environment predominate where the sequence is of intermediate thickness. Fine-grained black shale predominates in the southwestern part of the Appalachian basin where the sequence is thinnest. Among the better known and more extensive units included in the Devonian clastic sequence are the Hamilton Group, the "Portage" Group, the Jennings Group, the Ohio Shale, the Chattanooga Shale, the Chemung Formation, and the Catskill or Hampshire Formations.

The top and bottom contacts of the Devonian clastic sequence are placed at convenient lithologic breaks rather than at time planes defined on paleontologic criteria. In the northern Appalachians the base of the sequence is marked by the top of the Onondaga Limestone. In much of the central part of the Appalachian basin the base of the sequence is marked by the top of the Huntersville Chert, or the top of the "Corniferous" of the drillers in Kentucky. In most of the southern part of the basin the base is marked by the disconformable contact of the Chattanooga Shale with carbonate or noncarbonate rocks that range in age from Devonian to Ordovician. The upper boundary is placed at the base of the lowest relatively coarse grained rock (siltstone or sandstone) of Mississippian age. In much of the northeastern part of the Appalachian basin the top of the Devonian clastic sequence is defined as the base of the Pocono Formation or Group. In the northwestern part the top is defined as the base of the Berea Sandstone, the Cussewago or Corry Sandstone--whichever is the lowest sandstone at that point. In much of the central Appalachians it is defined as the base of the Price Sandstone. In most of the southern part of the basin the upper boundary is placed at the top of the Chattanooga Shale, closely approximating the Devonian-Mississippian boundary in that area (Hass, 1956, p. 2, fig. 1).

The stratigraphy of the Devonian clastic sequence will be described largely by means of generalized sections representative of various parts of the Appalachian basin. The facies changes that occur within the Devonian sequence can be noted by comparing the thicknesses, lithologies, stratigraphic relationships and, to some extent, the nomenclature applied to rock units in one section with other sections.

In northeastern Ohio, the Devonian clastic sequence consists largely of gray shale, calcareous gray mudrock, and carbonaceous black shale. The average thickness is approximately 1,700 feet. For the purposes of this report a thin sequence of rocks of Early Mississippian age--the Bedford Shale--is included at the top of the Devonian clastic sequence. The Bedford Shale is included here so that the top of the sequence will be defined by the base of an easily recognized, laterally extensive Sandstone unit, the Berea sandstone. The following stratigraphic sequence is recognized in northeastern Ohio:

Generalized section, Devonian clastic sequence in the shaft of the limestone mine of the Columbia Chemical Division of the Pittsburgh Plate Glass Co., at Barberton, Summit County, Ohio (from Stauffer, 1944)

Series		Formation	Thickness (feet)	Character
Lower Mississippian		Bedford Shale	55	Gray shale with some fine-grained sandstone near top.
		Cleveland Shale	60	Black shale.
		Chagrin	460	Gray shale with thin layers of sandstone and some black shale.
Upper Devonian	Ohio	Huron Shale	989	Largely black and very dark-brown shale; much gray shale; thin layers of limestone and siltstone.
Middle Devonian	Shale	Hamilton Shale	113	Gray to bluish-gray calcareous shale; basal 27 feet is fissile black shale.

The Devonian clastic sequence thickens eastward. The thickening is accompanied by a decrease in the percentage of black shale, an increase in the percentage of siltstone and sandstone, and the occurrence of red beds. In a broad belt that extends parallel to the Appalachian structural front across western Pennsylvania into western West Virginia, the coarse-grained rocks are segregated into many more or less distinct lenticular units which are recognized in the subsurface by drillers. In central Butler County, in west-central Pennsylvania, where the Devonian sequence is about 4,500 feet thick, Lytle and Heeren (1955, pl. 2) recognized 17 siltstone and sandstone units in the upper one-third of the sequence. Of the 17 coarse-grained units, 10 are productive of oil or gas in central Butler County. About 300 feet of red beds are also present in the upper part of the sequence. The productive sands of Late Devonian age in western Pennsylvania are discussed further on pages .

The sequence continues to thicken to the northeast and the content of siltstone, sandstone, and red beds increases. In north-central Pennsylvania, where the sequence is between 5,000 and 6,000 feet thick, the upper 1,400 feet is composed largely of gray and red coarse-grained rocks. The lithologic succession in the following table is typical of much of south-central New York and north-central Pennsylvania, although the validity of some of the formation names in the upper part of the sequence is questionable.

Generalized composite section, Devonian clastic sequence exposed in Cayuga, Tompkins, Chemung, and Steuben Counties, N. Y., and in Tioga County, Pa. (modified from many sources)

Series	Group	Formation	Thickness (feet)	Character
Upper Devonian		Oswayo	1,100	Greenish-gray to buff thick-bedded sandstone: only lower 700 feet included in Devonian clastic sequence.
		Cattaraugus	370-500	Alternating layers of red and greenish-gray shale, mudrock, siltstone and sandstone.
		Wiscoy Sandstone	250	Greenish irregular bedded siltstone and sandstone.
		West Falls	1,300	Interbedded gray shale and siltstone; thin black shale (Rhinestreet) at base; thick-bedded siltstone and sandstone (Nunda) at top.
		Sonyea	800	Interbedded gray shale and siltstone; thin black shale (Middlesex) at base; sandy siltstone (Rock Stream) at top.
		Genesee	950	Interbedded gray shale and siltstone; thin black shale (Genesee) at base.
Middle Devonian		Tully Limestone	60	Medium-gray thick-bedded limestone.
	Hamilton	Moscow Ludlowville Skaneateles Marcellus	920	Calcareous gray shale with nodules and thin beds of limestone; thick black shale (Marcellus) at base.

The Devonian clastic sequence continues to thicken eastward along the outcrop. The thickening is accompanied by an increase in the amount of red rock (shale, mudstone, siltstone and sandstone) and a corresponding decrease in the amount of gray and black shale. In the vicinity of the Catskill Mountains in eastern New York, the sequence is composed predominantly of red rock. In this area, however, the upper part of the sequence has been removed by erosion, so the total thickness cannot be measured. Recent work by members of the U. S. Geological Survey in the Anthracite region of east-central Pennsylvania, where the full thickness is present, has resulted in recognition of the following stratigraphic sequence, comprising approximately 9,800 feet of rocks.

Generalized section, Devonian clastic sequence exposed in Schuylkill County, Pa.
Based on data furnished by G. H. Wood, Jr. (oral communication, 1960).

Series	Group	Formation	Thickness (feet)	Character
Upper Devonian		Catskill	6,000-6,500	Alternating thin- to thick-bedded red sandstone, shale and quartz conglomerate; much greenish-gray sandstone, siltstone and shale in lower 800-900 feet.
		Trimmers Rock Sandstone of Willard	2,100-2,400	Thin- to massive-bedded greenish-gray quartzose sandstone with interbedded siltstone and shale.
Middle Devonian	Hamilton	Mahantango of Willard	1,000-1,300	Upper part fossiliferous slightly calcareous gray shale, mudrock and siltstone; lower 0 to 600 feet massive-bedded, locally conglomeratic sandstone (Montebello of Willard).
		Marcellus Shale	50-100	Soft fissile black shale; locally composed of gray laminated siltstone.

From east-central Pennsylvania the Devonian clastic sequence thins to the southwest. In the western part of Allegany County, Md., in the vicinity of Cumberland, the Devonian clastic sequence is approximately 6,900 feet thick. The following section, based on recent field studies, is typical of western Maryland and contiguous parts of Pennsylvania and West Virginia.

Generalized section, Devonian clastic sequence exposed in the western part of Allegany County, Md., and adjacent parts of Mineral and Hampshire Counties, W. Va. From Berryhill and others (1956).

Series	Group	Formation	Thickness (feet)	Character
Upper Devonian		Hampshire	2,000	Interbedded red and purplish shale, siltstone, and sandstone, barren of marine fossils.
	Jennings	Chemung	1,315	Interbedded fossiliferous micaceous very light-gray sandstone, gray siltstone and gray silty shale; a few conglomerate lenses.
		Woodmont Shale	2,350	Gray and olive-gray shale and mudrock, with many thin uniform layers of very light-gray siltstone and very fine-grained sandstone.
		Harrell Shale	135	Medium-gray shale with a few thin beds of siltstone; basal 0-50 feet composed of very dark gray to black silty shale (Burket Shale Member).
Middle Devonian	Hamilton	Mahantango	1,030	Gray shale and mudrock with calcareous concretions; scattered layers of light-gray sandstone, especially in upper part.
		Marcellus Shale	240	Soft fissile black shale; center part contains soft calcareous olive-gray shale, limestone concretions and beds.

The Devonian clastic sequence continues to thin southward from western Maryland along the outcrop belts in eastern West Virginia. As shown in the following table, the sequence is approximately 5,300 feet thick in eastern Greenbrier County, in southeastern West Virginia.

Generalized section, Devonian clastic sequence exposed in eastern Greenbrier County, W. Va. From Price and Heck (1939, p. 295-311), modified on basis of nomenclature used by Woodward (1943).

Series	Formation	Thickness (feet)	Character
Upper Devonian	Hampshire	0-400	Red shale interbedded with green or brown, commonly conglomeratic sandstone.
	Chemung	2,000-3,000	Thin- to thick-bedded lenticular gray to brown sandstones alternating with similar colored shales; a massive conglomeratic sandstone at top; many coquinoid lentils in lower part.
	Brallier Shale	2,000	Greenish-gray silty shale with many thin layers of greenish gray sandstone.
	Harrell Black Shale	50-100	Black fissile shale with thin layers of limestone and greenish-gray sandy shale.
Middle Devonian	Marcellus black Shale	400	Soft fissile highly carbonaceous brownish-black shale; highly deformed in most exposures.

As the Devonian clastic sequence continues to thin to the southwest, fewer formations are recognized. In western Scott County, Va., near the southwest corner of the State, Harris and Miller (1958) recognized three units between the highest unit included in the Silurian-Devonian carbonate sequence of this report and the lowest formation entirely of Mississippian age in the area. According to Harris and Miller, the Big Stone Gap Siltstone, the youngest of the three units, contains fossils of Late Devonian and Early Mississippian age. However, for the purposes of this paper it was convenient to include the full thickness of Big Stone Gap Siltstone in the Devonian clastic sequence. The total thickness of the Devonian clastic sequence in this area is approximately 1,000 feet.

Generalized section, Devonian clastic sequence exposed in western Scott County, Va. From Harris and Miller (1958).

Series	Formation	Thickness (feet)	Character
Lower Mississippian / Upper Devonian	Big Stone Gap Siltstone	200	Dark-gray to grayish-black carbonaceous siltstone with some interbedded shale.
Upper Devonian	siltstone (Portage of Stose, 1923)	400	Grayish-black to light-gray laminated siltstone with some gray and greenish-gray shale.
	shale (Genesee of Stose)	400	Dark-gray to grayish-black carbonaceous shale with some greenish-gray shale.

In most of the Appalachian basin south and west of Scott County, Va., the Devonian clastic sequence is composed entirely of the Chattanooga Shale. Hass (1956) has shown that the Chattanooga Shale is predominantly of Late Devonian age in much of the southern Appalachians. In parts of southeastern Kentucky, where data are available only from well samples, the Maury Shale of Mississippian age has been included in the upper part of the sequence. The Maury is less than 10 feet thick in most places, consequently its inclusion in the Devonian clastic sequence has little effect on the position of the thickness lines shown on figure 15.

The Chattanooga is divisible into three members in much of the southern Appalachians. The basal member—the Hardin Sandstone Member—is recognized only near the southern part of the Nashville dome in southern Tennessee and in the northwest corner of Alabama. According to Hass (1956, p. 15) it consists of as much as 16 feet of well-rounded quartz sandstone. The overlying Dowelltown Member consists of grayish-black carbonaceous shale below and gray mudstone above. The upper member, the Gassaway, consists largely of grayish-black carbonaceous shale in thin beds with some layers of gray mudstone near the middle. As shown on figure 15 the total thickness of the three members is less than 30 feet, throughout much of the southern Appalachians.

Difficulty was encountered in Kentucky in defining the top of the Devonian clastic sequence, and consequently in determining the thickness of the sequence in that area. The thickness lines in Kentucky shown on the thickness maps of the Devonian clastic sequence (fig. 15) are based largely on data from well-sample studies by Freeman (1951). In the area extending from Jackson County southward to the Kentucky-Tennessee border, the bottom and top contacts of the Chattanooga Shale (or the New Albany Shale of some workers in the area) delineate the bottom and top of the Devonian clastic sequence. East of this area to a north-south line extending from western Rowan County to western Perry County, different criteria were used. In this area the base of the lowest siltstone or sandstone reported by Freeman in the sequence referred to by that writer as Lower Mississippian or New Providence was considered to mark the top of the Devonian clastic sequence. Consequently the Devonian clastic sequence in this area consists of a lower black shale—the Chattanooga or the New Albany—and an upper gray shale, part of which may be Early Mississippian in age. East of the line between Rowan and Perry Counties, the top of the clastic sequence is considered to be the base of a siltstone or sandstone designated as the Berea by Freeman. In easternmost Kentucky, the top of the sequence as thus defined coincides with the top as defined in western West Virginia and in Ohio.

Thickness and depth.—As previously stated, and as shown on figure 15, the Devonian clastic sequence extends throughout most of the Appalachian basin. It extends beyond the limits of the basin in northeastern Alabama and northeastern Mississippi, where a thin Chattanooga Shale has been encountered in many wells drilled into Paleozoic rocks beneath the overlapping Cretaceous strata. The Devonian sequence is thickest—slightly more than 11,500 feet thick—in Carbon County and contiguous counties in Pennsylvania. From an axis of greatest thickness that closely coincides with the easternmost exposures of the sequence, the Devonian sequence thins to the northwest, west, and southwest. The axis of greatest thickness is interrupted in the vicinity of the Susquehanna River by a belt of relatively thin Devonian rocks that extends northwestward across Pennsylvania. The Devonian rocks appear to be anomalously thin in Hardy County, W. Va., which also lies along the trend of the axis of greatest thickness. In most of the northeastern part of the basin the sequence is more than 2,000 feet thick. In most of the southern part of the basin it is less than 100 feet thick. Along the western margin of the basins the thickness of the sequence ranges from about 600 feet in Ohio to a feather edge in south-central Tennessee and contiguous parts of Alabama.

Structure contours could not be drawn in most of the northeastern part of the basin and along the eastern side of the basin because of the structural complexity of the rocks and the lack of subsurface data. However, the following generalizations can be made. In most of the Appalachian basin, the top of the Devonian clastic sequence occurs at relatively shallow depths, that is, less than 2,000 feet below sea level (fig. 16). It lies above sea level and is exposed at the surface along the northern and western sides of the basin, and in many places in the Valley and Ridge province. At the south end of the basin, in northwestern Tuscaloosa County, Ala., Devonian rocks descend to depths greater than 3,500 feet. In some narrow synclines along the Valley and Ridge province, especially in the southern half of the province, the sequence occurs at considerably greater depths. In the trough of the Cahaba syncline, a short distance east of Birmingham, the sequence may be as deep as 10,000 feet below sea level.

Studies in the Southern Anthracite field in Schuylkill County, Pa., indicate that the top of the Devonian clastic sequence is about 14,000 to 15,000 feet below sea level (Wood, 1960, oral communication).

Mississippian sequence

The Devonian clastic sequence is overlain by a relatively thin sequence of rocks of Mississippian age--the Mississippian sequence of this report. The contact between the two sequences is conformable in most parts of the Appalachian basin. The Mississippian sequence is overlain by rocks of Pennsylvanian age. The contact between Mississippian and Pennsylvanian rocks is commonly unconformable, especially in the northwest part of the Appalachian basin. In general the average grain size of the constituent rocks is greatest along the eastern margin of the basin where the sequence is thickest. Red and tan sandstone, shale, and conglomerate predominate in the northeast part of the basin; gray shale and siltstone in the northwest; interbedded sandstone and limestone in the east-central and southeast parts; and limestone and shale in the southwest part. The greatest reported thickness known to the writer is in Scott and Washington Counties in southwestern Virginia, where Averitt (1941) reported more than 6,800 feet of rocks of Mississippian age (fig. 17). Thicknesses ranging from 4,000 to possibly 6,000 feet of Mississippian rocks have been measured in Schuylkill County in east-central Pennsylvania by G. H. Wood, Jr. (1960, oral communication). The sequence thins to the west and is less than 600 feet thick along most of the west side of the basin.

Among the better known and more extensive rock units in the Mississippian sequence are the Pocono Sandstone or Group, Price Formation, Berea Sandstone, Fort Payne Chert, Ste. Genevieve Limestone, Gasper Limestone, Greenbrier Limestone, Mauch Chunk Formation or Group and the Pennington Shale. Many of the rocks in the Mississippian sequence are highly productive of oil and gas. Among the better known units from which oil and gas have been obtained are the Berea Sandstone, Weir sand, Big Injun sand, Squaw sand, Murrysville or "Gas" sand, the Greenbrier "Big Lime", the Fort Payne Chert, and the Princeton Sandstone.

In general, the rocks of the Mississippian system are not believed to be well suited for the disposal of liquid radioactive wastes by injection through deep wells. Consequently the system is discussed in less detail than were most of the underlying sequences.

In northeastern Ohio the Mississippian sequence ranges in thickness from about 100 feet to about 600 feet (fig. 17). It is composed largely of shale and siltstone. The wide range in thickness is attributed to pre-Pennsylvanian erosion which removed some or all of the Upper Mississippian Series in the eastern part of the State. The sequence conformably overlies the Devonian clastic sequence, although locally the basal sandstone of the sequence--the Berea--is channeled into the underlying shales. The Mississippian sequence is abruptly and unconformably overlain by the basal sandstones of the Pennsylvanian system. Although facies changes are rapid and many constituent rock units are highly lenticular, the following section is typical of much of northeastern Ohio.

Generalized section, Mississippian sequence in wells in Tuscarawas County, Ohio (from Lamborn, 1956, p. 246, 254-257; and Wallace de Witt, Jr., 1961, oral communication)

Series	Formation	Thickness (feet)	Character
	unconformity		
	Big Injun sand of drillers	200	Sandstone with some interbedded shale, gas-bearing locally: upper part may be Pennsylvanian in age.
Lower Mississippian	Cuyahoga	350	Bluish-gray to olive-brown shale with some siltstone and fine-grained sandstone; hydrocarbon-producing Squaw and Weir sands of drillers present in this part of sequence in southeastern Ohio.
	Sunbury Shale	50	Brownish-black carbonaceous shale.
	Berea Sandstone	75	Light-gray micaceous siltstone to medium-grained sandstone, with some blackish shale, especially near middle; highly productive of oil and gas; a thin coarse-grained friable sandstone (Cussewago?) present locally 8-10 feet below Berea.

The stratigraphic relationships of the rocks in the lower part of the sequence along the outcrop in northeast Ohio and northwest Pennsylvania have been discussed in detail by de Witt (1946; 1951, p. 1347-1369). The Berea Sandstone of Ohio disappears near the Ohio-Pennsylvania boundary, the stratigraphically lower Cussewago Sandstone appears, then pinches out to the east to be replaced by the slightly younger Corry Sandstone in eastern Crawford County, Pa. At any point in this part of the basin, the base of the lowest sandstone present of the three is designated as the base of the Mississippian sequence of this report. Equally rapid changes in the stratigraphy occur east of Crawford County. In general, the percentage of shale in the sequence decreases and the thickness and grain size of the sandstone units increases. As a result of recent field work in southeastern Warren County and northeastern Forrest County, Pa., the following sequence is recognized, comprising about 345 feet of rocks of Early Mississippian age. Rocks of Late Mississippian age are not known in this area.

Generalized section, Mississippian sequence exposed in the subsurface in the Sheffield 15-minute quadrangle, Warren County, Pa. (from Ingham and others, 1956, p. 10-15)

Series	Formation	Thickness (feet)	Character
	unconformity		
Lower Mississippian	Patton	45	Thin-bedded greenish argillaceous sandstone with soft red and green shale.
	Shenango	200	Largely fine- to medium-grained, yellowish- to greenish-brown sandstone with thin conglomerate layers
	Cuyahoga		Dark bluish-gray sandy shales.
	Knapp	100	Brown, resistant, fine- to medium-grained ferruginous sandstone with interbedded shale and pebble conglomerates: upper part fossiliferous and may be equivalent to Corry Sandstone to the west.

As the section continues to thicken eastward along the outcrop in northern Pennsylvania, different names are applied. The following section is based on recent work in Clinton County. In this area the Mississippian sequence is about 575 feet thick and includes some rocks of Late Mississippian age.

Generalized section, Mississippian sequence exposed in northwestern Clinton County, Pa. (from Ebright and Ingham, 1951, p. 8-10, pl. 3)

Series	Formation	Thickness (feet)	Character
	unconformity?		
Upper Mississippian	Mauch Chunk Group	50-	Brownish- to greenish-gray shale and siltstone with some red shale or siltstone.
Lower Mississippian	Pocono Group	460	Upper 200 feet (Burgoon?) of medium- to very coarse-grained sandstone with quartz conglomerate near base: middle 100 feet of silty shale, thin siltstones and sandstones, with a thin red shale (Patton?) at base: basal 160 feet of alternating fine- to medium-grained brownish-gray or grayish-brown crossbedded sandstone and shale and a small amount of quartz conglomerate.

In this area, Ebright and Ingham included an additional 110 feet of shale and sandstone in the base of the Pocono Group. For this report, it is more convenient to draw the boundary between the Devonian and Mississippian sequences at the base of the lowest conglomeratic sandstone unit mentioned in the generalized section above.

The Mississippian sequence thickens rapidly across northeastern Pennsylvania. In the vicinity of the Southern Anthracite field in Schuylkill County in east-central Pennsylvania, G. H. Wood, Jr. and J. P. Trexler (1960, oral communication) have measured between 4,000 and 6,000 feet of Mississippian rocks. The range in thickness is due to uncertainty in obtaining reliable thickness measurements of the structurally deformed upper unit of the sequence. In this area the sequence is composed of two formations—the Pocono Sandstone below and the Mauch Chunk Formation above. Both were deposited in a nonmarine environment. The contact of the Pocono with the Catskill Formation in the upper part of the Devonian clastic sequence seems to be unconformable. The contact of the Mauch Chunk with the Pottsville Group, the lowest unit of the Pennsylvanian sequence, is conformable. The Pocono is about 1,000 feet thick and consists of medium-gray sandstone, numerous layers of quartz conglomerate, a small amount of silty dark-gray to buff shale, and a few lenses of coal. Most of the conglomerate is present in the basal and middle parts of the formation. The Mauch Chunk is about 3,000 to possibly 5,000 feet thick. It consists of reddish and purplish mudrock, siltstone, thin-bedded sandstone and smaller amounts of fissile red shale and massive-bedded red sandstone.

From east-central Pennsylvania the Mississippian sequence thins to the southwest as an increasing number of nonmarine beds grade laterally into marine beds. In the western parts of Washington and Allegany Counties, Md., and in parts of contiguous counties in West Virginia, the sequence is composed of 1,300 to 2,100 feet of Mississippian rocks which have been divided into seven formations. The following section is typical of this area.

Generalized section, Mississippian sequence exposed in western Washington and western Allegany Counties, Md., and contiguous northern West Virginia (from O'Harra, 1960, p. 109-113; Stose and Swartz, 1912, p. 13-14, and columnar section)

System	Formation		Thickness (feet)	Character
Mississippian	Mauch Chunk Shale		800	Largely argillaceous and silty red shale; about 100 feet of reddish-green to brownish-red sandstone near middle.
	Greenbrier Limestone		227	Upper part largely fossiliferous bluish-gray limestone; middle part largely red and green silty shale and red shaly sandstone; lower part bluish to greenish sandy limestone and pinkish-gray argillaceous sandstone.
	Pocono Group	Pinkerton Sandstone	125+	Massive white sandstone and quartz conglomerate; top not exposed in eastern part of area.
		Myers Shale	800+	Bright red soft sandy shale with thin sandstones in lower part.
		Hedges Shale	170	Dark-gray to black carbonaceous shale with thin seams of semianthracite coal.
		Purslane Sandstone	180-310	Massive resistant and nonresistant white sandstone and quartz conglomerate; thin beds of shale.
		Rockwell Formation	500-540	Soft arkosic sandstone, conglomerate and buff shale; some dark-gray carbonaceous shale near base locally.

From western Maryland the Mississippian sequence thickens gradually southwest across West Virginia along the outcrop belts in the eastern part of the State. In Greenbrier County, southeastern West Virginia, the sequence ranges from 2,200 to 4,500 feet in thickness. The rocks composing the sequence in Greenbrier County have been divided by the West Virginia Geological Survey into the units shown below.

Generalized section, Mississippian sequence in Greenbrier County, W. Va. (from Price and Heck, 1939, p. 214, 253-294).

	Name	Thickness (feet)	Character
Mauch Chunk Series	Bluestone Group	80-675	Red shale with some green shale and micaceous sandstone.
	Princeton Group	20-80	Greenish-gray to reddish-brown highly conglomeratic sandstone.
	Hinton Group	500-800	Largely red and green shale with gray to red calcareous sandstones; a 10- to 30-foot limestone (Avis) in upper part; a 30- to 50-foot white to reddish-brown massive sandstone (Stony Gap) at base.
	Bluefield Group	900-1,200	Upper half largely red, green, and brown shale with some sandstone: Lower half alternating white to grayish-brown sandstones (Droop, Webster Springs); yellow to red shales; gray to blue shaly very fossiliferous limestones (Reynolds, Glenray).
Greenbrier Series	Anderson Limestone	50-150	Dark-gray sandy fossiliferous resistant limestone.
	Greenville Shale	0-40	Lenticular brown to dark fissile calcareous fossiliferous shale.
	Union Limestone	150-200	White to dark resistant fossiliferous partly oolitic limestone.
	Pickaway Limestone	50-135	Dark sparsely fossiliferous limestone.
	Taggard Limestone	10-35	Oolitic fossiliferous limestone with red shale.
	Patton Limestone	90-150	Resistant blue limestone with some black chert nodules.
	Sinks Grove Limestone	40-90	Resistant siliceous fossiliferous blue limestone with black chert nodules.
	Hillsdale Limestone	30-100	Resistant extremely fossiliferous grayish-blue limestone with gray and black chert nodules.
	unconformity		
Maccrady Series		60-250	Nonresistant deep red shale and weakly bedded nonresistant sandstone.
Pocono Series	Sandstone	0-66	Gray and brown platy sandstone with dark-gray sandy shale; a lenticular shaly coal (Merrimac) at base.
	Broad Ford Sandstone	50-175	Gray to reddish-brown ferruginous thick-bedded sandstone.
	Shale and sandstone	100-210	Gray-green and brown sandstone interbedded with green, red, and black shales.
	Berea Sandstone	50-145	Gray and brown conglomeratic massive-bedded sandstone with shale partings.

The Mississippian sequence thickens rapidly southward from Greenbrier County. It is approximately 8,000 feet thick in some areas along the southern boundary of Virginia. The following stratigraphic sequence, encompassing about 7,700 feet of rocks of Mississippian age, has been recognized in parts of Washington and Scott Counties, Va. In this area the upper part of the sequence is not present.

Generalized section, Mississippian sequence at the surface and in wells in western Washington County and eastern Scott Counties, Va.
(from Butts, 1940, p. 336-354; and Averitt, 1941, p. 7-23 and pl. 2)

System	Formation	Thickness (feet)	Character
Mississippian	Pennington Shale	2,250	Top not exposed; upper 1,150 feet exposed is alternating gray to red shale and sandstone; 800 feet alternating thick beds of gray sandstone with some red sandstone and shale near top; basal 300 feet of alternating thin beds of calcareous dark-gray shale and sandstone.
	Cove Creek Limestone	1,150	Upper two-thirds is thin- to massive-bedded shaly limestone with some beds of thin coarse-grained sandstone; lower third is thick-bedded fossiliferous limestone.
	Fido Sandstone	50	Thick-bedded coarse-grained calcareous red to brown sandstone.
	limestones of Gasper and Ste. Genevieve ages	2,400	Upper 300 feet is thick-bedded fossiliferous limestone; next 760 feet of argillaceous nonfossiliferous limestone with 60 feet of red sandy limestone at base; 640 feet fossiliferous red limestone with a 30-foot ferruginous sandstone near top; 660 feet is medium-bedded argillaceous limestone; basal 65 feet is thick-bedded coarse-crystalline limestone.
	St. Louis Limestone	265	Very dark thick-bedded crystalline limestone; shaly at bottom and top.
	Little Valley Limestone unconformity	620±	Upper part dark-colored shale with some limestone: lower part largely argillaceous fossiliferous limestone, including two gas-bearing sandstones.
	Maccrady Shale	30-100	Largely red shale and silty mudrock, with some reddish sandstone.
	Price Sandstone	971±	Largely thin- to thick-bedded quartzose to argillaceous sandstone with some olive to blackish sandy shale especially in lower part; locally conglomeratic at base.

In this area the upper part of the Pennington Shale and younger Mississippian rocks are concealed by Cambrian rocks which are overthrust to the northwest along the Saltville thrust fault (fig. 2). Mississippian rocks younger than the Pennington are present in other parts of southwestern Virginia. Where the upper part of this Mississippian is present, the Pennington Shale (or the equivalent Hinton Formation) is overlain by the Princeton Sandstone, and the Princeton is overlain by the Bluestone Formation. The Princeton consists of about 50 feet of massive to crossbedded conglomeratic quartz sandstone. The Bluestone consists of as much as 1,000 feet of alternating beds of gray to red shale and fine-grained sandstone. Rocks of the Mississippian sequence are overlain in southwestern Virginia by the Lee Formation, the basal unit of the Pennsylvanian sequence. The contact is probably nonconformable (Wilpolt and Marden, 1959, p. 603).

The regional stratigraphic relationships of the rocks composing the Mississippian sequence in eastern Tennessee have been summarized by Rodgers (1953, p. 106-112). According to Rodgers the sequence consists of four major units. The basal units are the Fort Payne Chert in the western part of the Valley of East Tennessee and its eastern equivalent the Grainger Formation. The middle unit is the Newman Limestone, and the highest unit is the Pennington Formation. The Fort Payne consists of 100 to 200 feet of pure to siliceous fossiliferous limestone with layers of shale and sandstone, and much chert in nodular layers. It grades laterally into the Grainger Formation to the east. The Grainger consists largely of light-gray to brown shale, siltstone, and sandstone. Some layers of coal, highly glauconitic sandstone, conglomeratic sandstone and some red beds are present in the upper part. The Grainger ranges in thickness from 350 feet to about 1,100 feet in eastern Tennessee. It is overlain by the Newman Limestone, the middle unit of the Mississippian sequence. The Newman ranges from pure gray oolitic or crinoidal limestone to cherty dark aphanitic limestone to silty argillaceous limestone containing beds of siltstone and sandstone. Along the southern boundary of Tennessee the Newman grades into the Floyd Shale of northwest Georgia and northeast Alabama. The Newman ranges in thickness from 600 feet in the northwest part of the Valley of East Tennessee to 2,800 feet in the eastern part of the Valley. The upper unit of the Mississippian sequence, the Pennington Formation, consists of interbedded gray, green, brown, and red shale and sandstone and a small amount of yellowish limestone. In eastern Tennessee the thickness ranges from 200 feet or less near Chattanooga to perhaps 2,000 feet in Hawkins County.

The Mississippian sequence thins southwestward across Tennessee into Alabama. The thinning is caused by an abrupt decrease in the thickness of clastic units, a more gentle decrease in the thickness of some carbonate units, and by erosion during Mississippian time which resulted in several unconformities within the sequence. In Madison County in north-central Alabama, the sequence is slightly more than 1,000 feet thick and has been divided into the stratigraphic units shown in the section that follows.

Generalized section, Mississippian sequence in Madison County, Ala.
(from Malmberg and Downing, 1957, p. 34-61)

System	Formation	Thickness (feet)	Character
	unconformity		
Mississippian	Pennington	80-100	Red, green, and purple earthy shales interbedded with thin layers of limestone; a 20-foot massive crystalline limestone near top.
	Bangor Limestone	350-420	Largely massive-bedded dark-gray crystalline and oolitic limestone with some argillaceous limestone, shale, and dolomite.
	Hartselle Sandstone	8-16	Thin- to thick-bedded, friable to well-cemented sandstone with calcareous green shale and limestone: absent locally.
	unconformity		
	Gasper Limestone	40-90	Upper part massive-bedded light-gray coarse-crystalline limestone; lower part thin-bedded argillaceous limestone and shale.
	unconformity		
	Ste. Genevieve Limestone	180	Massive-bedded oolitic light- to dark-gray limestone.
	unconformity?		
	Tuscumbia Limestone	150-200	Thin- to thick-bedded, fine to coarsely crystalline highly fossiliferous limestone with some chert.
	Fort Payne Chert	95-160	White to light-gray, siliceous, finely crystalline limestone and white to blue-gray chert with some interbedded gray and green shale: unconformably overlies Chattanooga Shale.

From northern Alabama to Ohio, along the western side of the basin, the thickness of the sequence remains relatively uniform. The lithology of the sequence changes from predominantly limestone at the southern end of the basin to predominantly shale and siltstone in the northwestern part. In east-central Kentucky the sequence consists of approximately 25 percent carbonate rock and about 75 percent noncarbonate clastic rock. According to Freeman (1951, p. 273-276) the lower 500 feet or so of the sequence encountered in wells in Lee County, Ky., consists of interbedded greenish-gray silty shale, siltstone, very fine-grained sandstone, and a small amount of limestone. The upper 100 to 150 feet of the sequence consists largely of white oolitic partly cherty limestone with some tan dolomite, and some greenish-gray to dark-gray shale. The carbonate rocks, which constitute the Greenbrier Limestone, the "Big Lime" of drillers, contain oil and gas in parts of eastern Kentucky and western West Virginia. The Berea Sandstone, the Weir, and Big Injun sands in the lower clastic part of the Mississippian sequence are productive of oil and gas locally in the eastern part of Kentucky and in the western part of West Virginia.

Thickness and depth.--The Mississippian sequence, like the underlying sequences, is thicker along the east side of the Appalachian basin than along the west side. As stated earlier (p.) the sequence is thickest--nearly 7,000 feet--in Scott and Washington Counties, in southwestern Virginia. Another area where Mississippian rocks are thick is centered in Schuylkill County, in east-central Pennsylvania. Thicknesses reported by G. H. Wood, Jr. (oral communication, 1961) range from 4,000 to 6,000 feet in this area. The Mississippian sequence is less than 1,000 feet thick in most of the western half of the basin. It is thinnest, less than 200 feet thick, in northwestern Pennsylvania and northeastern Ohio. A broad belt of relatively thin Mississippian rocks extends from northeastern Ohio southward to west-central West Virginia. The thinness of this belt is due largely to erosion in Early Pennsylvanian time that removed some of the strata in the upper part of the Mississippian sequence.

Because of its stratigraphically high position, the sequence is exposed at the surface or is at relatively shallow depths in large parts of the basin. The bulk of the sequence is more than 2,000 feet below the surface only in three large areas. One such area is centered in parts of Putnam, Jackson, Roane, Wirt, and Wood Counties in west-central West Virginia. The second area is a narrow synclinal belt that extends from the southern tip of West Virginia southwestward under the Pine Mountain overthrust block. The third area is in the southern end of the Appalachian basin. It extends southwestward from Walker County, Ala., beyond the confines of the study area. All or parts of the sequence are more than 2,000 feet below ground level in the troughs of many synclines in the Valley and Ridge province, especially in east-central Pennsylvania, southern Virginia, and northeastern Alabama.

Pennsylvanian sequence

All Paleozoic rocks in the Appalachian basin younger than Mississippian in age are here grouped in the Pennsylvanian sequence. It is composed mainly of rocks of Pennsylvanian age, but also includes a relatively small volume of rocks of Permian age. The two systems are grouped together largely because they are very similar lithologically. The rocks of neither system are believed to be generally suitable for waste disposal purposes, consequently they are discussed very briefly.

The Pennsylvanian sequence spottily overlies the Mississippian sequence. The contact between the two sequences is commonly unconformable, especially at the northern and southern ends of the basin. As the bulk of the Pennsylvanian sequence has been removed by erosion since the end of Paleozoic time, only remnants are preserved in synclines and in larger basinal areas within the Appalachian basin. At no point in the basin is the original thickness of the sequence completely preserved. The areal extent of the sequence coincides closely with the extent of the coal fields shown on figure 18.

The rocks of the sequence originally constituted a thick wedge of relatively coarse grained clastic debris that was thickest and coarsest-grained along the eastern side of the basin. Conglomerate, conglomeratic sandstone, sandstone, siltstone, mudrock, and shale constitute the bulk of the sequence. Coal, clay, and limestone are minor constituents. Coal is commonly present in commercial quantities throughout most of the areal extent of the sequence.

Parts of the Pennsylvanian sequence are preserved in four synclinoriums in east-central and northeastern Pennsylvania. The four areas encompass the anthracite fields of the State. In the Southern Anthracite field in Schuylkill and contiguous counties, the sequence consists of 3,000 to 3,500 feet of rocks of Early Pennsylvanian age. Conglomerate and conglomeratic sandstone compose about 50 percent of the section. Sandstone forms most of the remainder of the section. Beds of anthracite occur throughout the sequence and have been intensively mined.

Rocks of the Pennsylvanian sequence are exposed throughout much of the central part of the basin. The sequence is most completely represented in an area that occupies the southwest corner of Pennsylvania, the southeast edge of Ohio, much of northern West Virginia, and parts of western Maryland. In this area the maximum preserved thickness is about 2,000 feet, and rocks of Pennsylvanian and Permian ages are present. The following sequence is commonly recognized.

Permian system	Dunkard Group	Greene Formation Washington Formation
Pennsylvanian System	Monongahela Group Conemaugh Group Allegheny Group Pottsville Group	

Each group comprises a heterogeneous succession of interbedded sandstone, siltstone, mudrock, and shale. Coal, clay, and limestone are minor constituents by volume, but are of great commercial value. Coal especially has been intensively mined throughout most of the central part of the basin.

In southern Virginia the Pennsylvanian sequence may be as thick as 6,000 feet. It comprises rocks of Pottsville and Allegheny ages and is composed largely of siltstone and sandstone. The basal unit, the Lee Formation, is composed in large part of sandstone with some beds of conglomerate and some thin beds of coal. The upper units—the Norton Formation, Gladeville Sandstone, and the Wise Formation—contain a higher percentage of fine-grained rocks and a greater number of minable coal beds. In nearby Kentucky the rocks above the Lee are named the Breathitt Formation.

In synclinal areas in Alabama the Pennsylvanian sequence may attain a thickness of about 9,000 feet. Only rocks of Pottsville age are preserved. Younger Pennsylvanian rocks, if originally present, have since been removed by erosion. At the southwestern margin of the basin where Cretaceous rocks are present above Pennsylvanian rocks, the contact between the two systems is an angular unconformity. The Pennsylvanian sequence is thickest and coarsest grained along the southeastern margin of the basin. In the vicinity of the Cahaba coal field, the basal 600 to 700 feet of the sequence consists largely of thick beds of conglomerate and conglomeratic sandstone. The remainder of the sequence consists of interbedded shale, mudrock, siltstone and sandstone, and contains many minable beds of bituminous coal.

WASTE-DISPOSAL POSSIBILITIES

General considerations

As a result of this preliminary survey it appears that several rock sequences associated with particular geologic environments in the Appalachian basin offer some geologic factors favorable for the disposal of radioactive waste solutions through deep wells, provided the requirement of safe containment can be met. Again it must be emphasized that hydrologic factors were not studied during the course of this investigation. It should also be emphasized that the paramount problem of complete containment of the fluid waste is not subject to analysis on a regional scale, and that very detailed analysis of a given area is required. Such detailed analysis is far beyond the scope of this study. The objective here is to show the general characteristics (lithology, thickness, distribution, and structural condition) of the stratified rocks in the basin, and to indicate which parts of the rock succession and which general areas seem relatively more favorable geologically for the disposal of radioactive wastes. Subsequent studies can then be made in areas that offer some promise for disposal to determine whether the requirements for safe containment can be fulfilled.

It is assumed that waste solutions will be available in rather large volumes and that the levels of radioactive decay will vary considerably. The pH of the wastes also will vary considerably. Some of the fission products of the waste solutions may be biologically dangerous, and consequently must be kept from contact with water supplies utilized by the biologic environment for an unknown length of time. A depth of 2,000 feet below ground level may be accepted as an arbitrary guide above which the disposal of radioactive waste solutions is not considered feasible because of the possibility of contamination of water supplies. Further study in some areas may show, however, that waste disposal is feasible only at depths greater than 2,000 feet below ground level.

The type or types of reservoir most likely to be considered will depend ultimately on the characteristics and volumes of the wastes involved. In general however, the following types of reservoir appear to be most suitable in the Appalachian basin.

(1) Artifically created cavities in salt beds in thick salt-bearing sequences - if relatively small or moderate volumes of waste products are being considered.

(2) Thin lenticular sandstone bodies surrounded by impermeable shale or mudrock.

(3) Portions of thick sequences composed largely on noncarbonate clastic rocks.

(4) Relatively thin clastic sequences with natural or artificially created openings overlain by impermeable strata in the plate of a thrust fault.

(5) Thick, essentially undeformed carbonate sequences may have some possibilities as reservoirs, especially for non-acid or neutralized wastes. However, the writer believes that disposal in the carbonate sequence in the Appalachian basin is in general potentially more hazardous than in the other types of reservoirs listed above.

From the present study some areas are recognized (fig. 18) on broad geologic and geographic grounds as being generally unsuitable for waste-disposal purposes. In general, crystalline rocks of the basement complex do not have the physical characteristics that would make them suitable for waste disposal through wells. It has been assumed for the purposes of this study that disposal in sedimentary rocks must be at depths greater than 2000 feet to lessen the possibility of contamination of potable water supplies. Consequently areas underlain by less than 2000 feet of sedimentary rocks would be unsuitable. Figure 18 shows an area of approximately 4,600 square miles along the south and southwest flanks of the Adirondack uplift where less than 2000 feet of sedimentary rocks are present between ground level and the top of the basement complex. Small areas with too thin a sedimentary cover also occur along the east edge of the basin. However, available data are insufficient to outline these areas and they are not shown.

Areas underlain by rocks containing coal, oil, and gas in large volumes may be generally unsuited for the underground disposal of radioactive wastes. Figure 18 shows the location of coal fields and of oil and gas fields. The occurrence of potential mineral resources undoubtedly will lessen, and in many instances will eliminate such areas from consideration for waste disposal purposes. Certainly the presence of underground mines and of well holes will constitute a complicating factor if waste-disposal operations are planned.

Another area that appears to be generally unfavorable is the narrow belt extending the full length of the study area (fig. 18) in the easternmost part of the Valley and Ridge province. Conditions do not appear favorable in this belt because of complex structure, especially the presence of numerous thrust faults, high-angle faults, and the highly fractured and folded condition of the rocks. However future detailed work might show that small areas within the belt may be suitable for some waste-disposal purposes.

A large area where waste-disposal possibilities are limited because suitable rocks are absent is suggested on figure 18. This area coincides closely with the unpatterned belt between the line marking the west edge of the study area and the patterned belt showing the main coal-, oil-and gas-producing area. In most of this belt the sedimentary column is composed predominantly of carbonate rocks. Shale and sandstone are minor components. As will be explained later neither the shale nor sandstone units in most of this part of the study area appear to be suitable for waste-disposal purposes.

For convenience in broadly evaluating the waste-disposal possibilities of areas within the basin, the location of cities are shown by symbol on figure 18. The size of the symbols (circles) enclosing the cities indicates their population only. The concentration of densely populated areas along the northwest margin of the study area is apparent.

Waste-disposal possibilities of individual sequences

Late Precambrian stratified sequence.--The Late Precambrian stratified sequence has been studied and mapped in detail only in a few areas. Consequently it is difficult to assess the possibilities of disposing of liquid radioactive wastes in it by means of wells. Several facts appear to militate against waste disposal in the sequence. First, it is structurally complex. Faults are common and axial-plane cleavage is well developed in many areas. Further detailed work in most areas will probably uncover previously unmapped faults. Faults and cleavage planes might serve as escapeways for radioactive fluids. Secondly, the porosity of most rocks comprising the sequence is low, owing to recrystallization during metamorphism. Thirdly, available evidence indicates that the Precambrian stratified sequence does not extend far enough westward (see pg. 27) in most places in the Appalachian basin to be found at depths greater than 2,000 to 3,000 feet.

The writer believes however, that the sequence should not be completely removed from consideration for two reasons. First, the Late Precambrian strata comprise a thick sequence of rocks of relatively little economic significance occupying large areas of the sparsely settled Blue Ridge Mountains. Second, many of the rocks are brittle and may be susceptible to artificial fracturing; if so this might be used to increase the potential reservoir space, provided the fracturing can be controlled. In any event extremely detailed subsurface and surface site studies will be necessary, especially to assess the structural environment of the rocks at the site.

Early Cambrian clastic sequence.--The Early Cambrian clastic sequence is poorly suited for the disposal of liquid radioactive wastes in most parts of the Appalachian basin. Throughout most of the basin it lies at depths too great to be considered at the present time. In parts of southern Ohio, northeastern Kentucky, and northern Tennessee where the sequence is present and occurs at depths between 2,000 feet and 10,000 feet below ground level, its usefulness for waste disposal is limited by the following facts. First, it is relatively thin (ranging from a feather edge to about 1000 feet in thickness) in most of this area. Second, it probably contains much interbedded carbonate rock, and it is directly overlain by a carbonate sequence. Furthermore, as the clastic sequence has been encountered in only a few wells, little is known about its lithology in the subsurface.

In a narrow belt along the eastern margin of the basin where the Lower Cambrian sequence can be reached at moderate depths (that is, less than 10,000 feet below the surface) other factors limit its usefulness for waste disposal. Firstly, the sequence is complexly folded and faulted. Secondly most of the rocks in the sequence are tightly cemented, thus resulting in a low degree of porosity. The permeability of some of the rock units may be high locally owing to fracturing and jointing, but the occurrence of these ruptures increases the possibilities of leakage along ruptured surfaces. Nevertheless, detailed site studies (both surface and subsurface) of the lithology, stratigraphy, and structure of the Lower Cambrian rocks might lead to the discovery of some relatively small areas along the eastern margin of the basin that may be suitable for the underground disposal of liquid radioactive wastes.

Cambrian-Ordovician carbonate sequence.--The writer believes that the Cambrian-Ordovician carbonate sequence is, in general, poorly suited for the disposal of high-level liquid radioactive wastes for the following reasons:

1. In most parts of the basin the rocks of Middle Cambrian to Middle Ordovician age are composed largely of calcium carbonate (limestone) and calcium-magnesium carbonate (dolomite) in varying proportions. Both minerals are soluble in many common acids. The reactions of acidic aluminum nitrate high-level radioactive waste solutions with calcium carbonate is discussed by Roedder (1959, p.32-36). Under laboratory conditions a gel is formed by the reaction of these compounds. The gel presumably would be effective in greatly decreasing the permeability and porosity of the carbonate strata in contact with the acid radioactive wastes. If waste products which will not form a gel in contact with carbonate rocks are available, the the above objection based on the chemical composition of the sequence may not be valid. However, carbonate rocks are in general very susceptible to fracture by deformative stresses and to solution by ground water. In areas where such openings exist, the sequence probably will not be suitable for disposal purposes because of the uncertainty of safe containment.

2. Porous layers, which might provide the space required for injected waste solutions, are numerous in the Cambrian-Ordovician carbonate sequence. Bayles and others (1956, p. 18-28) report the occurrence of salt water at seven horizons and shows of gas at 27 horizons in the sequence in the Hope Natural Gas Company and others' well in Wood County, W. Va. Little has been published about the hydrologic characteristics of the aquifers in the sequence or about the physical characteristics of the gas-bearing horizons. However, the frequency with which aquifers and shows of gas have been reported from wells drilled into the sequence in many parts of the basin suggests that some of the porous layers are continuous over large distances. The writer believes that widespread porous layers would not be suitable for waste disposal because of the increased chances of escape, especially along fractures or faults or through drill holes. If, on the other hand, an isolated porous layer between impermeable strata is discovered at convenient depth in an area where few if any wells have been drilled, then the layer might be suitable as a reservoir for waste solutions. However, a very thorough testing program will be necessary to prove the presence of a suitable environment from which waste solutions cannot escape vertically or laterally.

3. Along much of the west side of the Appalachian basin where the Cambrian-Ordovician sequence lies at relatively shallow depths, many wells have been drilled into or through the carbonate sequence in search of oil or gas. These wells--many of which are old and have not been accurately located --could serve as escapeways for radioactive wastes stored in the vicinity. Recently there has been much interest in the oil- and gas-bearing potentialities of the carbonate sequence and the exploration pace has accelerated. In the past 5 years a number of wells testing the sequence have been drilled in New York, northwestern Pennsylvania, Ohio, Kentucky, western West Virginia, and northern Tennessee. In 1960, gas, oil, or distillate were discovered in the carbonate sequence in wells in three places. The three successful wells are in Erie County, Pa., and in Medina and Morrow Counties in northern Ohio. Presumably these discoveries will encourage further exploration of the Cambrian and Ordovician carbonate rocks.

4. In most of the central part of the basin, where the sequence has not been penetrated by wells in search of oil and gas, the carbonate sequence lies at depths ranging from 6,000 to 12,000 feet below sea level. Disposal at such depths may be much more difficult than at more shallow depths.

5. Along much of the eastern edge of the Appalachian basin where the carbonate sequence is less than 5,000 feet below the surface, the rocks are complexly folded and faulted. The intensity of structural deformation of the Cambrian-Ordovician carbonate sequence along the east edge of the basin is well shown in two quadrangles in Lebanon County, Pa., recently mapped by Gray and others (1958) and Geyer and others (1958). Fracture cleavage and other types of rock fracture accompanied the intense folding and faulting.

The noncarbonate clastic rocks which comprise the lower and upper parts of the Cambrian-Ordovician sequence in eastern Tennessee and along the strike in southwestern Virginia and northwestern Georgia (fig. 19) may be suitable locally for storage of radioactive wastes. These rocks, especially the Nolichucky Shale, the Tellico Formation, and the Sevier Shale, are of little economic importance in the subsurface at the present time. However, they are composed largely of fine-grained shale and siltstone and the porosity is low. Permeability is probably be low except possibly in areas where structural deformation has opened up fractures and other ruptures in the rock. Future work may show that the clastic parts of the carbonate sequence could be used for liquid radioactive waste storage in local areas along the east edge of the Appalachian basin; however, extremely detailed site studies will be necessary to evaluate thoroughly the bedrock conditions at a site.

Late Ordovician clastic sequence.--The Late Ordovician clastic sequence offers slightly better possibilities for the underground disposal of radioactive wastes than the underlying Cambrian-Ordovician carbonate sequence. A number of factors which are believed to favor consideration of the sequence as a potential reservoir are listed below:

1. The Late Ordovician series is composed largely of noncalcareous rocks, largely shale, mudrock, siltstone, and sandstone. They are less apt to be fractured than carbonate rocks, and are much less subject to solution.

2. Parts of the Oswego Sandstone and sandstones in the Juniata Formation may be permeable enough in some areas to serve as reservoirs with a minimum amount of artificial fracturing treatment. The thickness and extent of the Oswego are shown on figure 9. However, the few available detailed descriptions of surface exposures of the Oswego and Juniata indicate that the sandstones are tightly cemented, largely by silica.

3. The Martinsburg Shale and its partial equivalent, the Reedsville Shale, may have a high degree of permeability in areas of intense fracturing and shearing owing to structural deformation, but containment of a liquid within a specific area seems unlikely. Fractured and deformed shale would more likely be encountered where these rock units are thick and where deformative stresses were great. Both conditions are probably present in some areas in central Pennsylvania, western Maryland, and northeastern West Virginia a short distance west of the Appalachian structural front.

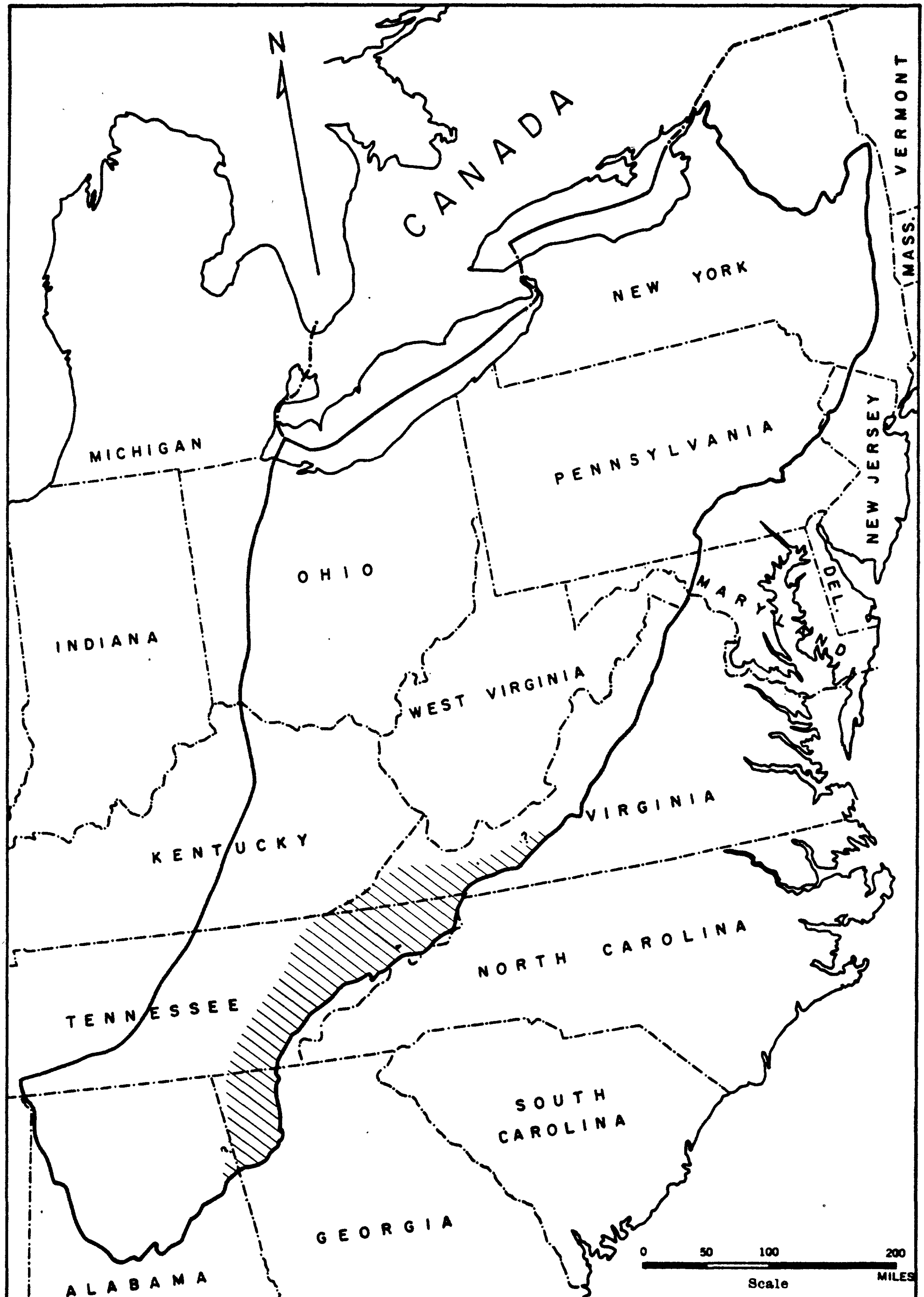

FIGURE 19 —Map showing general area where geologic environment of Cambrian-Ordovician carbonate sequence may be locally suitable for waste-disposal purposes.

4. The top of the Late Ordovician series lies within the desirable range (2,000-10,000 feet) of depth below the surface in large parts of the Appalachian basin.

5. In the subsurface the Late Ordovician clastic sequence is virtually nonproductive of mineral resources throughout the Appalachian basin. It has been used to some extent (mainly for slate, flagstone, dimension stone, and road metal) where it crops out, especially along the eastern side of the basin. The writer knows of no oil or gas produced on a commercial scale from rocks of Late Ordovician age, except in Warren County, Tenn., where relatively small quantities of gas have been discovered.

The areas in which the more favorable features occur are not numerous, however, and in much of the Appalachian basin the Late Ordovician clastic sequence does not appear to be suited as a host rock for the underground disposal of radioactive wastes. The areas where the writer believes that the waste-disposal possibilities are poor are listed below:

1. Along much of the eastern edge of the basin where the sequence lies at shallow depths and is complexly deformed, especially by thrust faults.

2. Along the northern margin of the basin where the sequence is thin, occurs at shallow depths, and rises toward the outcrop.

3. In much of western Ohio, central Kentucky, and central Tennessee where the sequence is thin, lies at shallow depths, rises toward the outcrop areas, and furthermore is composed largely of calcareous rocks.

4. In northern Alabama, west of the Valley and Ridge province, where the sequence is thin and consists largely or entirely of carbonate rocks.

5. In some areas in the central part of the basin where the top of the clastic sequence lies at depths greater than 10,000 feet below sea level.

In summary, the Late Ordovician sequence may be suitable for the underground disposal of radioactive wastes through deep wells in areas where the sequence is thick, is composed of noncalcareous rocks, has appreciable porosity and permeability, or is susceptible to artificial fracturing, has not been densely penetrated by oil and gas wells, and occurs at depths ranging from 2,000 to 10,000 below the surface. In general a greater number of these conditions appear to be met in south-central New York and north-central Pennsylvania than in other parts of the basin (fig. 20). Conditions appear to be generally less favorable in parts of southeastern and southwestern New York, western Pennsylvania, eastern Ohio, and parts of West Virginia, although the sequence has some possibilities in these areas.

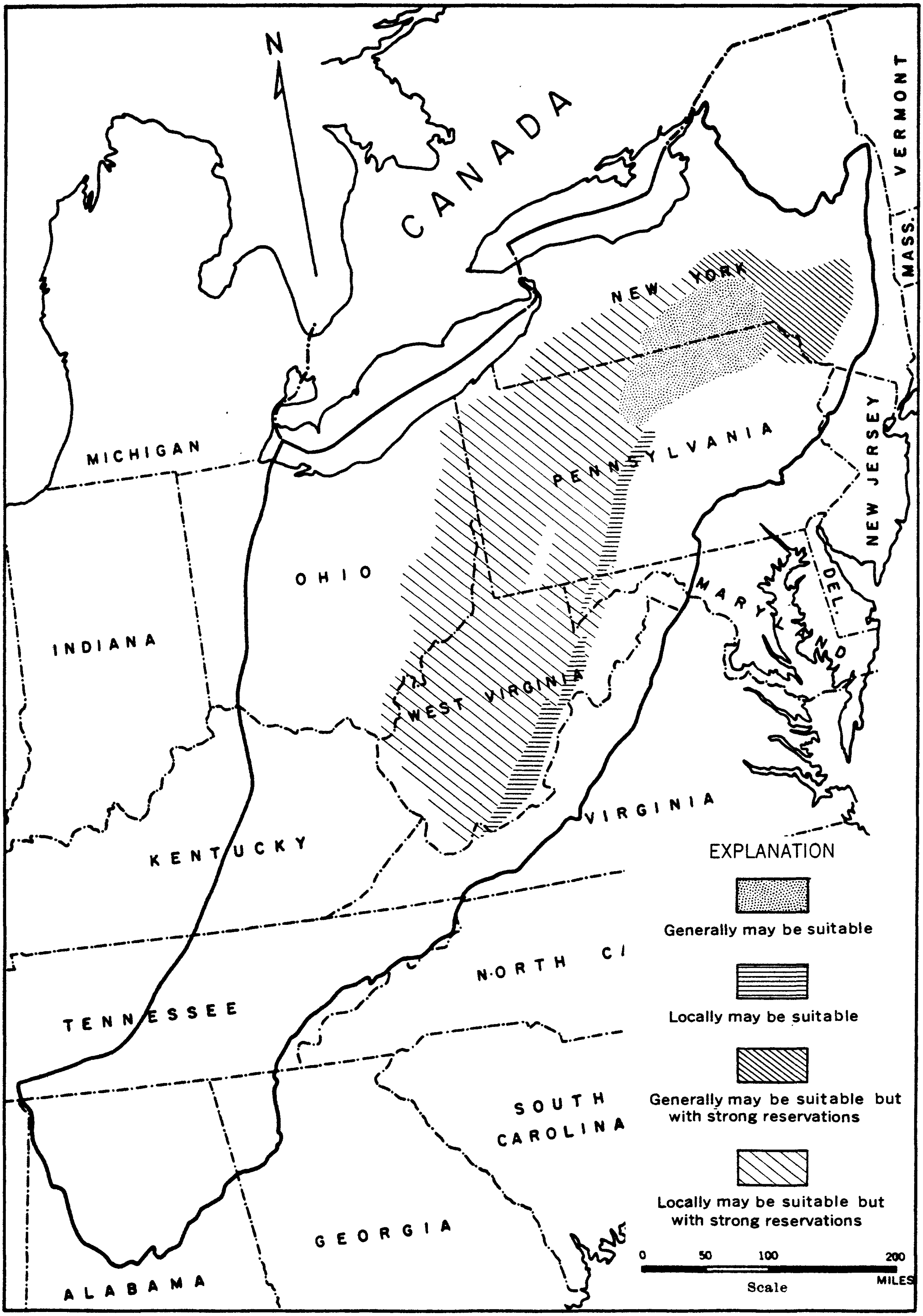

FIGURE 20.—Map showing general areas where geologic environment of Late Ordovician clastic sequence may be suitable for waste-disposal purposes.

Early Silurian clastic sequence.--In most parts of the Appalachian basin the Early Silurian clastic sequence is not considered by the writer to be a promising reservoir for the underground storage of liquid radioactive wastes. First, the sequence is highly productive of oil and gas in large parts of the Appalachian basin. Second, the structural attitude and the lithology of the sequence is generally not favorable in most parts of the basin where hydrocarbons probably do not occur in large volumes. The Early Silurian sequence has been densely drilled for oil and gas, especially in the shallower parts of the basin in the eastern half of Ohio, northwestern Pennsylvania, western New York, and in parts of eastern Kentucky. As the industry continues to drill to greater depths in its search for oil and gas, the sequence will be penetrated by an increasing number of drill holes in the deeper parts of the basin. Within the last few years the search for oil and gas at greater depths has resulted in the drilling of a number of deep test wells to or through the sequence in previously untested areas, especially in western and central Pennsylvania, south-central New York, eastern Kentucky, and western West Virginia.

The environment of the Early Silurian sequence in the Valley and Ridge province, where the rocks are tightly folded, appears generally less favorable for the accumulation of oil and gas. Nevertheless the structural altitude of the Early Silurian clastic sequence in the folded Appalachians is generally unfavorable for the disposal of radioactive wastes. The Lower Silurian rocks crop out in a number of closely spaced belts parallel to the axis of the basin. Rocks of the sequence have been removed by erosion from the crests of many anticlines. From the troughs of the intervening synclines, the Lower Silurian rocks rise rapidly toward the surface, affording a relatively short migration route to the surface. The possibility of up-dip migration of radioactive wastes in tabular sandstone bodies was suggested by Repenning (1959, p. 50). If tests should show, however, that the generation of heat by radioactive decay will not cause waste fluids to migrate upward, then disposal in synclines may be feasible if other conditions are favorable. Conditions such as depth, thickness, porosity and composition appear to be most favorable in the northern part of the folded Appalachians in northwestern Virginia, northeastern West Virginia, western Maryland, and central Pennsylvania (fig. 21).

In most of Tennessee, northwest Georgia, and northern Alabama, the Early Silurian sequence is composed largely of carbonate rocks which are particularly subject to fracturing and solution, or the sequence is too shallow to be suitable for waste disposal.

In spite of the general objections raised above, rocks of the Early Silurian clastic sequence might serve as disposal media in some local areas where the geologic environment is unusually favorable. In the part of the Valley and Ridge province where thrust faults are numerous, relatively undisturbed Lower Silurian sandstones may be overlain by impermeable older rocks in the thrust plate. For example, in the Brooks well in southwestern Lee County, Va., (Miller and Fuller, 1954, p. 296-298) 500 feet of Clinch Sandstone and Clinton Shale was encountered at a depth of about 2,000 feet. The Pine Mountain overthrust fault is present at the top of the Clinton. The Clinton is overlain by nearly 2,000 feet of rock consisting largely of shale of Early and Middle Cambrian age. In this, and in similar areas where

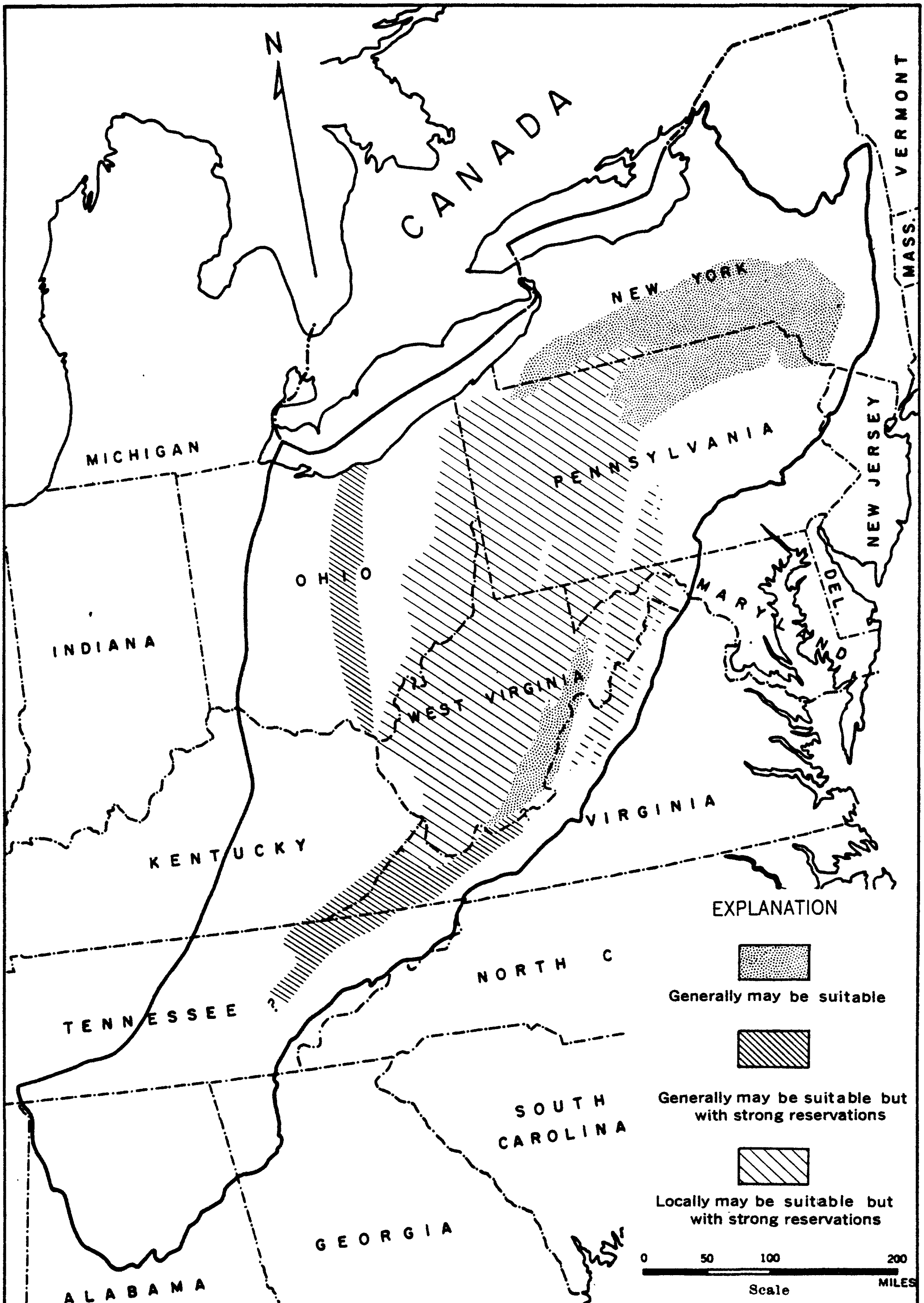

FIGURE 21.—Map showing general areas where geologic environment of Early Silurian clastic sequence may be suitable for waste-disposal purposes.

thrust faults are present, detailed surface and subsurface site studies may show that the Early Silurian can be utilized for radioactive-waste disposal.

In the northwestern part of the Appalachian basin, where the Early Silurian clastic sequence is thin, sandstones may occur as lenticular bodies isolated in shale. Lenses of porous sand completely surrounded by impermeable strata may offer some of the best possibilities in the Appalachian basin for the disposal of radioactive-waste solutions. Figure 22 shows the approximate extent and thickness of the upper two of the three "Clinton" sands reported by drillers in Worthington Township, Richland County, in north-central Ohio, and the location of oil and gas pools in the two sandstones. The stratigraphic positions of the sandstones are shown in a generalized manner in figure 13. In this part of Ohio the "Clinton" sands dip gently eastward at approximately 45 feet per mile, and in Worthington Township they range in depth below sea level from about 1260 feet to about 1540 feet. The average ground elevation in the township is between 1050 and 1100 feet. Precise data on the porosity and permeability of the producing rocks in the township are not available. Alkire (1952, p. 4) reports that the porosity of samples of the "Clinton" sands in Perry County, about 60 miles south of Richland County, range from 12 to 17 percent, and that the permeability ranges from 0 to 150 millidarcys. The accumulation of hydrocarbons is controlled largely by the porosity of the sandstone bodies. Water is rarely present, most pore space being occupied by gas or more rarely by oil. The "Clinton" sands are underlain by 20 to 30 feet of shale of Silurian age which in turn is underlain by nearly 1300 feet of predominantly shaly rocks comprising the Late Ordovician clastic sequence. The sandstones are overlain by about 110 feet of calcareous shale including a thin unit of coarsely crystalline limestone--the "Packer Shell" or the "Little lime" of the drillers. The shale above the "Clinton" sands is in turn overlain by dolomite and limestone of the Silurian-Devonian carbonate sequence. An extensive saline aquifer occurs in the lower part of the carbonate sequence about 270 to 370 feet above the uppermost "Clinton" sand.

In Worthington Township the "Clinton" sandstones have been heavily drilled for oil and gas, and in parts of north-central Ohio they are presently being used for the underground storage of natural gas. However, similar isolated bodies of porous sand of Early Silurian age may occur in other less densely drilled townships along a north-south belt in central Ohio (fig. 21).

Silurian-Devonian carbonate sequence.--On the basis of this preliminary study of some of the geologic factors involved, the Silurian-Devonian carbonate sequence does not appear to be suitable for disposal purposes in most parts of the basin.

In the western and northern parts of the basin the sequence has been penetrated by a great many wells drilled for oil and gas within the sequence or in rocks not far below. As the search for oil and gas continues, more wells will be drilled into and through the carbonate sequence in the deeper parts of the basin. Along much of the periphery of the basin the sequence is exposed at the surface or lies at depths too shallow to be considered for waste disposal. In many places in the Valley and Ridge province also, rocks of the sequence crop out or are too shallow to be suitable for waste disposal.

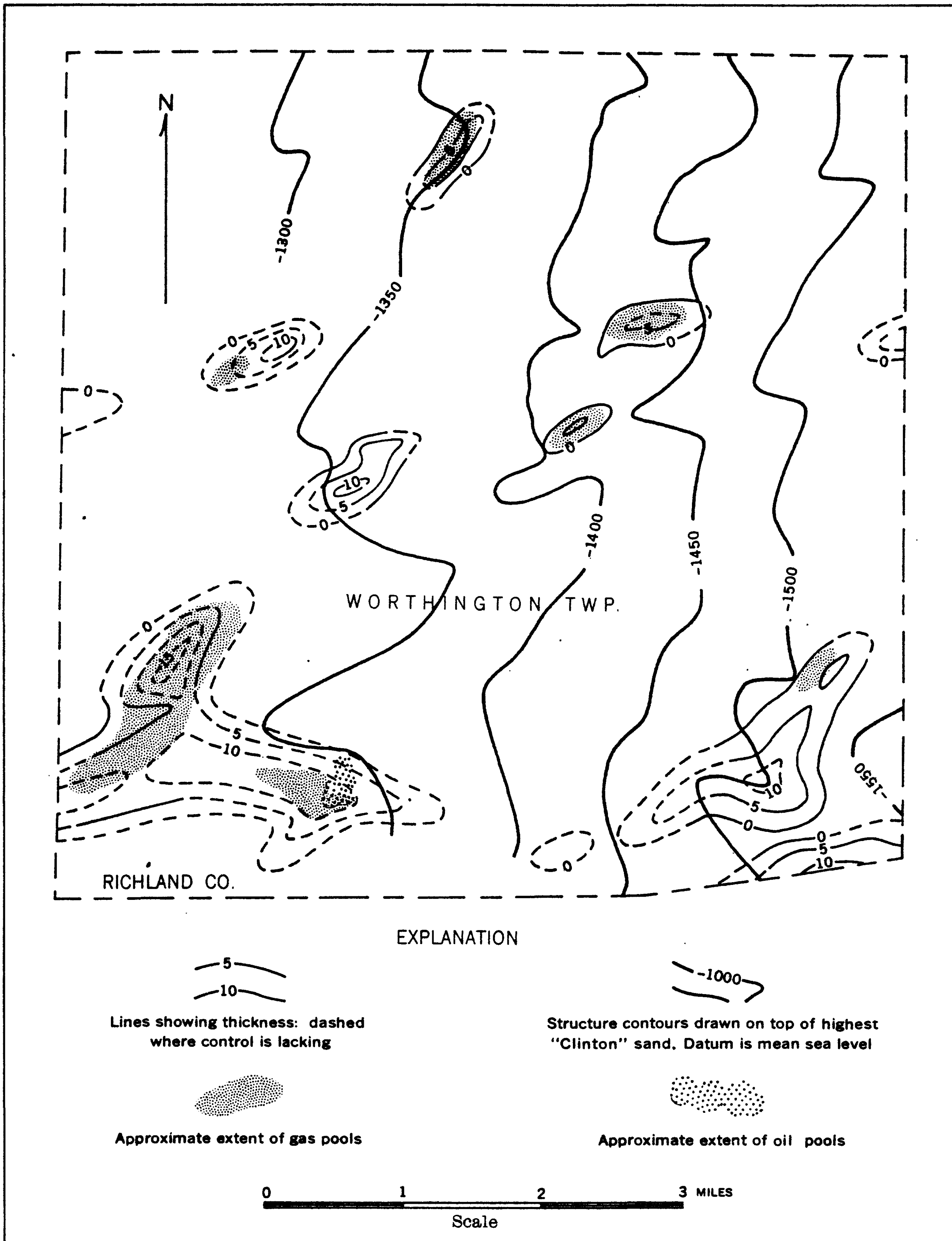

FIGURE 22.—Map of a township in north-central Ohio showing thickness of two of the "Clinton" sands and location of oil and gas pools.

Two highly porous and permeable saline-water-bearing zones are present in the carbonate sequence (fig. 13) in the subsurface in much of the northwestern part of the basin. Roedder (1959, p. 2) used the term salaquifer for porous and permeable beds containing salt water in the subsurface. Although salaquifers have been considered as likely host rocks for the disposal of radioactive wastes, those in the Silurian-Devonian carbonate sequence do not seem to be suitable for this purpose. The lower salaquifer occupies a zone of dolomitized organic reefs (Floto, 1955, p. 44-47) overlain and underlain by more impermeable strata. It is named the "Newburg sand" or the "Second Water" by drillers in Ohio, and is named the "Black Water" by drillers in northwest Pennsylvania because of its high content of hydrogen sulfide. The "Newburg" contains commercial quantities of oil and gas in many places in Ohio (Floto, 1955, fig. 8) and is largely untested in other parts of Ohio and most of northwest Pennsylvania, western West Virginia, and eastern Kentucky. Little is known about its hydrologic properties, especially about its continuity as a water-bearing zone. However, the very high percentage of wells in the northwest part of the basin recording heavy flows of salt water at this approximate stratigraphic position indicate that it is an extensive salaquifer. For the above reasons the writer believes that the "Newburg" is not suitable for the disposal of acid radioactive wastes.

The upper salaquifer is the Oriskany Sandstone or a sandstone or sandy dolomite close to the stratigraphic position of the Oriskany. Along the outcrop in Pennsylvania, Maryland, and West Virginia, the Ridgley sandstone is recognized in this part of the stratigraphic column. The Oriskany and its near equivalents do not appear to be suitable for waste disposal for several reasons. The Oriskany is highly productive of gas in southern New York, north-central and western Pennsylvania, eastern Ohio, and parts of West Virginia, and has been penetrated by many drill holes. The locations of gas fields in the Oriskany and Ridgeley sandstones as well as the thickness of the sandstones are shown in figure 23. Most gas fields occur on or near the crests of anticlines. Recent discoveries of gas in western Pennsylvania in the Oriskany in a synclinal area may lead to the drilling of wells in previously untested synclinal areas, thus decreasing the size of the area underlain by Oriskany Sandstone that has not been drilled. In most places where the Oriskany has been productive of gas, available data indicate open reservoirs with a high degree of permeability and a rather uniform water drive. In the northwestern part of the basin the Oriskany is thin, averaging about 18 feet in thickness in Ohio (Hall, 1952, p. 39). Consequently, radioactive wastes injected into the sandstone would probably come into direct contact with acid-soluble carbonate rocks immediately above and below the Oriskany. In the north-central part of the basin, where the Oriskany or the equivalent Ridgeley Sandstone is thicker (fig. 23), it is commonly faulted. Figure 24 shows the structural configuration of an Oriskany gas field in the north-central part of the basin, about 30 miles northwest of the Appalachian structural front. Movement along some of the faults shown in figure 24 has brought the Oriskany Sandstone into direct contact with older and younger carbonate rocks in many places. In summary, the salaquifer occupied by the Oriskany and Ridgeley sandstones or by closely equivalent rocks is believed to be unsuitable for the disposal of radioactive waste solutions, mainly for the following reasons: 1) it is highly productive of gas and has been densely drilled in many areas; 2) it is too thin in most places; 3) it is embedded in carbonate rocks throughout most of its extent; 4) it is commonly faulted into contact with carbonate rocks which may contain fractures and solution channels, thus complicating the problem of safe containment.

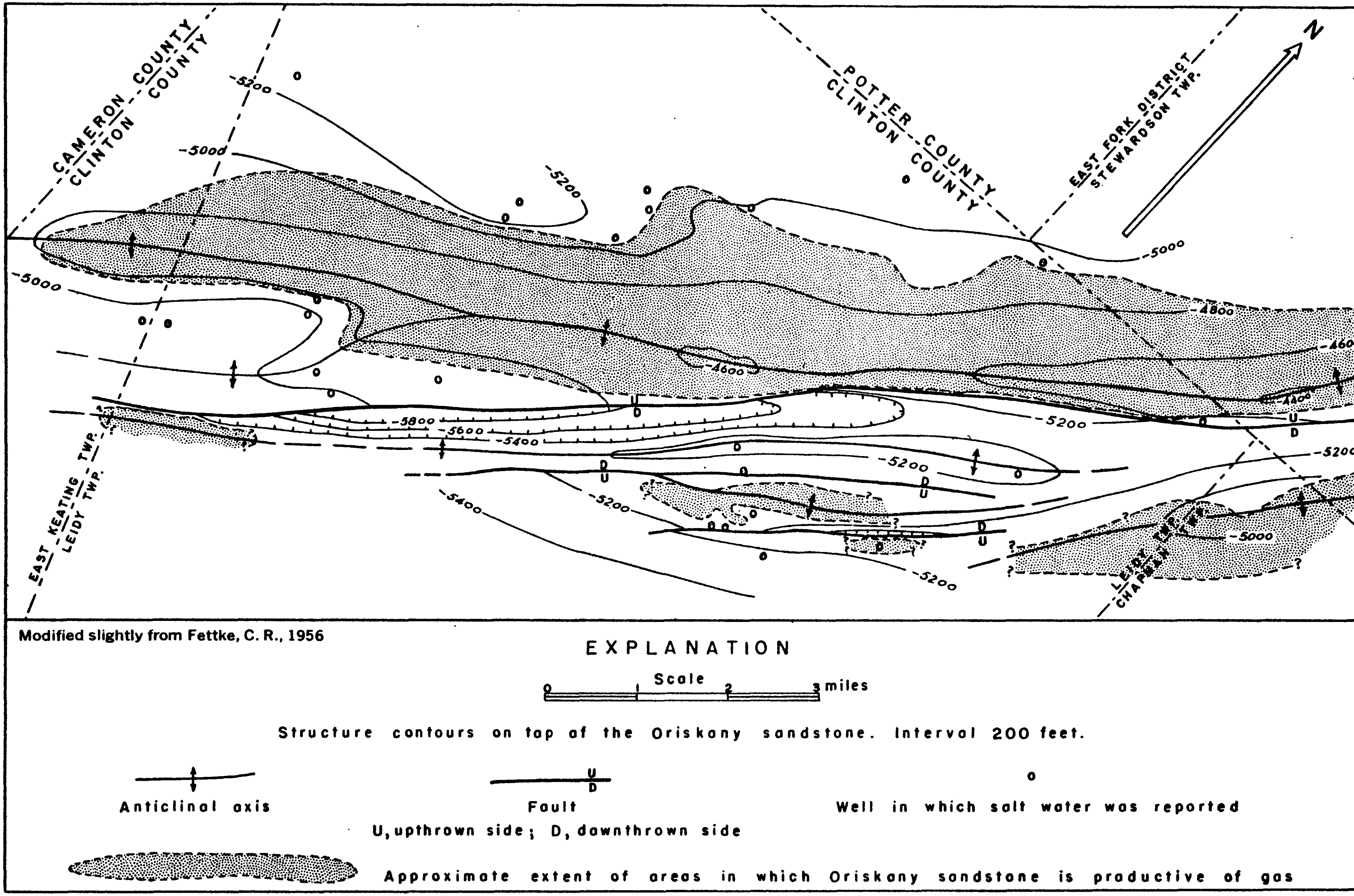

FIGURE 24.—Map of the Leidy gas field, Clinton County, Pa.

Although the bulk of the carbonate sequence in most of the Appalachian basin is not a promising medium for waste disposal, and the two salaquifers in the sequence are not suitable, two rock units within the sequence are more promising. These are the evaporites (especially rock salt) of the Salina Group, and the beds of red sandstone, shale, and mudrock in the Bloomsburg Red Beds. As shown in figure 12, salt beds of the Salina Group underlie much of south-central and southwestern New York, the northwestern half of Pennsylvania, eastern Ohio, and northwestern West Virginia. A generalized map showing the aggregate thickness of salt beds in the Appalachian basin was complied by Griggs (1958, fig. 3), consequently an isopach map of the salt-bearing strata was not prepared for this study. The area of greatest aggregate thickness of salt beds (more than 800 feet) is in Schuyler and Chemung Counties, south-central New York. Parts of contiguous counties in New York and parts of Bradford and Tioga Counties, are underlain by more than 500 feet of salt beds.

In much of the area underlain by salt the topmost bed of salt lies approximately 500 feet below the top of the Silurian-Devonian carbonate sequence as defined in this report. Consequently, the depth below sea level of the topmost bed of salt will be approximately 500 feet lower than the top of the carbonate sequence shown on figure 12. In south-central New York and north-central Pennsylvania where the salt sequence is thick, the topmost salt bed lies between 2,000 feet and 6,500 feet below sea level. The shallow elevations occur along the crests of anticlines and the deeper elevations in the troughs of synclines. In general, the geologic environment of the salt-bearing rocks in south-central New York and north-central Pennsylvania (fig. 25) favors further consideration of the Salina Formation or Group as a host rock for the disposal of radioactive wastes. The salt section is moderately thick in this area, lies at moderate depths below the surface, and the structural deformation is relatively gentle. The Salina has not been developed commercially in this area, except in the north halves of Schuyler and Tompkins Counties, N. Y. The writer knows of only 9 wells that have penetrated the salt-bearing portion of the Salina Formation within the area outlined by the 500-foot aggregate salt-bed thickness contour shown by Fettke (1955) and on figure 12 of this report. However, as exploration for oil and gas at greater depths continues, more wells will probably be drilled into and through the salt sequence in this area. The prolific gas-producing Oriskany Sandstone, which lies approximately 400 feet above the highest salt bed, has been densely drilled in parts of south-central New York and north-central Pennsylvania, so in such areas, any possibiliity of migration of waste into the Oriskany would have to be eliminated.

The Bloomsburg Red Beds are a thick sequence of noncarbonate clastic rocks that are commercially unimportant in the subsurface. Further study may show that this sequence of interbedded predominantly red sandstone, siltstone, shale, and mudrock could serve as a reservoir rock, especially if the red beds are susceptible to artificial fracturing, and if it is determined that fracturing will produce the desired effects. Presumably the red beds would be most suitable for waste disposal in areas where they are thickest. Figure 12 outlines the approximate area in which the Bloomsburg is 1,500 feet thick or more. It is apparent that the area of thickest Bloomsburg is in Monroe, Lackawanna, Luzerne, Carbon, Schuylkill, and parts of adjacent counties in Pennsylvania, a short distance southeast of the area of greatest aggregate thickness of salt beds.

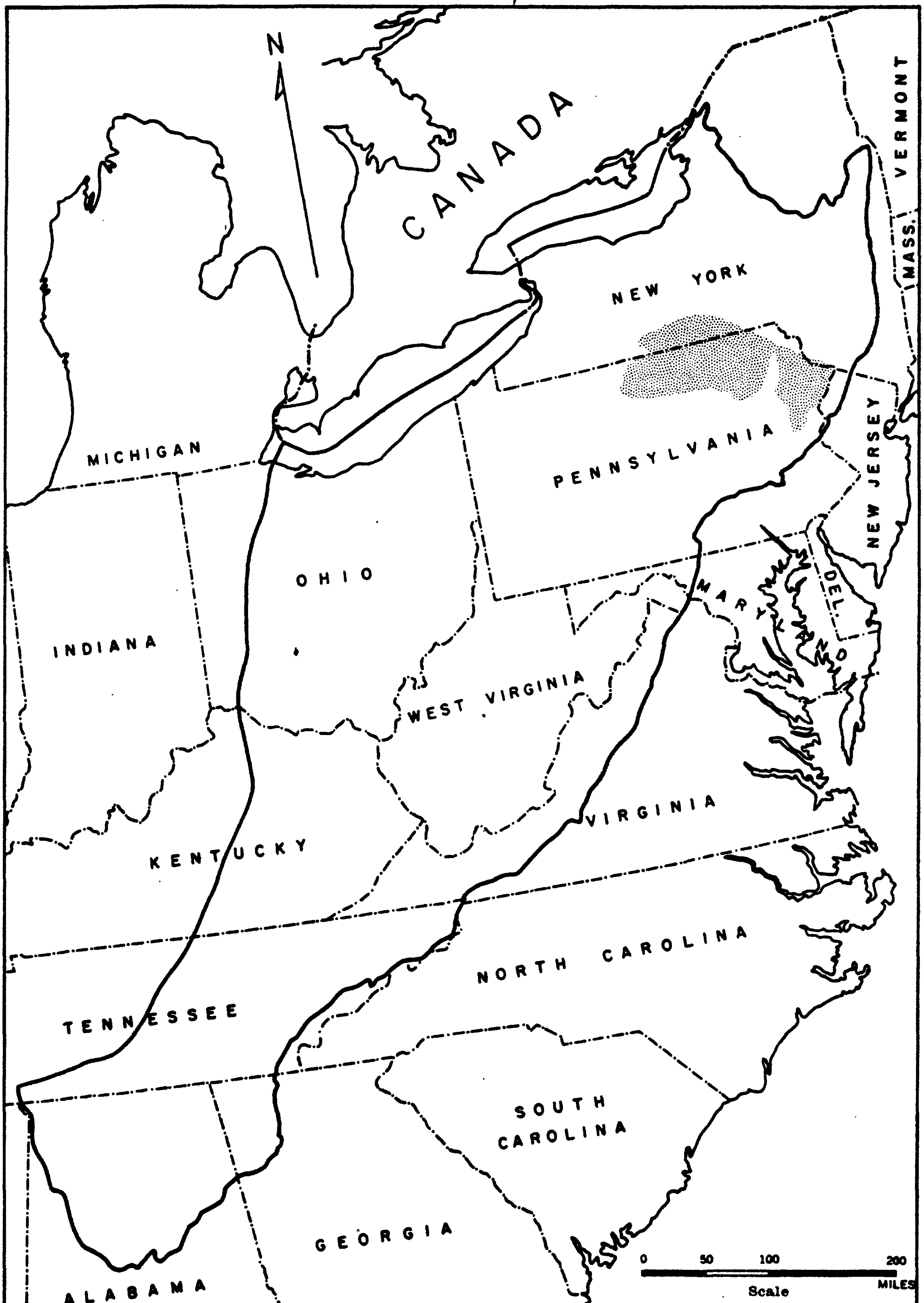

FIGURE 25.—Map showing general area where geologic environment of Silurian-Devonian carbonate sequence may be suitable for waste-disposal purposes.

The geologic factors influencing the waste-disposal possibilities of the Silurian-Devonian carbonate sequence can be summarized as follows: The carbonate rocks which comprise the bulk of the sequence in most of the Appalachian basin are not suitable, nor are the two extensive salaquifers in the sequence. Salt beds of the Salina Formation or Group, especially in south-central New York and north-central Pennsylvania, seem to deserve consideration as potential host rocks. The thick Bloomsburg Red Beds in parts of northeastern Pennsylvania (fig. 25) also seem to have possibilities as host rocks for the disposal of liquid radioactive wastes, provided disposal space can be created in them.

Devonian clastic sequence.--In many respects the Devonian clastic sequence does not appear to be well suited for the underground disposal of radioactive waste solutions. Possible exceptions to this statement may occur in the north-central part of the basin, especially in south-central New York, northern and western Pennsylvania, and central West Virginia (Fig. 26).

The structural environment of the sequence is generally unfavorable for waste disposal. In most of the peripheral, western and southern parts of the basin the sequence occurs less than 2,000 feet below the surface or crops out at the surface. In the troughs of many synclines in the Valley and Ridge physiographic provine, the sequence lies at considerable depths, but in most areas it rises rapidly from the synclinal troughs to the surface along the flanks and crests of nearby anticlines.

The lithology of the Devonian clastic sequence may not be favorable in some areas. In much of the northwestern part of the basin the rocks comprising the sequence are very fine grained, consisting largely of black shale, calcareous gray shale, and thin layers of siltstone. The writer does not know whether such rocks will be susceptible to artificial fracturing or if fracturing processes can be controlled to produce the desired openings without producing potential escape routes for injected fluids. The common occurrence of natural gas in parts of the black shale sequence is another deterrent to using the sequence for waste disposal purposes. Shale gas is produced in commercial quantities in parts of southeastern Ohio, westernmost West Virginia, and eastern Kentucky.

In most of the southern half of the basin, the sequence is too thin to be considered for waste-disposal purposes.

In much of the north-central part of the basin the lithology and depth of the sequence appear to be favorable locally. However the sequence has been penetrated by tens of thousands of drill holes for oil and gas within the clastic sequence and in stratigraphically lower rocks. A broad belt in which Upper Devonian rocks are highly productive extends southwestward across western Pennsylvania and West Virginia into easternmost Kentucky. Figure 27 shows the oil and gas pools in two townships in west-central Pennsylvania in the middle of the productive belt. More than 950 wells have been drilled into the Devonian clastic sequence in the 48-square-mile area encompassed by the two townships. Figure 28 is a generalized composite columnar section of the Mississippian and Upper Devonian rocks encountered in the subsurface in the area. As shown on the figure, oil and gas occur in seven sandstones of Late Devonian age and in one sandstone of Mississippian age. Additional sandstone

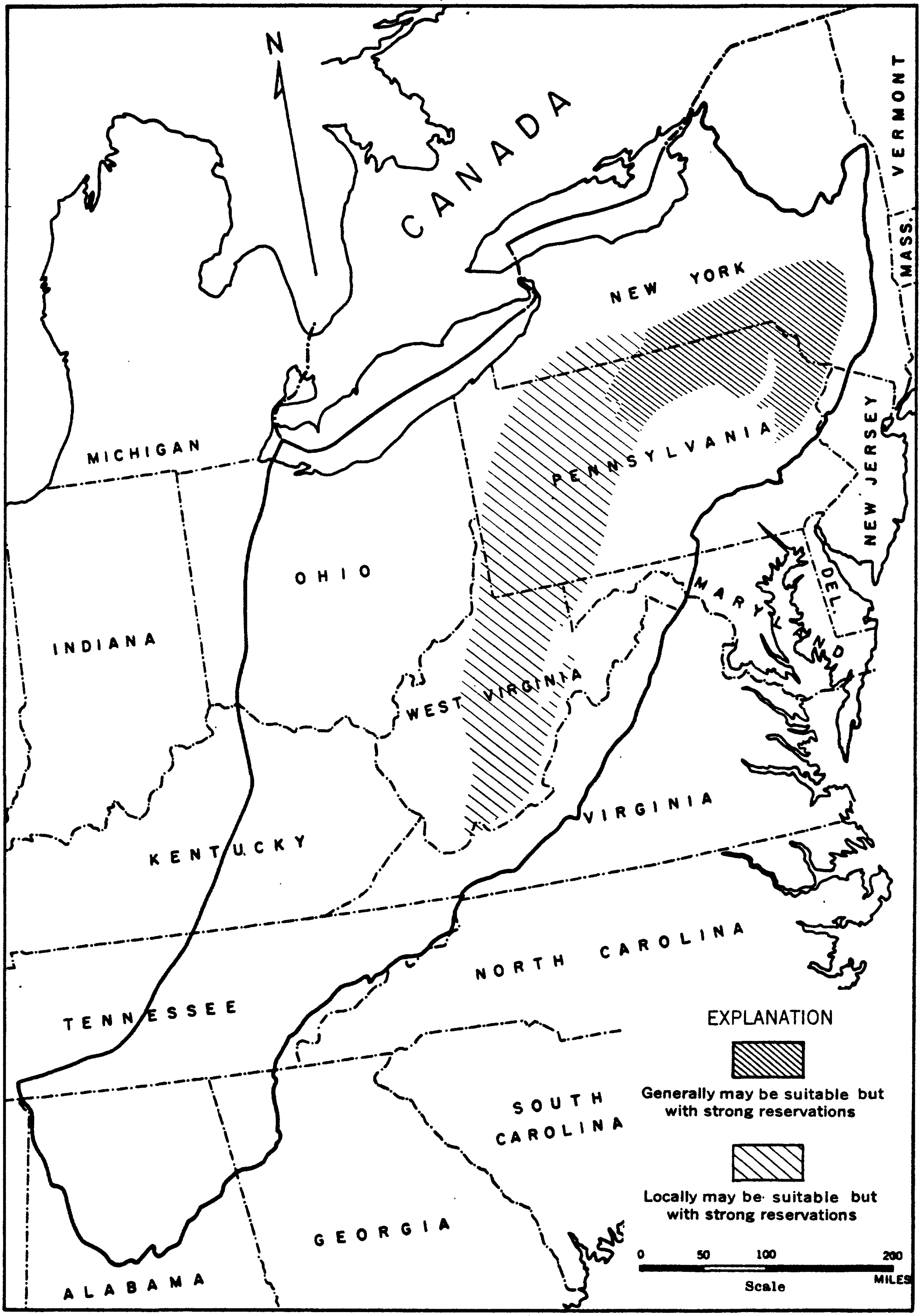

FIGURE 26.—Map showing general areas where geologic environment of Devonian clastic sequence may be suitable for waste-disposal purposes.

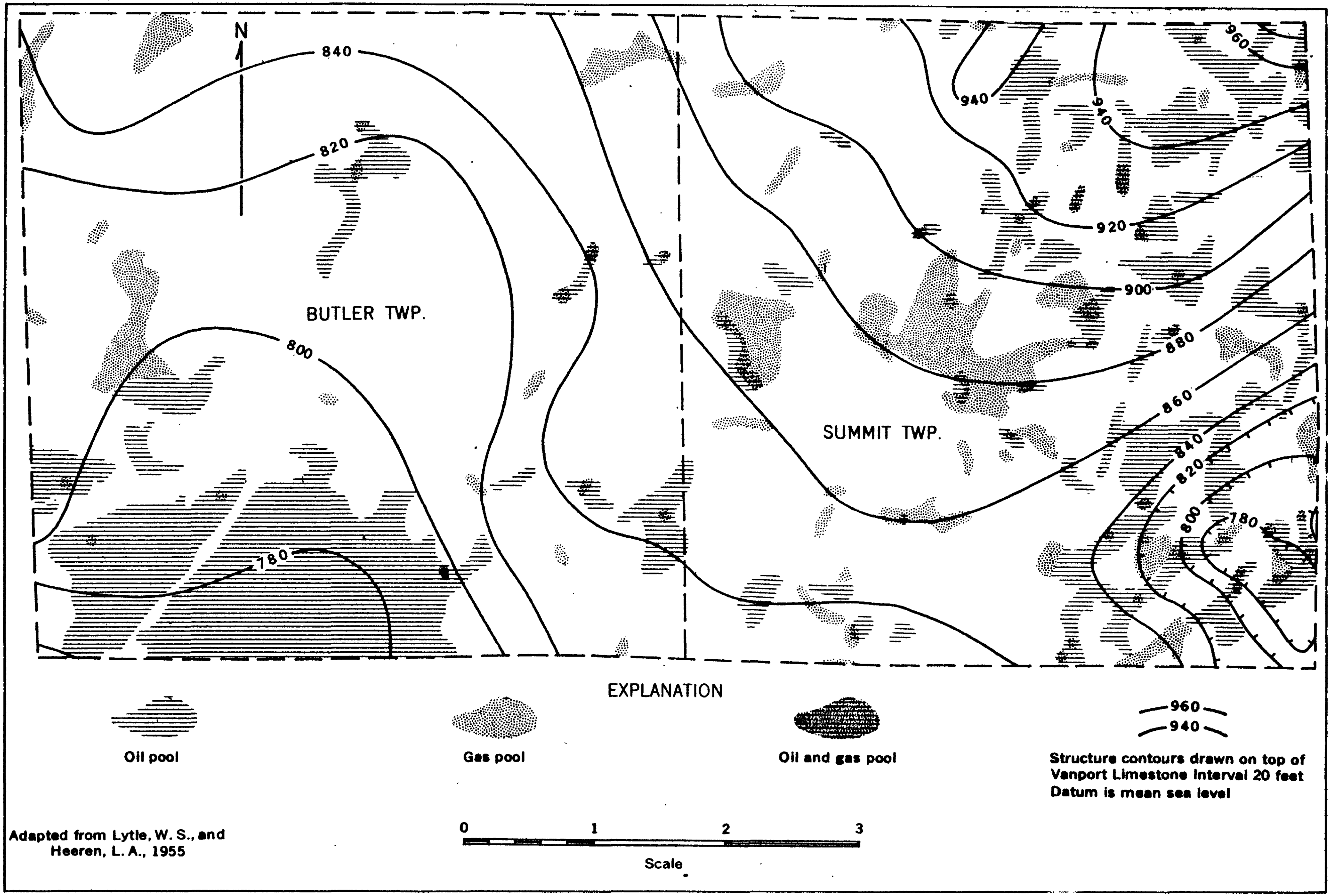

FIGURE 27.—Map of oil and gas pools, Butler and Summit Townships, Butler County, Pa.

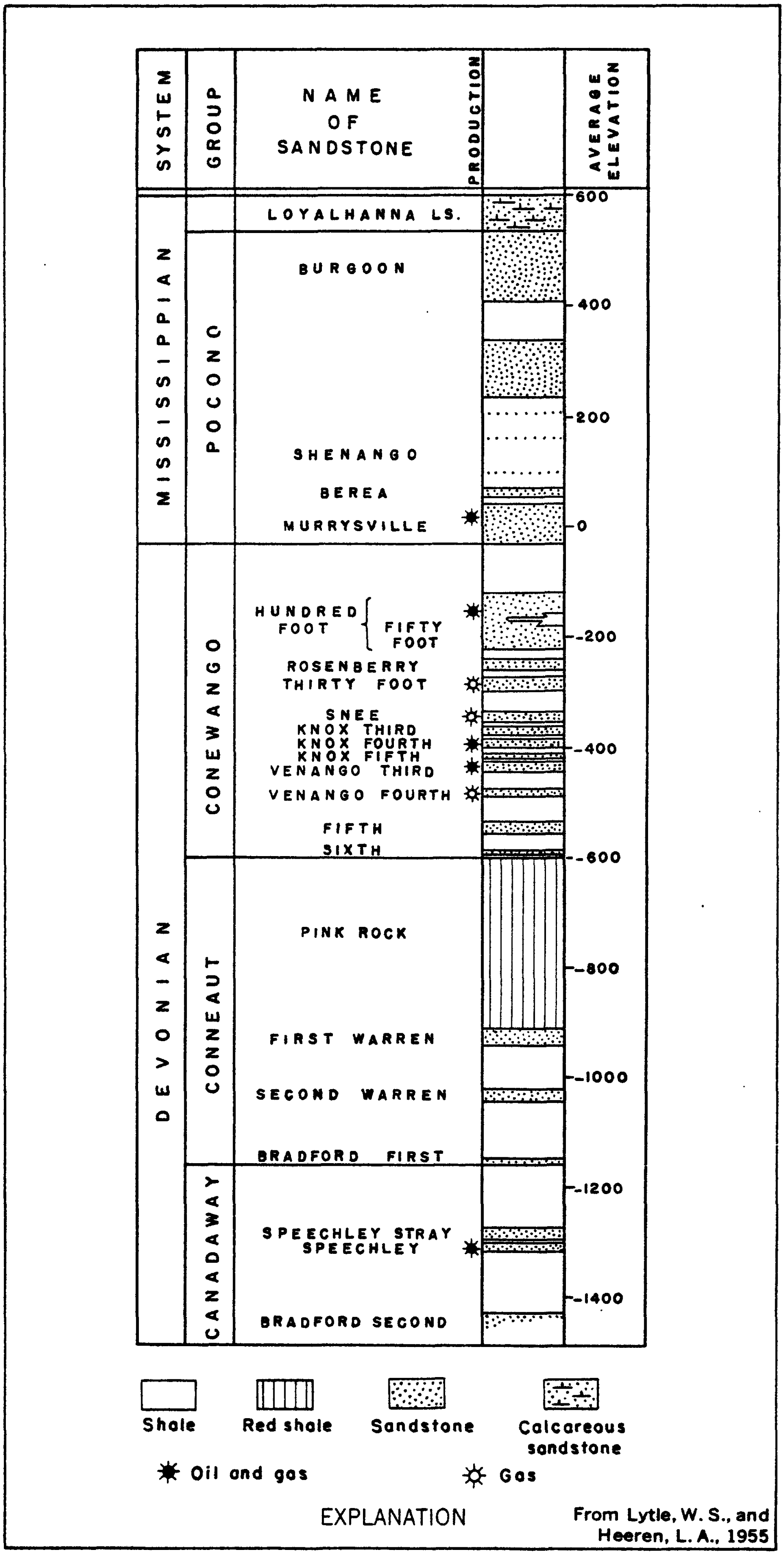

FIGURE 28.—Composite columnar section showing rocks encountered in the subsurface in Butler County, Pa.

units are productive in contiguous townships. In this area there is little or no observable relationship between structure and hydrocarbon accumulation. The shape and extent of the pools are controlled largely by the shape and extent of the producing sandstones lenses. As stated earlier, bodies of porous and permeable sandstone surrounded by shale may be suitable for the disposal of radioactive wastes. With additional study, areas with less drilling may be discovered where nonproductive lenticular bodies of sandstone in the Devonian clastic sequence might have lithologic properties that are compatible with radioactive waste solutions. Thorough testing will be necessary to prove that the sandstone body is completely isolated from other sandstones above and below and from stratigraphically equivalent sandstones in nearby producing areas.

Parts of the Devonian clastic sequence conceivably may be usable for waste disposal in some areas in south-central New York and northern Pennsylvania where the sequence is thick and has been penetrated by relatively few wells. In most of this area the upper part of the sequence crops out at the surface, but because of its great thickness (5,000 to 10,000 feet), the lower parts of the sequence commonly occur at sufficient depths below the surface to be considered for waste-disposal purposes. The Devonian sequence consists largely of interbedded gray shale, mudrock, siltstone, and sandstone, and contains many red beds in the upper part. Quantitative data regarding the porosity and permeability of the sandstones in the sequence are lacking, but megascopic examination of surface exposures suggests that both are low. However, it might be possible to provide some storage space by artificial fracturing. As many of the sandstone beds exposed at the surface are lenticular, it may be possible to locate isolated sandstone beds surrounded by essentially impermeable shale in the subsurface. The general area in which conditions appear to be most favorable for the discovery of reservoirs in the Devonian clastic sequence is shown on figure 26, and includes all or parts of the following: Susquehanna, Wyoming, Luzerne, Sullivan, Bradford, Lycoming and Tioga Counties, Pa., and Sullivan, Delaware, Tioga, Broome and Chemung Counties, N. Y.

<u>Mississippian sequence</u>.--The Mississippian sequence appears to be less well suited for waste-disposal purposes than the underlying Devonian clastic sequence. Because of its stratigraphically higher position the sequence generally lies at shallower depths and occupies a smaller area in the basin than the Devonian sequence. Throughout most of it extent the Mississippian sequence lies less than 2,000 feet below the surface. It is present at the surface in large areas along the north and west sides of the basin, and crops out in many narrow belts in the Valley and Ridge province in the vicinity of the Appalachian structural front. The bulk of the sequence lies more than 2,000 feet below the surface only in three areas of appreciable size. The first area encompasses the southwest corner of Pennsylvania, parts of northwest West Virginia, and the southeast edge of Ohio, and is approximately outlined by the outcrop area of the Dunkard group (Permian) shown on the Geologic Map of the United States (Stose and Ljungstedt, 1932). The second is a broadly synclinal area that extends from the south-west edge of the Pine Mountain overthrust in Tennessee northeastward along the axis of the Middlesboro syncline and continues into southern West Virginia. The third large area is in Alabama at the extreme southern end of the Appalachian basin as defined in this paper.

In general the geologic environment of the sequence in the northern and southern areas is unfavorable for the disposal of radioactive wastes, whereas it appears to be more favorable in the central area (fig. 29). In the northern area both the sequence and the underlying rocks have been extensively drilled for oil and gas. Furthermore the overlying Pennsylvanian rocks are extensively used for coal, and to some extent for clay, shale, and limestone. Some rocks of Pennsylvanian age are also productive of oil and gas. Among the more productive rocks of the Mississippian sequence are the Berea Sandstone near the base of the sequence, the Squaw, Big Injun, and Keener sands in the middle, and the Ravencliff and Maxton sands in the upper part. Rocks of the Mississippian sequence probably can not be utilized for waste disposal in this area because of the intense exploitation of coal, oil, and gas.

It is difficult to evaluate the waste-disposal possibilities of the Mississippian sequence in the vicinity of the Pine Mountain overthrust block because relatively little subsurface data are available, especially in the southern part of the area. The lower part of the sequence consists largely of interbedded sandstone and shale. Too little subsurface data are available to indicate whether or not any of the sandstone units might be considered for waste-disposal purposes. The middle part of the Mississippian sequence consists largely of limestone and is considered to be a potential oil and gas producer. The upper part of the sequence is composed largely of alternating layers of shale and quartzose sandstone, including some coarse-grained sandstone and conglomeratic sandstone. Detailed studies by Wilpolt and Marden (1959, p. 28, 29) show that many of the sandstone units are lenticular. It is possible that one or more lenticular sandstones with properties suitable for containing waste solutions can be located by means of a detailed subsurface exploration program in this area. Three factors, however, may eliminate the Mississippian rocks in this area from further consideration. First, much coal is mined, largely by underground methods, from the overlying Pennsylvanian rocks. Second, gas has been obtained from the middle and upper parts of the sequence locally and shows of oil have been encountered in many wells. Parts of the Mississippian sequence are considered to be potentially productive of hydrocarbons in untested areas along the Middlesboro syncline and northeastward into southern West Virginia. Third, in much of this area, the upper part of the sequence, which appears to be most favorable for waste disposal in some respects, is probably too near the surface, for it is at a depth of about 2,000 feet.

It is also difficult to evaluate the waste-disposal possibilities of the Mississippian rocks where they occur at sufficient depth in Alabama. As shown by Welch (1959), most of the sequence is composed of chert and oolitic limestone in Blount, Walker, and Winston Counties. Less is known about the sequence farther south toward the southern margin of the basin. McGlamery (1955) did not recognize rocks of Mississippian age in a well drilled in northern Tuscaloosa County. In general the Mississippian sequence in Alabama does not appear to be well suited for radioactive waste disposal for the following reasons: it is a potential target for oil and gas production, and it is composed largely of limestone which is commonly susceptible to solution and fracturing

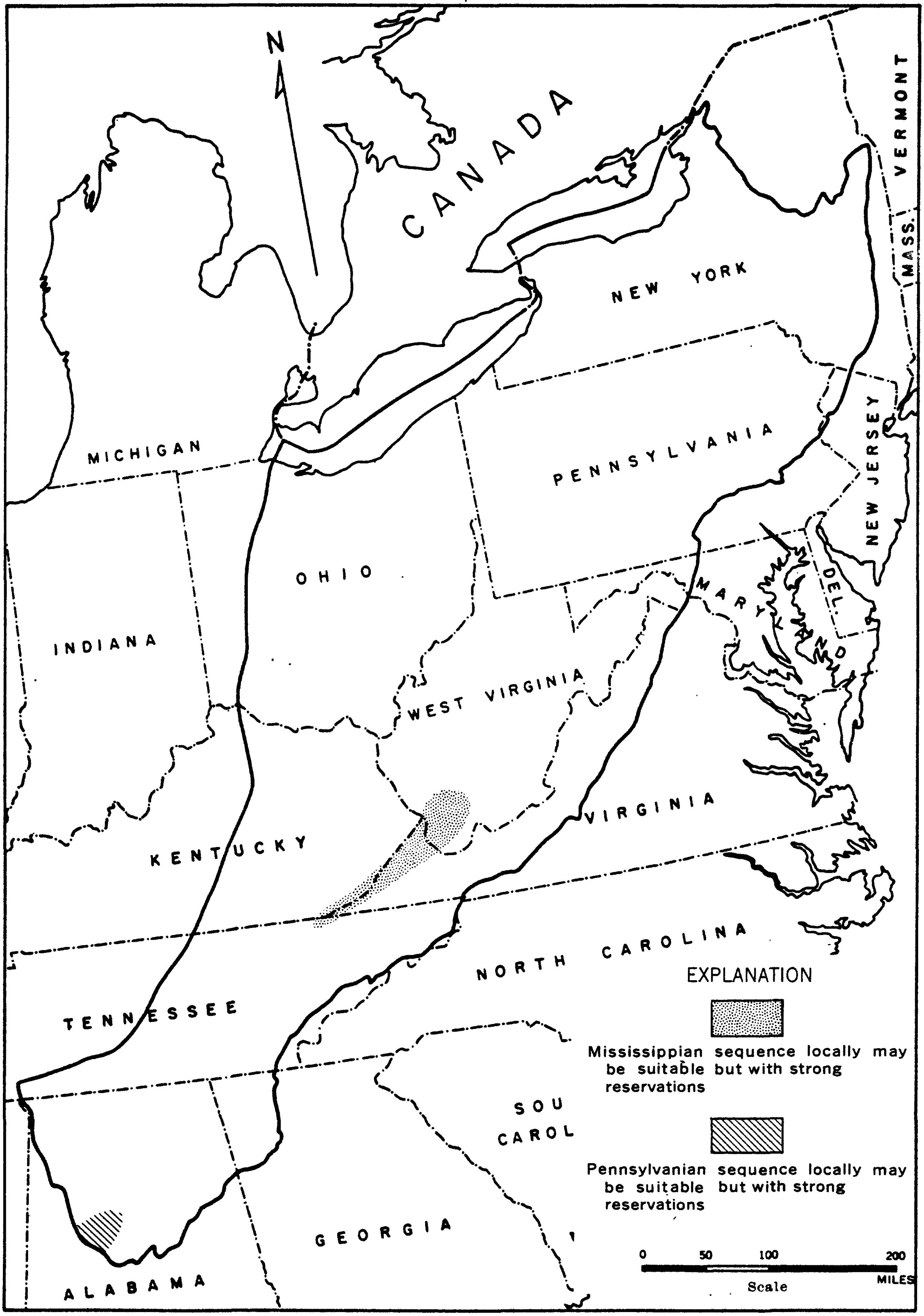

FIGURE 29.—Map showing general areas where geologic environment of Mississippian and Pennsylvanian sequences may be suitable for waste-disposal purposes.

Pennsylvanian sequence.--In general the Pennsylvanian sequence appears to be poorly suited for waste-disposal purposes owing to economic and geologic conditions. Throughout most of its extent in the basin the sequence is an important source of coal. It has been mined and quarried at many places for clay, limestone, and shale. In the central part of the basin, especially in western West Virginia, and eastern Kentucky sandstones in the lower part of the sequence locally yield oil and gas. In parts of the basin, especially in central Alabama, where the sequence has not yielded oil and gas, it has been penetrated by wells drilled into underlying rocks. On geologic grounds the Pennsylvanian sequence is not a likely host rock for radioactive wastes for the following reasons. Throughout most of its extent, it is too shallow. In synclines along the east edge of the basin, parts of the sequence may lie more than 2,000 feet below the surface, but in such areas, beds that are deeply buried in the trough of a syncline rise rapidly to the surface along the flanks of contiguous anticlines.

A possible exception to some of the objections listed above may occur in the vicinity of northern Tuscaloosa County, Ala., at the extreme southern end of the Appalachian basin (fig. 29). In Tuscaloosa County, the lower part of the sequence is more than 2000 feet below the surface. The sequence consists largely of alternating layers of carbonaceous black shale, sandy gray shale, and medium-to coarse-grained micaceous sandstone (McGlamery, 1955, p. 380-385). A gentle dome about $3\frac{1}{2}$ miles in diameter with approximately 200 feet of closure is present in sec. 2, T. 18 S., R.9 W., in the northern part of the county (Semmes, 1929, map 5). Two wells (Semmes, 1929, p. 168-169, and McGlamery, 1955, p. 380-385) penetrated about 3400 feet of Pennsylvanian rocks. Several coal beds were penetrated in the upper part and several shows of gas were reported in one well. If the presence of coal and the possible occurrence of hydrocarbons in commercial quantities do not eliminate the area from consideration, the Pennsylvanian sequence seems to offer possibilities for waste disposal. Porous and permeable coarse-grained quartzose sandstones on the dome mentioned above, or on a similar dome in west-central Alabama, possibly might serve as satisfactory reservoirs.

Summary

The waste-disposal possibilities of the nine sequences of stratified rocks recognized in the Appalachian basin are summarized in the table that follows. The evaluations are based on geologic factors and are, in general, independent of hydrologic and economic factors. From top to bottom the sequences are listed in descending stratigraphic order, that is, from youngest to oldest. The terms in the second column are an attempt to compare or contrast the waste-disposal possibilities of one sequence with or to the waste-disposal possibilities of other sequences. Consequently the terms are relative within the Appalachian basin. No attempt is made here to compare or contrast the suitability for waste-disposal purposes of rocks in the basin or the basin in general with other areas.

SEQUENCE	GENERAL SUITABILITY	DISADVANTAGES	ADVANTAGES	ROCK UNIT(S) MOST SUITABLE	AREAS WHERE GEOLOGIC FACTORS MAY BE FAVORABLE
Silurian-Devonian carbonate	poor	1) Yields gas, oil, salt, and limestone, and is utilized for underground storage of gas in northern part of basin. 2) Has been penetrated be many wells in western half of basin. 3) As 3) above. 4) Is composed largely of carbonate rocks. 5) Contains two extensive aquifers in contact with carbonate rocks: both aquifers contain hydrocarbons.	1) Contains moderately thick evaporite succession (Salina Formation) in north-central part of basin. 2) Contains thick succession of red beds (Bloomsburg) in northeast part of basin.	1) Salina Formation 2) Bloomsburg Red Beds	1) North-central Pennsylvania and south-central New York: where Salina Formation is thick, contains much rock salt, and occurs at appropiate depths. 2) Northeast Pennsylvania: where Bloomsburg is thick, occurs at appropriate depths, is of little commercial value in the subsurface, and where porosity may exist or can be created artificially.
Early Silurian clastic sequence	poor: perhaps fair	1) Important source of oil and gas and is used for underground storage of gas in northwest part of basin. 2) Has been penetrated by many drill holes in western half of basin. 3) Is composed largely of carbonate rocks in southwest part of basin. 4) Commonly contains carbonate cementing material or interbedded carbonate rocks. 5) Is thin and is directly overlain by a carbonate sequence. 6) Is too shallow or too closely situated to outcrop belts in many peripheral areas.	1) Contains moderate volume of porous quartz sandstone. 2) Contains some quartz sandstone lenses enclosed in shale. 3) Structural environment may be especially favorable locally.	1) "Clinton" sands 2) Clinch Sandstone 3) Tuscarora Sandstone	1) Central Ohio: undrilled sandstone lenses at appropriate depth and with desirable lithologic properties may occur. 2) Southwest Virginia and contiguous parts of Kentucky and Tennessee: thrust-faulted areas where Clinch Sandstone is locally overlain by impermeable older shales, and where other conditions may be favorable. 3) Central folded Appalachians: if Tuscarora Sandstone has sufficient porosity in troughs of synclines, and if fluids can be contained. 4) Western Pennsylvania, southeastern Ohio, western Maryland and much of West Virginia: in Tuscarora Sandstone and "Clinton" sands if storage is feasible where younger rocks yield coal, oil, and gas.

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SEQUENCE	GENERAL SUITABILITY	DISADVANTAGES	ADVANTAGES	ROCK UNIT(S) MOST SUITABLE	AREAS WHERE GEOLOGIC FACTORS MAY BE FAVORABLE
Pennsylvanian	poor	1) Is intensely exploited for for coal, clay, shale, limestone, oil, and gas. 2) Has been penetrated by great many wells drilled for oil and gas in underlying strata. 3) Is too shallow in most areas.	1) Contains large volume of coarse-grained porous quartz sandstone, commonly in highly lenticular bodies. 2) Contains little carbonate rock.	1) Pottsville Group	1) Central Alabama: some possibilities may exist where porous quartz sandstones bodies on gentle domes may be suitable.
Mississippian	poor	1) Important source of oil and gas in central part of basin. 2) As 2) above. 3) Is too shallow in many areas 4) Consists largely of carbonate rocks in southern part of basin.	1) As 1) above. 2) Contains large volume of red beds (Mauch Chunk) of no economic value in subsurface.	1) Price Sandstone 2) Pennington Group	1) Southern West Virginia and vicinity of Kentucky-Virginia boundary: some possibilities may exist in porous quartz sandstones in trough of Middlesboro syncline, if presence of coal in younger rocks does not eliminate them from consideration.
Devonian clastic	poor	1) Important source of oil and gas in central and north-central parts of basin. 2) As 2) above. 3) Is too shallow in many peripheral areas. 4) Consists largely of fine-grained nonbrittle shale with little porosity in north-central part of basin. 5) Is too thin in southern part of basin.	1) Contains many porous lenticular bodies of sandstone enclosed in shale. 2) Contains large volume of rock without known commercial value in the subsurface. 3) Has great thickness, especially in northeast part of basin. 4) Contains little carbonate rock.	1) Catskill Formation 2) Chemung Formation and other Upper Devonian clastic formations 3) Hamilton Group	1) Northeast Pennsylvania and south-central New York: where sequence is thick, has no known commercial value in the subsurface, contains very few carbonate rocks, and where parts of sequence may have natural porosity or be susceptible to artificial fracturing. 2) Western Pennsylvania and central West Virginia: possible small undrilled areas where porous sandstone bodies without oil and gas in commercial quantities may occur.

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SEQUENCE	GENERAL SUITABILITY	DISADVANTAGES	ADVANTAGES	ROCK UNIT(S) MOST SUITABLE	AREAS WHERE GEOLOGIC FACTORS MAY BE FAVORABLE
Late Ordovician clastic	moderately fair	1) Consists largely of carbonate rocks along west side of basin. 2) Is too shallow in many areas near periphery of basin. 3) Lies more than 10,000 feet below surface in much of central part of basin. 4) Is complexly deformed along east side of basin.	1) Is composed largely of noncarbonate rocks with little or no commercial value in the subsurface. 2) Includes two units composed largely of sandstone and a thick succession of shale. 3) Underlies large areas of the basin at depths greater than 2,000 feet below the surface. 4) Has been penetrated by few drill holes in central part of basin.	1) Oswego Sandstone 2) Juniata Formation 3) Martinsburg Shale 4) Queenston Shale	1) South-central New York and north-central Pennsylvania: where sequence is thick, contains no carbonate rocks, lies at appropriate depths, and where further study may show that sufficient porosity exists or can be created artificially. 2) Southern New York, western Pennsylvania, southeastern Ohio, western Maryland and West Virginia: in Martinsburg and/or Queenston Shale if sufficient porosity and permeability exist or can be created, and if (in part) disposal is feasible where younger rocks yield coal, oil, and gas.
Cambrian-Ordovician carbonate	poor	1) Has been productive of oil and gas locally along west and north sides of basin, and is considered to be potentially productive in other areas. 2) Consists largely of carbonate rocks. 3) Contains many salaquifers and other porous layers whose physical characteristics are poorly known. 4) Lies more than 10,000 feet below surface in central part of basin. 5) As 2) above. 6) As 4) above.	1) Contains some noncarbonate rocks of little commercial value in the subsurface in southeast part of basin. 2) As 3) above. 3) As 4) above.	1) Bays Formation 2) Ottosee Shale 3) Sevier Formation 4) Chota Formation 5) Tellico Formation	1) Eastern Tennessee, northwestern Georgia, and southwestern Virginia: where sequence contains a thick succession of noncarbonate rocks, and where further study may show that lithology and structure locally are favorable.

SEQUENCE	GENERAL SUITABILITY	DISADVANTAGES	ADVANTAGES	ROCK UNIT(S) MOST SUITABLE	AREAS WHERE GEOLOGIC FACTORS MAY BE FAVORABLE
Early Cambrian clastic	poor	1) Is thin or absent along north and west sides of basin. 2) Is directly overlain by a carbonate sequence. 3) Probably has low porosity and permeability in most areas. 4) As 4) above. 5) Is complexly deformed along east side of basin.	1) Is barren of oil and gas in commercial quantities. 2) Contains large volume of non-carbonate clastic rocks, especially shale, sandstone, and quartzite. 3) May be highly permeable locally due to structural deformation.	1) Waynesboro or Rome Formations 2) Formations of Chilhowee Group and some associated rocks	1) Southern Virginia, eastern Tennessee, and northwest Georgia: local areas where sequence lies at appropriate depths, and where lithology and structure may be favorable.
Late Precambrian stratified	poor	1) Is absent in most parts of the basin. 2) Structural environment is complex: is commonly metamorphosed and complexly faulted. 3) Probably has low porosity due to recrystallization. 4) Sequence is not adequately mapped in large areas and little is known about it in subsurface.	1) Thick sequence of noncarbonate rocks with little or no known commercial value in the subsurface.	1) Ocoee Series 2) Catoctin Greenstone 3) Mount Rogers Group	1) Southern Virginia and east-Tennessee along west flank of Blue Ridge: where great thickness of the sequence suggest that it should be considered. Further evaluation unwarranted here because stratigraphy, lithology, and structure of the sequence are poorly known in large areas.

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